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# Cognitive control in working memory : an individual differences approach based on the Dual Mechanisms of Control framework

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UNIVERSITY OF GRENoble



## THESIS

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In partial fulfillment of the requirements for the degree of

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By

**Corentin GONTHIER**

Advised by **Jean-Luc ROULIN** and **Monica BACIU**

prepared in the **Laboratoire de Psychologie et NeuroCognition – CNRS, UMR5105 – University of Grenoble and University of Savoie**

in the **École Doctorale Ingénierie pour la Santé, la Cognition et l'Environnement (EDISCE)**

# Cognitive control in working memory: An individual differences approach based on the Dual Mechanisms of Control framework

Defended **December 12, 2014**.

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UNIVERSITÉ DE GRENOBLE



## THÈSE

Pour obtenir le grade de

## DOCTEUR DE L'UNIVERSITÉ DE GRENOBLE

Spécialité : **Sciences cognitives, psychologie cognitive et neurocognition**

Arrêté ministériel : 7 août 2006

Présentée par

**Corentin GONTHIER**

Thèse dirigée par **Jean-Luc ROULIN** et **Monica BACIU**

préparée au sein du **Laboratoire de Psychologie et NeuroCognition – CNRS, UMR 5105 – Université de Grenoble et Université de Savoie**

dans **l'École Doctorale Ingénierie pour la Santé, la Cognition et l'Environnement (EDISCE)**

# Contrôle cognitif en mémoire de travail : une approche différentielle dans le cadre du modèle à Deux Mécanismes de Contrôle

Thèse soutenue publiquement le **12 décembre 2014**, devant le jury composé de :

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*You don't use science to show that you're right,  
you use science to become right.*

– Randall Munroe, *xkcd 701*

*And here, poor fool! with all my lore,  
I stand no wiser than before.*

– Johann Wolfgang von Goethe, *Faust*

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# ABSTRACT

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The constructs of working memory and cognitive control are conceptually close; a high working memory capacity is hypothesized to be associated with an efficient cognitive control. This hypothetical association has large implications for human cognition and provides an elegant explanation for the frequently reported relationship between working memory capacity and fluid intelligence. However, the difficulty in operationalizing and measuring cognitive control makes this hypothesis hard to test. One model of cognitive control, the Dual Mechanisms of Control (DMC) framework, constitutes a possible solution to this problem: the model proposes two distinct mechanisms of cognitive control which can be efficiently operationalized and studied. There is reason to believe that one of these two mechanisms, proactive control, is specifically related to working memory capacity. The objective of the present research work was to assess the relationship between individual differences in working memory capacity and the tendency to use proactive control. This relationship was tested in four steps: 1) by using innovative measures of the tendency to use proactive control, based on newly developed paradigms; 2) with classic cognitive control tasks sensitive to proactive control; 3) with a neuroimaging approach using electro-encephalography and functional magnetic resonance imaging; and 4) by testing whether the use of proactive control explains the relationship between working memory and fluid intelligence. Overall, our results do not support the idea that working memory capacity is uniquely related to the tendency to use proactive control; the data tend to indicate a general advantage of participants with a high working memory capacity in all situations.

**KEYWORDS:** working memory; cognitive control; fluid intelligence; dual mechanisms of control (DMC); individual differences; neuroimaging

# RÉSUMÉ

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La mémoire de travail et le contrôle cognitif sont des construits proches ; on suppose généralement qu'une forte capacité en mémoire de travail est associée à un contrôle cognitif efficace. Cette hypothèse a des implications importantes pour la cognition humaine et apporte une explication élégante à la corrélation fréquemment reportée entre mémoire de travail et intelligence fluide. En revanche, les difficultés d'opérationnalisation et de mesure du contrôle cognitif rendent l'hypothèse difficile à tester. Un modèle récent du contrôle cognitif, le modèle à Deux Mécanismes de Contrôle (DMC), offre une solution à ce problème : ce modèle propose l'existence de deux mécanismes de contrôle cognitif distincts et permet de les opérationnaliser de façon efficace. La littérature prédit que l'un de ces deux mécanismes, le contrôle proactif, devrait être lié à la mémoire de travail. L'objectif de ce travail de recherche était de tester l'existence d'une relation entre les différences inter-individuelles en mémoire de travail et la tendance à mettre en place un mécanisme de contrôle proactif. Cette relation a été testée sous quatre axes de travail : 1) en utilisant de nouveaux paradigmes expérimentaux pour mesurer la tendance à utiliser le contrôle proactif, 2) grâce à des tâches classiques de contrôle cognitif choisies pour leur sensibilité au contrôle proactif, 3) à travers une approche par imagerie cérébrale incluant électro-encéphalographie et imagerie par résonance magnétique fonctionnelle, et 4) en tant que facteur explicatif de la relation entre mémoire de travail et intelligence fluide. Dans l'ensemble, nos résultats ne soutiennent pas l'idée selon laquelle la capacité en mémoire de travail est spécifiquement liée à la tendance à utiliser un mécanisme de contrôle proactif ; les données suggèrent plutôt un avantage général en faveur des participants à forte capacité en mémoire de travail dans toutes les situations.

**MOTS-CLEFS** : mémoire de travail ; contrôle cognitif ; intelligence fluide ; dual mechanisms of control (DMC) ; différences inter-individuelles ; imagerie cérébrale

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# INTRODUCTION

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# PREAMBLE

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The present work has its roots in an undergrad research project asking an easy question: why does working memory matter? This initial project involved stroke patients, a working memory task and a rather crude measure of controlled attention; unsatisfactory results led to a graduate research project which led to a thesis. Five years later, the problem has not been solved and the Nobel prize seems out of reach for good; however, this manuscript is entirely coloured by the original question. Well then, why does working memory matter?

Working memory refers to the ability to store information in short-term memory while performing another cognitive process. As its name suggests, working memory is primarily a mnemonic ability; yet it is also an excellent predictor of performance in a variety of high-level tasks that seemingly do not require memory at all. Working memory is especially efficient at predicting fluid intelligence, a construct that is not supposed to involve memory in any way. A number of explanations have been proposed to account for this puzzling relationship, and these explanations generally seem unsatisfactory. Chapter 1 in this introduction will offer a broad view of the working memory construct, present evidence for its relationship with high-level cognition and fluid intelligence in particular, and review a few hypotheses attempting to explain this relationship.

One hypothesis in particular is based on the notion of cognitive control, or the ability to regulate one's behaviour in a complex situation. The hypothesis states that working memory is related to fluid intelligence because cognitive control plays a role in both working memory tasks and high-level cognitive tasks. This sounds plausible, since working memory and fluid intelligence have ties with cognitive control. On the other hand, attempts at directly testing whether cognitive control actually drives their relationship have met little success. Chapter 2 will present the notion of cognitive control, provide evidence that it is related to working memory on one hand and to fluid intelligence on the other hand, and review the experiments testing its role in the relationship between working memory and fluid intelligence.

Although direct tests of the cognitive control hypothesis have not been overly successful, this may be due to the difficulty in adequately operationalizing the notion of cognitive control: the construct is elusive and hard to measure. Fortunately, one recent model

of cognitive control, the dual mechanisms of control (DMC) framework, proposes to break down cognitive control into two constituent mechanisms that can be efficiently operationalized. One of these mechanisms, proactive control, is generally more efficient than the other; this mechanism also has ties to working memory. On this basis, we propose the thesis that participants with high working memory capacity are more likely to use proactive control, and that this tendency to use proactive control drives their higher performance in fluid intelligence tasks. Chapter 3 will present the DMC framework and the associated studies, review the evidence in favour of a three-way relationship between working memory, proactive control and fluid intelligence, and detail the rationale for our thesis.

# CHAPTER 1. WORKING MEMORY AND HIGH-LEVEL COGNITION

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## **Objectives**

The purpose of this chapter is to introduce the key notion of working memory and to discuss its relationship with high-level cognition. We begin with a presentation of working memory and a rough outline of a few working memory models, with a focus on the notion of control processes. We then summarize the existing evidence of a relationship between working memory and high-level cognition, with a special focus on fluid intelligence. The third section discusses some of the most prevalent hypotheses attempting to explain this relationship.

## **1. A general view of working memory**

### **1.1. Overview of the working memory construct**

#### *1.1.1 Definition and terminology*

Working memory as a construct is central to human cognition in general and to this work in particular. The notion of working memory specifically refers to a cognitive system that carries out the temporary storage and manipulation of information (Baddeley & Hitch, 1974). This dual function of simultaneous maintenance and processing of information is the defining feature of the working memory system, even though different authors have very different outlooks on the construct and may place greater emphasis on either storage or manipulation (Miyake & Shah, 1999; Conway, Jarrold, Kane, Miyake, & Towse, 2007).

The best way to get acquainted with working memory is through a direct real-life example: imagine that you are reading a stodgy thesis manuscript with never-ending sentences, often stretching on multiple lines, developing a collection of various arguments without any apparent logic, and that you are to disentangle the meaning of these sentences, which requires you to carry out complex information processing, while at the same time accurately storing the content of the previous lines in memory because understanding the meaning of the sentence as a whole requires that you piece together all the information from the different parts of the sentence, and the combination of these processing and storage

demands creates difficulty in the task, requiring a specific cognitive system in the form of working memory. One could say that reading the previous sentence imposed a high working memory load on you, since it demanded the temporary maintenance of a significant amount of information in the face of concurrent processing. Because complex situations requiring the simultaneous storage and processing of information are ubiquitous in everyday life, working memory is thought to play an important role in daily cognitive functioning.

Although the notion of working memory is often used interchangeably with short-term memory, the two are distinct constructs that should not be confused with each other (see e.g. Cowan, 2008): the notion of short-term memory only encompasses the passive storage of information, without reference to concurrent manipulation demands. There is, however, some amount of overlap between working memory and short-term memory; indeed, it is possible to view working memory as the combination of short-term memory and additional control processes (Engle & Kane, 2004; Kane & Engle, 2003; Cowan, 2008). This view does not consider short-term memory and working memory as two completely distinct cognitive systems; instead, working memory is only functionally different from short-term memory because of the additional processing requirements in working memory tasks. In other words, working memory may be seen as the simultaneous recruitment of short-term memory for storage, and loosely defined control processes dealing with the selection, coordination and manipulation of information. These control processes constitute a critical aspect of working memory because they are its fundamental defining feature, in contrast to short-term memory.

When compared to short-term memory, working memory is a relatively recent addition to the field of cognitive psychology; according to Conway et al. (2007), the first use of the words "working memory" seems to date back to 1960 (G. A. Miller, Galanter, & Pribram, 1960), although the concept itself is slightly older (Johnson, 1955). Considering working memory from a historical perspective makes the distinction with short-term memory more explicit: the notion of working memory actually evolved on the basis of previous short-term memory research (Baddeley, 2003a). The first works on working memory sought to extend the concept of short-term memory so as to bridge the conceptual and empirical gap between memory and other cognitive processing tasks. Indeed, the idea that all complex information processing requires the temporary maintenance of the information being processed, along with the manipulation of this information, led to the conception of a general cognitive system encompassing both processing and storage. This general cognitive system, combining short-term memory with control processes, ultimately took the form of working memory (Baddeley & Hitch, 1974).

The novel idea that all the information necessary for complex processing has to transit through working memory had an interesting consequence: these early works featured an intuitively appealing approach to working memory as a workspace for cognition (e.g. Baddeley & Hitch, 1974). Johnson (1955, p. 82) used the notion of a « workshop wherein ideas are processed »; G. A. Miller et al. (1960) viewed working memory as the mental place where intentions are stored before they can be executed. More recently, Baars (1997) poetically described working memory as the stage of a theater, where the ideas play the part of actors, illuminated by the spotlight of attention. The notion of a global workspace directly refers to a central integrative hub for cognition (e.g. Baars, Franklin & Ramsay, 2013); as a consequence, this view places working memory at the very heart of human cognition as a whole (Miyake & Shah, 1999). In the same logic, working memory has strong ties with conscious awareness: conscious processes are thought to be critical for working memory functioning (Baars, 2003), but working memory has also been viewed as the stage where consciousness operates (Baars, 1997). Some authors even went as far as equating working memory with consciousness (see Andrade, 2001), and even though this view may be regarded as a little extreme, it helps highlighting the importance that many theorists confer to working memory. The workspace approach to working memory was mainly emphasized in early works on the subject, but the idea is still widespread in more recent literature (e.g. Logie, 2003) and is often implicit in modern research.

### *1.1.2. Working memory: a modal or amodal system?*

It is a common habit to separate memory processes depending on the type of to-be-remembered material; a distinction is often drawn, for example, between spatial and verbal memory. This distinction is found in memory tests used for clinical practice, but also in certain theoretical models of short-term memory which suppose the existence of different systems for spatial short-term memory and verbal short-term memory – among others. This idea raises the question of the unitary nature of working memory: can we refer to a single, general working memory construct, or is it necessary to distinguish modality-specific working memories?

Several theoretical accounts of working memory posit the existence of different processes depending on the type of material to be memorized. The most influential example of this conception is the working memory model of Baddeley (1986); in its original version, the model hypothesized the existence of two different memory systems: a phonological loop storing verbal information and a visual sketchpad for visuo-spatial information. The visual

sketchpad itself might be divided in two modality-specific subsystems: the inner scribe, storing information about spatial locations, and the visual cache for objects and shapes. Another example is the continuum model (Cornoldi & Vecchi, 2003), in which the processes used to maintain information in memory vary as a function of modality-specific features; similar to Baddeley's model, the continuum model proposes a distinction between visual and spatial information. Certain models are also specifically concerned with one type of sensory modality: for example, the object files model (Kahneman & Treisman, 1984) and the object tokens model (Marr, 1976) only deal with the storage of visual information. These two models intimately tie memory storage with sensory processing and rely on the implicit assumption that different types of materials call for different storage processes – although they may be considered as short-term memory rather than working memory models. Conversely, the object-oriented episodic record (O-OER; Jones, Beaman, & Macken, 1996) model is mainly concerned with auditory working memory, even though it can be extended to other sensory modalities.

Empirical data also point towards the existence of distinct storage systems (for a review, see Jonides et al., 1996). A first argument is the observation that performing two tasks simultaneously elicits less interference when the two tasks involve different types of material. For example, the temporary maintenance of a visual image is impaired by concurrent visual processing, but the maintenance of verbal information is not (Postle, Idzikowski, Della Sala, Logie, & Baddeley, 2006); conversely, the concurrent presentation of irrelevant verbal material disrupts the maintenance of verbal, but not visual information (Kroll, Parks, Parkinson, Bieber, & Johnson, 1970). The same dissociation is observed for spatial and visual information: overall, spatial interference selectively impairs spatial working memory whereas visual interference impairs visual working memory (Klauer & Zhao, 2004). Other arguments for the existence of distinct storage systems include the observation of double dissociations between visual and verbal short-term memory deficits in certain pathologies (e.g. Wang & Bellugi, 1994) and certain brain lesions (see Jonides et al., 1996), and the distinct neural substrates for the memory of different types of materials (e.g. Mecklinger & Müller, 1996; E. E. Smith, Jonides, & Koeppel, 1996).

In summary, there is considerable evidence in the literature that the maintenance of information in memory relies on different storage processes as a function of the type of to-be-remembered stimuli. Are these sufficient grounds to distinguish separate working memories? Not necessarily. In contrast with the proposal of different storage systems for different types of material, most working memory models view the control processes involved in working

memory as a unitary system, common to all working memory tasks (e.g. Baddeley, 2003a; Kane, Conway, Hambrick, & Engle, 2007). Latent variable analyses unambiguously show that the scores on various working memory tasks are highly correlated, independently of the specific material being used (Kane et al., 2004; Ackerman, Beier, & Boyle, 2002; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002; Oberauer, Süß, Wilhelm, & Wittman, 2003; see also Conway & Engle, 1996; Turner & Engle, 1989; Conway, Cowan, Bunting, Theriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999). The various working memory tasks are reliably observed to load on a common factor, rather than on different factors depending on the type of material (Ackerman et al., 2002; Oberauer et al., 2003; Kane et al., 2004; Conway et al., 2002; Engle et al., 1999). Different working memory tasks using different types of materials tend to demonstrate the same predictive validity and show similar correlations with other cognitive tasks (Kane et al., 2004; Turner & Engle, 1989; Conway et al., 2002; Engle et al., 1999). There is also evidence that working memory tasks involving different types of materials tend to recruit mainly overlapping neural networks (e.g. Chein, Moore, & Conway, 2011). As a consequence, working memory may be viewed as a domain-general construct (Kane et al., 2004), involving largely transversal mechanisms. This amodal character is moderated by the existence of specific sub-processes for the maintenance of various types of stimuli, but the core working memory ability seems independent of the material being memorized. Another way to phrase this idea is to say that working memory is the association of domain-specific storage processes and domain-general control processes (Kane et al., 2004).

## ***1.2. Control processes in theoretical models of working memory***

The working memory construct is remarkable for the very large number of theoretical models that have been developed over the years; the objective of the following section is to provide some context by giving a brief overview of some of these theoretical models. As we have seen, two of the defining features of working memory are the role of control processes, and the view of the working memory system as the workspace of cognition; many theoretical models of working memory, including the most influential, place a strong emphasis on these two aspects of the construct. Since both control processes and the workspace approach are

particularly relevant to the present work, the following review will be focused on the models emphasizing these two features of working memory.<sup>2</sup>

### *1.2.1. Early models of working memory*

The first theoretical models of working memory have been retired from active service for several decades, but they still warrant our attention for one major reason: they give us an insight into the conceptions which presided over the development of working memory as a construct, and which served as the basis of more current models. Here are three examples of these early models.

Firstly, although not formally a theoretical account of working memory, Broadbent's (1958) model of information processing set the stage for later works. Briefly, the model proposes that the information detected by perceptive sensors is moved into a short-term memory store, equivalent with short-term memory. A selective filter is applied on the information contained within the short-term store, and the information that is not filtered out is then analyzed by a limited capacity processor. While this model predates the term "working memory", the first signs of the concept are apparent in this conception. The short-term store is not an autonomous subsystem, operating in isolation; rather, it functions in combination with a selective attention mechanism that effectively controls which information is processed. In this respect, the association of a selective filter and a limited capacity processor is a precursor of control processes in working memory. Interestingly, this model is mainly notorious for being the first formal model of attention; this emphasizes the close relationship between research on attentional control processes and working memory models.

Secondly, the influential Atkinson and Shiffrin multi-store model (1968) might be considered as the first theoretical account of working memory. The authors proposed that human memory functions with three different stores: a sensory register, a short-term store, and a long-term store. The sensory register is closely based on Sperling's work and is made up of a collection of sensory buffers – one for each sensory modality. The short-term store and

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<sup>2</sup> We do not intend to exhaustively review all existing theoretical accounts of working memory, since such an undertaking would lie far beyond the scope of our research; as a consequence, several influential accounts of working memory have been left off this review. Notable omissions include Unsworth's view of working memory as involving secondary memory (Unsworth & Engle, 2007a), as well as the time-based resource sharing model (Barrouillet, Bernardin, & Camos, 2004), the feature model (Nairne, 1990), the O-OER model (Jones et al., 1996), the long-term working memory model (Ericsson & Kintsch, 1995), and modelizations based on the ACT architecture (J. R. Anderson, Reder, & Lebiere, 1996).



long-term store are broadly equivalent with short-term and long-term memory, respectively. Similar to Broadbent's (1958) information processing model, the multi-store model follows a "pipeline" organization: information has to transit from each store to the next in succession. Whenever a stimulus is detected, the corresponding information is stored in the corresponding sensory buffer for up to a few seconds. An information that is attended to moves from the sensory register to the short-term store, where it can be held for longer durations of 20-30 seconds. The authors underlined the fact that information in the short-term store can be rehearsed – intentionally held in mind – through a form of mental refreshing. The longer an information is maintained in the short-term store, the more likely it is to become represented in the long-term store, where information can be held permanently.

At first glance, the multi-store model deals with short-term memory rather than working memory; however, several features of the model are actually characteristic of working memory. First, the authors consider that all mental processes are performed on information contained within the short-term store, an idea that echoes the conception of working memory as the workspace of cognition. Second, Atkinson and Shiffrin (1971) assign to the short-term store the role of an executive system, tasked with controlling and monitoring information (see Baddeley & Hitch, 1974); in other words, the short-term store is associated with control processes. In this sense, the short-term store effectively functions as a working memory. The demise of the multi-store model was brought about by a number of criticisms, one of the most prominent being the observation that information can directly access long-term memory despite impaired short-term memory, as evidenced by neuropsychological studies (see Baddeley & Hitch, 1974). The unitary view of the short-term store as dealing both with the maintenance of information and with control processes was also questioned (Baddeley & Hitch 1974). Despite these shortcomings, the multi-store model contained the key ingredients of a working memory theory and laid the groundwork for more elaborate designs, among which the famous Baddeley (1986) model.

Lastly, the maltese cross model (Broadbent, 1984) attempted to improve on previous short-term memory models (see Cowan, 1988), notably by giving a more active role to the individual in the processing of incoming information. The model logically took the form of a maltese cross (see Figure 1). The center of the cross is occupied by a processing system (an office worker). According to the model, the processing system receives information from a sensory store (the in-box) and places this information in a limited capacity short-term store (the desktop). While in the short-term store, information is processed according to rules or

other elements present in a long-term store (the filing cabinet). It is then forwarded to an effector system (the out-box).

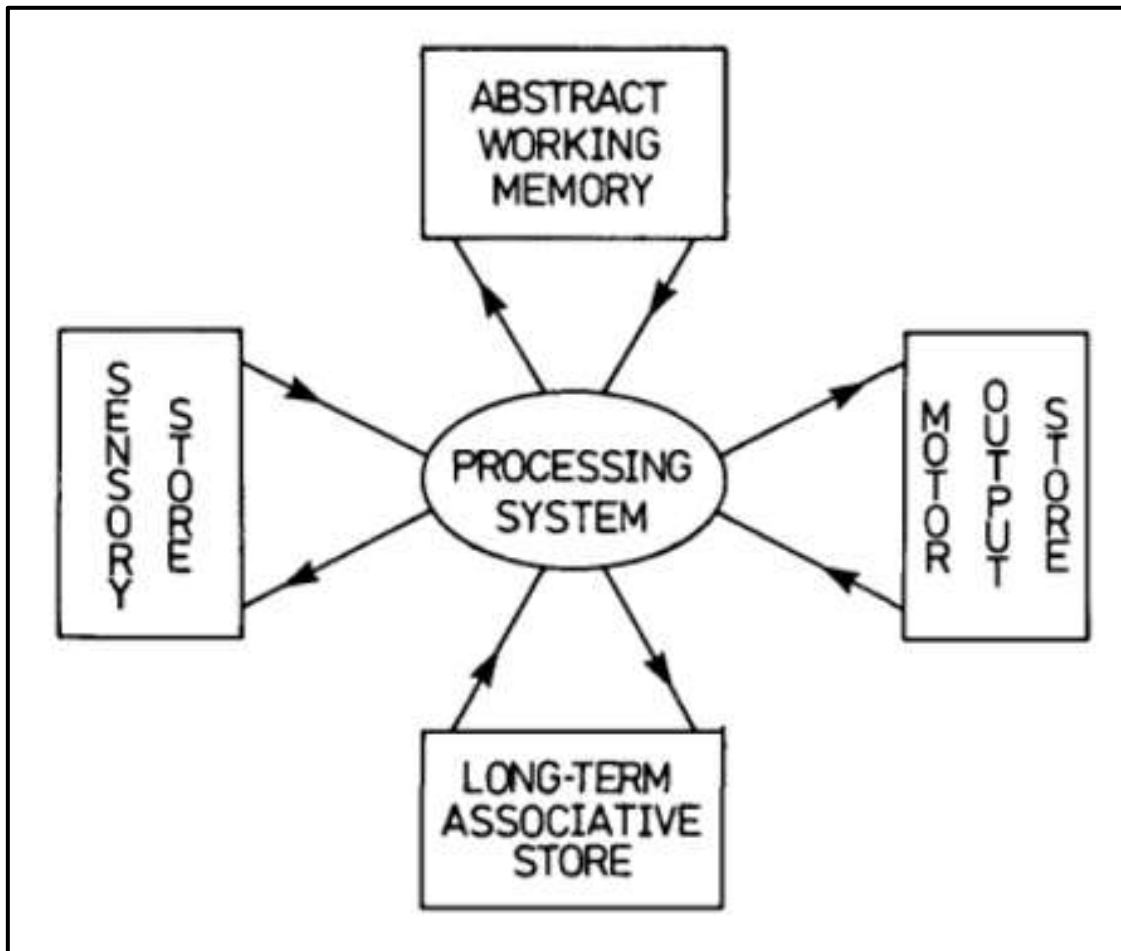


Figure 1. The Maltese cross model. The four boxes represent the different stores in the model and arrows represent the flow of information. From "The maltese cross: A new simplistic model for memory" by D. E. Broadbent, 1984, *Behavioural and Brain Sciences*, 7(1), p. 59. Copyright 1984 by Cambridge University Press.

A conceptual view of working memory emerges from the various elements in the maltese cross model. The limited capacity short-term store acts as the short-term memory component, while the processing system represents the control processes in working memory. Since the short-term memory store constitutes the desktop where information is processed, the model also gives a role to immediate memory as a workspace for cognition. While the maltese cross model does not introduce any new ideas, it is interesting not only for its evocative power (the picture of an office worker classifying files on his desktop provides an expressive view of the dual nature of working memory as processing and storage), but also as one of the first structural models of working memory, clearly dissociating control processes from short-term memory. It is above all an excellent illustration of the pitfall encountered by all three of

these early models: no attempt was made by the authors to detail the nature of control processes in memory, which act as a highly necessary but completely underspecified part of the model. In the maltese cross model, these control processes are simply handed down to an office worker who performs the necessary tasks, but whose functioning is never explained. This idea of delegating a function to an unexplained little man within the mind can be summarized under the depreciative notion of a "homunculus" (Cowan, 1988), a looming problem for theoretical models of working memory in general (Miyake & Shah, 1999) and control processes in particular.

### *1.2.2. A structural model of working memory: Baddeley's work*

Baddeley's model (1986) marks an important difference with previous works: working memory constitutes the true focus of this theory, rather than an epiphenomenon emerging from the functioning of other systems. The model was initially based on Atkinson and Shiffrin's multi-store account of memory, but it attempted to further specify the role and the functioning of the short-term store as a workplace using control processes. The first specification of the model largely drew upon previous work (Baddeley & Hitch, 1974) proposing a separation between control processes and short-term storage. As a result, Baddeley's model features a structural view of working memory; in other words, it assigns different functions to separate subsystems.

In its original form, the model proposed three main components of working memory (Baddeley, 1986). The first two components are slave systems devoted to the temporary storage of information; each system stores a different type of material. Verbal information is stored within the phonological loop. This system comprises a phonological store that is able to hold a trace of verbal information for a few seconds before it decays, and an articulatory loop tasked with refreshing information within the phonological store through a rehearsal process based on subvocal articulation. Visuo-spatial information, by contrast, is stored by the visuo-spatial sketchpad. Like the phonological loop, the sketchpad can be fractionated in two components: a passive visual cache tasked with temporarily holding a trace of visual information, and a rehearsal mechanism named the inner scribe and particularly devoted to spatial information (Logie, 1995). Both the phonological loop and the visuo-spatial sketchpad are subordinated to the third system, the central executive. The central executive acts as a supervisory system and is analogous to control processes; it coordinates the functioning of the phonological loop and visuo-spatial sketchpad, shifts between retrieval strategies, selects relevant information, and generally performs all the tasks that are not assigned to one of the

slave systems (Baddeley, 2003a). In its more recent version (Baddeley, 2000), the model was extended to incorporate a fourth component, the episodic buffer. This new subsystem is tasked with binding information of different types into a single integrated representation; interestingly, Baddeley (2003) proposed that the episodic buffer acts as a global workspace for cognition.

The central executive is comparable to the office worker in the earlier maltese cross model: placed at the center of the model, it is also the most important component (Baddeley, 2003a). Baddeley's model slightly improved over previous accounts, however, with a preliminary attempt to specify the role of control processes in working memory. Baddeley proposed that the central executive performs four main functions: coordinating performance on two concurrent tasks, switching between different retrieval strategies, attending selectively to certain stimuli while ignoring others, and manipulating and retrieving information from long-term memory (Baddeley, 1996). The central executive was also hypothesized (Baddeley, 1986) to be similar to the supervisory attentional system described by Norman and Shallice (1986). These two authors proposed that behaviour is mainly controlled through learned schemata. Whenever a situation is encountered, the most appropriate schema is selected and the corresponding behaviour is triggered. Competition between several possible schemata is solved through an automatic contention scheduling mechanism. This contention scheduling mechanism may be overridden by the supervisory attentional system, a high-level component that is recruited when automatic selection of schemata does not lead to a correct response – such as when a novel situation is encountered or when the task is too complex. The supervisory attentional system is associated with awareness and operates in a wilful, controlled, deliberate manner; it acts by helping activate or inhibit particular schemata (Norman & Shallice, 1986).

By applying this view of the supervisory attentional system to the central executive, Baddeley (1986) made what was probably the first attempt to detail the functioning of control processes in working memory. Despite this progress, however, the central executive in Baddeley's model remains little more than a homunculus (Baddeley, 2003a), with the same shortcomings as the office worker in the maltese cross model: it solves all the problems but its functioning is never fully explained. This is not a big issue for Baddeley's model, since it is mainly concerned with the functioning of the slave systems: the model has met a lot of success in accounting for empirical results related to short-term storage (Baddeley, 2003a), particularly for verbal information, despite being severely limited in its approach of control processes.

### *1.2.3. Functional models of working memory*

Several models propose a functional view of working memory, in contrast with the former structural accounts. A first example is the embedded processes model of working memory, which describes memory as an essentially unitary entity (Cowan, 1995, 1999). Working memory is viewed as an emergent property that derives from the functioning of various memory processes, rather than a separate subsystem. In this model, long-term memory passively contains all the representations stored in memory. A subset of long-term memory is formed by activated memory, or the portion of long-term memory that is in a transitorily heightened state of activation. Activated memory constitutes a sort of short-term store, although a large number of long-term memory representations may be activated at the same time. Lastly, a small part of the activated representations is illuminated by the focus of attention, corresponding to conscious awareness. The focus of attention is thought to hold about four items at the same time (Cowan, 2010) and broadly represents the information readily available in working memory, although activated memory and long-term memory may also contribute to performance in a working memory task. The model was later updated with the addition of a narrow focus of attention holding a single item at the same time; complex information processing would take place specifically within the narrow focus of attention (Oberauer, 2002). Interestingly, the focus(es) of attention in the model are supervised by a central executive, tasked both with directing attention and controlling voluntary processing (Cowan, 1999). In opposition to Baddeley's model, however, the central executive is not described as a unitary control structure, but rather as the sum of a set of effortful control processes.

The embedded-processes model has several features in common with previous accounts: because they direct the focus of attention, control processes play a central role in determining which activation is directly accessible to working memory. Complex cognitive processing is assumed to take place within the narrow focus of attention, broadly consistent with the idea of working memory as a workspace. The embedded-processes model is also interesting because of the central role that is given to attention and conscious awareness in working memory. Contrary to Baddeley's model, the nature of storage processes for memory representations is not critical to the embedded-processes framework; it is the focus of attention and the way it is directed that directly determines functioning in a working memory task.

The final entry in this review is devoted to Engle's controlled attention framework (Engle, 2002; Engle & Kane, 2004; Kane, Conway, et al., 2007). Engle and colleagues simply

described working memory capacity as « short-term memory capacity + central executive or controlled attention » (Engle et al., 1999, p. 313; see also Kane & Engle, 2003). Controlled attention directly reflects the notion of control processes in working memory. It is thought to perform two main roles: actively maintaining a task goal so as to appropriately bias behaviour in the task, and resolving interference whenever competition between two stimuli arises (Kane & Engle, 2003).

Similar to the embedded-processes model, the controlled attention framework stands in stark contrast with previous theoretical accounts of working memory because it assigns a relatively unimportant role to short-term storage; of course, storage processes are required for working memory performance, but the interesting phenomena in working memory are not attributed to the functioning of these processes. In this view, the efficiency of working memory is instead primarily driven by the ability to control attention: the amount of information that can be held in working memory directly depends on the efficiency of attentional control. In other words, a participant whose control attention is inefficient or otherwise impeded will be unable to efficiently maintain relevant information and ignore irrelevant information, which will translate as a low working memory performance. Although the controlled attention framework is sometimes described as a direct competitor of Baddeley's structural model of working memory, there is no real antinomy between the two: they simply adopt different approaches, and "short-term memory" in the controlled attention framework may be thought of as the combination of a phonological loop and a visuo-spatial sketchpad. In some ways, the controlled attention framework represents the current outcome of the evolution of working memory models, with a progressive shift of emphasis from storage to control processes.

### ***1.3. Measuring working memory capacity***

Because working memory is primarily a scientific construct, less phenomenologically obvious than, say, visual perception, language or short-term memory, working memory research is intimately tied with working memory tasks. What could be considered a "good" working memory test? Actually, a wide range of tasks seems to correctly assess working memory; this is true even for paradigms in which the combination of processing and storage is not immediately obvious (Oberauer, 2005). For example, spatial short-term memory tasks without an apparent processing demand have been observed to tap working memory; this includes tasks only requiring participants to recall a simple pattern of spatial locations (Oberauer, 2005). A likely explanation is that a task efficiently measures working memory

inasmuch as it requires the intervention of control processes, which includes certain tasks without a processing demand clearly separate from storage (Oberauer, 2005). For example, a simple task requiring participants to recall a spatial pattern could require control processes because it does not allow for subvocal rehearsal like simple verbal memory tasks, and instead requires active attentional refreshing emphasizing control processes. Regardless, the various and widely different working memory tasks all seem to load onto a common factor (Wilhelm, Hildebrandt, & Oberauer, 2013), again advocating a domain-general view of working memory.

A particular paradigm, the complex span task, has represented the lion's share of working memory research over the past decades (Unsworth, Redick, Heitz, Broadway, & Engle, 2009). The first published complex span, the reading span task, was developed by Daneman and Carpenter (1980). The task was designed by the authors to combine storage and processing demands. In this sense, it is perfectly aligned with the fundamental definition of working memory as the system performing the simultaneous storage and manipulation of information. In the reading span, participants are confronted with a series of sentences; they are instructed to read all sentences and successively decide whether they are correct, while memorizing the last word of each one. At the end of a series of sentences, participants are asked to recall all the words they have memorized, in the order of presentation. Reading and assessing the validity of the sentences constitutes an information processing task performed concurrently with the maintenance of words in memory.

The complex span paradigm can be applied to any type of processing task and any type of material to memorize. As a result, the reading span task was complemented by the development of other complex span tasks over the years. Besides the reading span, the most widely used complex span tasks are probably the operation span and the symmetry span (Redick et al., 2012). The operation span task consists of the interleaved presentation of arithmetic operations to solve and verbal stimuli to memorize (Turner & Engle, 1989). In the symmetry span task, the participant performs symmetry judgments while memorizing spatial locations (Kane et al., 2004); the symmetry judgments are performed on geometrical designs that are either symmetrical along a vertical axis or not. Together, these three tasks have been used in the majority of studies based on the complex span paradigm, although other complex span tasks exist (see Kane et al., 2004).

Complex span tasks have been used in many studies over the years, and they have distinguished themselves with very satisfying psychometric properties (Unsworth, Heitz, Schrock, & Engle, 2005; Conway et al., 2005; Redick et al., 2012). The reliability of complex

spans is notably high: the estimates of their internal consistency are typically around .80 (Conway et al., 2005; Redick et al., 2012). Their stability also appears very good: Klein and Fiss (1999) reported a correlation coefficient of .76 between two sessions of the operation span separated by nine weeks, while Hitch, Towse, and Hutton (2001) observed a .71 reliability for the reading span over one year. More generally, test-retest reliability seems to range from around .50 to .75 depending on the task, the population and the timescale. Significant correlations are observed between complex span tasks, even when they use different types of material such as verbal and spatial; cross-task correlations are typically in the range of .50 (Redick et al., 2012). Complex span tasks also correlate with other working memory measures based on different paradigms (Redick et al., 2012).

It is interesting that there exist efficient tasks to measure working memory; but the mere idea of measuring working memory implies that working memory capacity – or the amount of information that an individual is able to store in working memory – is limited. How much data are we able to recall from working memory? The precise amount of information that can be encoded and retrieved is extremely dependent on the task, in part because different situations allow for different ways to process stimuli, as well as different encoding and retrieval strategies (Cowan, 2010). Miller (G. A. Miller, 1956) famously proposed a limit for the number of items stored in immediate memory as the « magical number seven, plus or minus two »; however, this limit was estimated using verbal short-term memory tasks allowing for rehearsal strategies and did not control for chunking, which means it is probably an overestimate. In an influential literature review, Cowan (2001, 2010) estimated the maximal number of items in working memory as « about four », or « three to five ». This figure refers to the maximal number of unitary representations stored in working memory, whatever the nature of these representations; in this logic, working memory could similarly hold four pictures, four three-syllable words or four dates.

Of particular interest is the presence of error bars around Miller's magical number seven (plus or minus two) and Cowan's magical number four (three to five). These confidence intervals do not only reflect performance differences as a function of the task; they also refer to individual differences in working memory capacity (Cowan, 2010). The substantial psychometric qualities of complex span tasks hint at the same notion: first, the fact that working memory tasks correlate at all (with other tasks and between themselves) means that some variability exist in the range of scores within a task; second, the high reliability of these tasks suggests that they assess some stable property of the human mind. In short, it seems that individuals are not equal when it comes to the amount of information they are able to store in



working memory; some individuals demonstrate a reliably higher working memory capacity than others (e.g. Klein & Fiss, 1999; Ilkowska & Engle, 2010). These individual differences in working memory have been the subject of a considerable amount of research over the past decades (see Conway et al., 2007). A particularly interesting characteristic of these individual differences is that they are highly predictive of performance in high-level cognitive tasks.

***In summary***

- Working memory is defined as the simultaneous maintenance and processing of information. It is assigned a role as the workplace of cognition by many theorists.
- Working memory may be viewed as the association of domain-specific storage systems and transversal control processes.
- A number of the most influential models of working memory have in common an emphasis on control processes.
- Certain authors view control processes as the source of individual differences in working memory.
- Working memory capacity is efficiently measured with complex span tasks. These complex span tasks reveal stable individual differences in working memory.

## **2. The relationship between working memory and high-level cognition**

### **2.1. Overview**

High-level (or higher-level, or higher-order) cognition is an umbrella term that includes a very wide range of complex cognitive tasks (see König, Kühnberger, & Kietzmann, 2013). No definite classification of high-level cognition exists, in part because the activities listed in such a classification would be largely overlapping. In practice, high-level cognition generally excludes elementary sensory processes such as visual perception as well as basic cognitive functions such as attention and memory. In contrast, high-level cognition tends to include such functions as reasoning and intelligence, creativity, language, monitoring and coordination of performance, decision making, and any complex task involving a combination of these functions (König, Kühnberger, & Kietzmann, 2013). More generally, high-level cognition encompasses any task that is sufficiently complex, lengthy, or that requires the intervention of multiple cognitive functions (Orzechowski, 2010).

As we have seen in the previous section, working memory holds a strong conceptual tie with high-level cognition because it has been theorized as the mental workspace where complex cognitive processing takes place. This is not, however, the only reason: empirical observations also demonstrate a positive correlation between performance in working memory tasks and performance in high-level cognitive tasks. This relationship has been evidenced in a tremendous number of research works; it is so consistently observed, in fact, that high-level cognitive tests are frequently used as a concurrent validity indicator when validating working memory tasks (e.g. Redick et al., 2012; Unsworth et al., 2005; Conway et al., 2005). Working memory capacity is predictive of a set of apparently unrelated real-world situations: in no particular order, it correlates with the ability to learn a programming language (Lehrer, Guckenberger, & Lee, 1988; Shute, 1991), the amount of information that one is able to transcribe when taking notes (Kiewra & Benton, 1988), the ability to learn and follow logical rules (Kyllonen & Stephens, 1990), the ability to repress intrusive thoughts (Geraerts, Merckelbach, Jelicic, & Habets, 2007), the accuracy of probability judgments (Dougherty & Hunter, 2003), and the ability to write high-quality essays (Benton, Kraft, Glover, & Plake, 1984).<sup>3</sup> The predictive value of working memory capacity is not limited to a heterogeneous collection of tasks; at a much broader level, it also predicts academic achievement (Gathercole & Pickering, 2000; Hitch et al., 2001; Gathercole, Brown, & Pickering, 2003; Gathercole, Pickering, Knight, & Stegmann, 2004) and scores on the Scholastic Assessment Test (SAT), a standardized test used to assess a student's academic level in the United States (Daneman & Carpenter, 1980; Daneman & Hannon, 2001; N. P. Friedman & Miyake, 2004). Even though they are quite fragmented, these works provide a convincing clue that working memory may be related to high-level cognition. Aside from these heterogeneous pieces of evidence, a few specific fields of high-level cognition have been the subject of a particularly large number of studies. The objective of the following sections is to summarize this consistent evidence in favour of the relationship between working memory and high-level cognition. We will focus on two main aspects of high-level cognition: specific high-level abilities in the form of verbal and mathematical skills, which

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<sup>3</sup> Other results are very frequently cited (e.g. Kane & Engle, 2004), but appear problematic in practice. Working memory capacity is claimed to be related to the ability to follow complex instructions (Engle, Carullo, & Collins 1991), but the authors used a "following directions" task with heavy demands on working memory, with up to 12 propositions to memorize and execute sequentially. Another example is the claim that working memory is related to the ability to play bridge (Clarkson-Smith & Hartley, 1990): this experiment actually shows that those persons who do play bridge tend to have a higher working memory capacity than those who do not.

have been the focus of a significant portion of all studies assessing the predictive value of working memory capacity, and reasoning abilities, which will be of particular relevance to this work.

## **2.2. Working memory as a predictor of specific high-level abilities**

### *2.1. Working memory and verbal skills*

Among the relationships between working memory and various high-level abilities, the link with verbal skills was historically the first to be evidenced. In the same study where they proposed the first version of the reading span, Daneman and Carpenter (1980) showed that complex span tasks are predictive of reading comprehension: participants with high working memory capacity tend to understand written texts better, are better able to summarize them, and are more efficient at associating a pronoun with its referent. A major problem in this seminal study, however, is that the questions assessing reading comprehension asked participants to recall specific elements presented within a short text – such as the name of a character. In order to correctly answer these questions, participants therefore needed to remember pieces of information while reading the rest of the text. In other words, the comprehension questions in this study assessed working memory as much verbal abilities. This shortcoming illustrates one of the major concerns when assessing the relationship between working memory and high-level cognition: making sure the experimental tasks are as pure as possible and disentangling the contributions from the various constructs in play.

The problem was largely resolved in subsequent studies, however. Daneman and Carpenter (1983), for example, observed that a higher working memory capacity is predictive of the ability to reinterpret the meaning of a word so as to resolve semantic ambiguity. Daneman and Green (1986) showed that participants with high working memory capacity are more efficient at inferring the meaning of new words based on their surrounding context. A possible interpretation for this finding is that a high working memory capacity makes it easier to store mental representations of the components of a text, which in turn makes it easier to compute the semantic and syntactic relations between these elements (e.g. Daneman & Merikle, 1996). As a result, working memory has been assigned a central place in various theories of reading comprehension (see Just & Carpenter, 1992; Caplan & Waters, 1999; Farmer, Misyak, & Christiansen, 2012). A significant number of studies have evidenced a relationship between working memory and reading comprehension since Daneman and Carpenter's initial work (e.g. King & Just, 1991; N. P. Friedman & Miyake, 2004); a link has also been consistently observed between working memory capacity and language acquisition

and comprehension in children (e.g., Pickering & Gathercole, 2001; Gathercole, Brown, & Pickering, 2003; Engle, Carullo, & Collins, 1991). Interestingly, this relationship is observed even when word reading and vocabulary skills are controlled for (Cain, 2006).

The relationship between working memory and verbal skills is not limited to verbal comprehension: other works related working memory capacity with the ability to learn new words (see Baddeley, 2003b), or with the ability to write well-structured essays with a high degree of cohesion (Byrd, 1993). It would be impractical to list the wide range of verbal tasks demonstrating a relationship with working memory (although a partial review may be found in Gathercole & Baddeley, 1993). Fortunately, two meta-analyses have tested this relationship and can help us get a quick overview of published studies. The first meta-analysis (Daneman & Merikle, 1996) summarized 77 studies and observed that working memory capacity is predictive of verbal skills, with correlation coefficients comprised between .30 and .50 on average. A second meta-analysis (Linck, Osthus, Koeth, & Bunting, 2013) summarized 79 studies related to the mastery of a second language, and concluded that working memory capacity is associated with both verbal comprehension and production, with an estimated correlation coefficient of .25. Interestingly, several studies concluded that the relationship between working memory and verbal skills is not contingent on the verbal nature of the working memory task (Turner & Engle, 1989; Daneman & Merikle, 1996), and that working memory is a better predictor of verbal abilities than short-term memory (see Daneman & Merikle, 1996).

## *2.2. Working memory and mathematical skills*

Similar to verbal abilities, the relationship between working memory and mathematical abilities has been the focus of an extensive literature (a review can be found in Wiley & Jarosz, 2012, although it contains a number of reporting errors). The first piece of evidence for this relationship was documented more than three decades ago (Hitch, 1978), in a research concerned with performance in multi-digit calculations. The study showed that people tend to solve complex calculations in multiple steps: when adding three-digit numbers together, for example, a frequent strategy is to add the units together, then the tens and the hundreds, for a total of three calculation steps. In this study, the error rate increased with the time separating the calculation of a step and the moment when the answer was written down by the participant. Conversely, presenting the calculations in a written form significantly decreased the error rate. Taken together, these results were interpreted as evidence that

solving a complex calculation requires the calculation of intermediate products and the maintenance of these products in working memory.

The idea of a link between working memory and multi-step calculations was supported by later studies (see Wiley & Jarosz, 2012) using various methodologies. Although a significant proportion of these studies suffered from conceptual flaws – many authors worked under the questionable assumption that dual tasking procedures directly assess working memory (e.g. Ashcraft & Kirk, 2001), while others made the debatable choice of using arithmetic tests to assess working memory (e.g. Geary & Widaman, 1992) – the conclusion seems relatively robust. The involvement of working memory in numeric cognition is not limited to multi-step operations: participants with high working memory capacity also seem to perform better in simple addition tasks with single-digit numbers (Lemaire, Abdi, & Fayol, 1996; De Rammelaere, Stuyven, & Vandierendonck, 1999), although these studies also suffer from a confusion between working memory tasks and the dual tasking procedure.

Another line of evidence concerns the relationship between working memory and word problems (mathematical problems presented in a complex verbal form). Participants with high working memory capacity tend to be more efficient at solving word problems (Passolunghi, Cornoldi, & De Liberto, 1999; Swanson & Beebe-Frankenberger, 2004; Thevenot & Oakhill, 2006). The common interpretation is that working memory is required to translate all the information contained in the wording into an abstract mathematical representation (Wiley & Jarosz, 2012). This interpretation is supported by the fact that participants with high working memory capacity are more likely to remember the relevant information and less likely to remember the irrelevant information in the problem (Passolunghi et al., 1999). It is also observed that participants with low working memory capacity perform better when a word problem is phrased in a way that decreases the need to form a complex mental representation (Thevenot & Oakhill, 2006).

Beyond its involvement in component processes of arithmetic performance such as performing multi-step calculations and forming mental representations of the problems, working memory is consistently observed to be a good predictor of complex arithmetic tests (Wiley & Jarosz, 2012). One of the most influential studies in this domain found working memory to be predictive of the ability to perform a range of complex calculations, including divisions with remainders and algebra tests (Kyllonen & Christal, 1990). At an even higher level, working memory predicts math achievement in children, as assessed by school grades (Lehto, 1995) and standardized achievement tests (St Clair-Thompson & Gathercole, 2006; Bull, Espy, & Wiebe, 2008). Important for our purposes, working memory is predictive of

mathematical abilities above and beyond short-term memory (Geary, Hoard, & Hamson, 1999; Passolunghi & Siegel, 2004); moreover, this predictive power is not limited to working memory tests with a mathematical component (such as the operation span or the counting span): the same relationship appears with other working memory tasks, such as visuo-spatial tests (St Clair-Thompson & Gathercole, 2006; Bull et al., 2008).

### **2.3. The case of reasoning**

#### *2.3.1. Working memory and deductive reasoning*

Just like verbal and arithmetic skills, reasoning is part of the constellation of high-level cognition. Reasoning may be broadly defined as the ability to "reason", or to draw conclusions on the basis of previous information. Deductive reasoning, in particular, refers to the process of applying logical rules to derive a conclusion from premises. This form of reasoning is characterised by the fact that all the information necessary to draw a conclusion is available in the context; in other words, the situation requires no extrapolation and can be solved using purely formal logic. An adequate example of deductive reasoning is a syllogistic task, in which a person is to judge the validity of a conclusion based on several premises. Working memory is conceptually required to perform a deductive reasoning task (for a review, see Orzechowski, 2010); while several competing theories on deductive reasoning coexist, their predictions about working memory involvement are broadly similar. For example, according to the mental models theory, deductive reasoning requires that a mental model of the problem be created; working memory is necessary to store and combine the mental representations of the various pieces of information (Orzechowski, 2010). According to the rule theory, solving a deductive reasoning problem is a multi-step process, and the results of the different mental steps need to be stored in working memory (Orzechowski, 2010). In both cases, deductive reasoning requires the formation of mental representations and their storage in working memory; the more complex a problem, the greater the corresponding working memory load.

Given this conceptual relationship, it does not come as a surprise that working memory capacity appears predictive of performance in deductive reasoning tasks. The first evidence of this relationship probably appears in Kyllonen and Christal (1990), who showed that working memory capacity is predictive of performance in syllogistic reasoning tasks. This result was replicated in several studies (Capon, Handley, & Dennis, 2003; Copeland & Radvansky, 2004). Interestingly, working memory capacity seems slightly more predictive of performance in problems with a greater amount of information to be represented in working

memory, although the difference is not statistically significant (Copeland & Radvansky, 2004). Participants with high working memory capacity also seem more likely to use a formal step-by-step strategy relying on mental models to solve a problem (Verschueren, Schaeken, & D'Ydewalle, 2005); conversely, participants with low working memory capacity seem more likely to use heuristic shortcuts such as probabilistic inferences (Copeland & Radvansky, 2004; Verschueren et al., 2005).

The relationship between working memory capacity and deductive reasoning extends to other paradigms such as conditional reasoning, a specific class of deductive reasoning tasks where premises are phrased under the form "if  $p$ , then  $q$ ". Barrouillet and Lecas (1999) observed that performance on a complex span task was predictive of conditional reasoning performance in children, even when controlling for academic level; interestingly, working memory capacity actually mediated part of the effect of academic level on conditional reasoning. In another study in children, working memory capacity predicted not only performance in a conditional reasoning task, but also the ability to draw a logical conclusion despite this conclusion being contradictory with one's experience (Handley, Capon, Beveridge, Dennis, & Evans, 2004). Other studies also observed a relationship between working memory capacity and conditional reasoning in adults (Markovits, Doyon, & Simoneau, 2002; De Neys, Schaeken, & d'Ydewalle, 2005). Apart from conditional reasoning studies, one work in children observed working memory capacity to be predictive of performance in a class-inclusion task ("there are five dogs and four cats; are there more dogs or more animals?"; Rabinowitz, Howe, & Saunders, 2002). Taken together, these studies suggest that the relationship between working memory capacity and deductive reasoning is relatively independent of the specific tasks being used.

### *2.3.2. Working memory and fluid intelligence*

The concept of fluid intelligence (Gf) refers to the Cattell-Horn-Carroll theory of cognitive abilities, in which it constitutes one of the factors of general intelligence (g). Fluid intelligence is classically defined as « the use of deliberate and controlled mental operations to solve novel problems that cannot be performed automatically » (McGrew, 2009, p. 5). This definition includes activities such as generating hypotheses to understand a problem, extrapolating information and drawing conclusions; it encompasses the narrower notion of deductive reasoning, and extends to inductive reasoning. Contrary to verbal and arithmetic skills, fluid intelligence is conceptually independent from all acquired knowledge.

Kyllonen and Christal (1990) were probably the first authors to evidence a correlation between working memory capacity and fluid intelligence. In this classic study, an impressive number of 2144 participants completed an array of 13 different reasoning tasks, as well as six working memory tasks. A latent variable analysis yielded a very high estimate of the correlation between working memory capacity and a broad reasoning factor ( $r = .80$ ). The same approach – having a large number of participants complete working memory and fluid intelligence tasks, and assessing the results via latent variable analyses – was used in a number of subsequent works with very similar results (e.g. Engle et al., 1999; Conway et al., 2002; Kane et al., 2004).

A very large number of studies have evidenced a relationship between the two constructs. In the most comprehensive meta-analysis on the subject, Ackerman, Beier and Boyle (2005) reviewed 86 samples relating working memory capacity to fluid intelligence. They observed an average correlation of .48 between the two constructs, indicating the existence of a consistent relationship in a significant number of studies. Research works posterior to this meta-analysis did not fail to replicate the relationship (e.g. Colom, Abad, Rebollo, & Shih, 2005; Salthouse & Pink, 2008; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008). There is considerable debate regarding the magnitude of the correlation between working memory capacity and fluid intelligence, as illustrated by the fact that a reanalysis of the Ackerman *et al.* (2005) data with a different statistical procedure yielded a substantially higher coefficient ( $r = .85$ ; Oberauer, Schulze, Wilhelm & Süß, 2005). The correlation even appears near unity in certain studies (e.g.  $r = .96$ ; Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004). The exact size of this coefficient notwithstanding, working memory seems to be the single cognitive construct that correlates best with measures of fluid intelligence (Oberauer et al., 2005). Interestingly, this correlation exists for various working memory tasks, independently of the type of to-be-remembered material (e.g. Kane et al., 2004); working memory capacity is also generally observed to be a better predictor of fluid intelligence than short-term memory (e.g. Engle et al., 1999; Conway et al., 2002; Kane et al., 2004; but see Unsworth & Engle, 2007b; Colom et al., 2008).

It should be noted that some authors directly relate working memory capacity with *g* itself, rather than fluid intelligence (e.g. Colom et al., 2004; Ackerman et al., 2005). The notion of *g* is much broader than fluid intelligence; it includes fluid intelligence as well as a number of other factors, such as crystallized intelligence, or the amount of cultural knowledge and the ability to apply this knowledge (McGrew, 2009). Although it is possible that the predictive value of working memory extends to general intelligence (as suggested by the



relationship between working memory capacity and various general criteria such as academic achievement), very little experimental data is available to directly test this hypothesis: the vast majority of studies have only assessed intelligence with classic reasoning tasks (Ackerman et al., 2005) that lack the generality of *g*. This problem is further compounded by the near-unity correlation between *g* and fluid intelligence (see Kvist & Gustafsson, 2008), which makes it even more difficult to assess them separately. In other words, empirical evidence is as yet lacking to establish the relationship between working memory capacity and *g*; as a result, we can only safely conclude that working memory is related to fluid intelligence.

***In summary***

- Individual differences in working memory seem related to performance on a wide range of high-level cognitive tasks. While a lot of research has concerned arithmetic and verbal skills, working memory seems to correlate with most complex activities, as well as real-life achievements such as academic success.
- Among high-level cognitive abilities, reasoning skills seem particularly related to working memory. This is especially true for the construct of fluid intelligence: the correlation between fluid intelligence tests and working memory tasks is typically moderate to high, and working memory is the construct most frequently associated with fluid intelligence in the literature.

### **3. Explaining the link between working memory and fluid intelligence**

The consistent relationship between working memory capacity and fluid intelligence raises a problematic question: what drives this relationship? This is not a trivial problem, since it has implications for the theory of both working memory and fluid intelligence. Different authors have adopted widely different positions on this matter, with explanations ranging from "working memory is the same thing as intelligence" to "some external factor contributes to performance on tasks measuring both constructs". The objective of this section is to review some of the most prevalent explanations that have been proposed for the relationship between working memory and fluid intelligence (see also Engle & Kane, 2004, for another review).

### **3.1. Endogenous explanations**

Some authors have attempted to interpret the relationship between working memory and fluid intelligence with endogenous explanations; these explanations consider that the relationship is due to the intrinsic nature of the two constructs, rather than to the contribution of external factors. One possibility, defended by a few theorists, is that working memory capacity and fluid intelligence are actually isomorphic – in other words, that they are essentially the same construct of which two facets are measured (Blair, 2006; Kyllonen & Christal, 1990). For example, Blair (2006) uses the notion of "fluid cognitive functioning", a general cognitive process encompassing working memory, fluid intelligence, and the ability to apply control processes. Although he recognizes that there might be some amount of separability between these three abilities, Blair considers that they directly refer to the same overarching construct. This position is based on three main arguments. First, there are conceptual links between working memory and fluid intelligence: both refer to the implementation of controlled processes to perform complex tasks. Second, the correlations between the two constructs range from moderate to very high, even approaching unity in certain studies. Third, working memory and fluid intelligence share a largely common neural substrate (see Kane & Engle, 2002; Kane, 2005): a set of prefrontal regions, particularly in the dorsolateral prefrontal cortex, is recruited by both working memory tasks (Braver et al., 1997; Duncan & Owen, 2000; Kane & Engle, 2005) and fluid intelligence tasks (Gray & Thompson, 2004; Kane & Engle, 2005). For these reasons, the idea that the two constructs are related because they are basically identical does seem appealing. However, the vast majority of researchers agree on the fact that the observed correlations are generally too small to substantiate such a claim (Ackerman et al., 2005); as a result, this extreme position does not generally receive much support (Oberauer et al., 2005).

A second possibility is that the tasks are related because one ability contributes to the successful functioning of the other. On one hand, a high intelligence may help participants perform better in working memory tests through the ability to « adapt quickly to a new task and perform effectively » (Salthouse & Pink, 2008, p. 6). This proposition is not technically incompatible with the theoretical definition of fluid intelligence. The main problem with this idea, however, is that it is extremely vague: it is difficult to imagine how a high intelligence could help participants perform effectively in a working memory task. Participants with low working memory capacity typically tend to demonstrate near-perfect performance in working memory tasks on trials with a very low working memory load, which suggests that their lower performance stems less from an inability to adapt to the task than from an inability to hold a

large number of items in working memory. Additionally, the ability to use efficient strategies in working memory tasks does not seem related to either verbal comprehension or fluid intelligence (Dunlosky & Kane, 2007; Bailey, Dunlosky, & Kane, 2008; Bailey, Dunlosky, & Kane, 2011). In sum, this hypothesis is both hard to test and hard to defend.

Conversely, working memory may be required to complete fluid intelligence tasks (Baddeley & Hitch, 1974). As we have seen, working memory is often described as the workspace of cognition, or the place where complex processing is performed. If the cognitive processing required in fluid intelligence tasks is performed within working memory, it is not absurd to suppose that the two constructs may be related. Theoretical models of reasoning provide a hint as to how individual differences in working memory may play a role in intelligence tasks: if reasoning is based on the manipulation of mental representations corresponding to the various rules or premises in a problem, then being able to hold more representations at the same time (or hold them more accurately) in working memory could be an advantage. A similar way to phrase this is that understanding a problem requires the creation of a mental representation of the problem; the more available space in working memory, the more complex and detailed a representation can be (Oberauer, Süß, Wilhelm, & Sander, 2007). This hypothesis seems more defensible than the previous one, but it is not without two major flaws. Firstly, it is easier to apply to formal deductive reasoning tasks than to other high-level cognitive tasks; how would this hypothesis translate to verbal skills? Secondly, the hypothesis mainly relies on a conceptual idea, which means it is really difficult to test. Validating this hypothesis would require one to operationalize the notion of mental representations in a problem, and try to relate the number or complexity of these mental representations to working memory capacity; few to no studies have gone through this process (with the exception of Copeland & Radvansky, 2004, who reported mixed results).

In summary, none of these endogenous explanations seem entirely convincing. Another possibility – and perhaps the most heuristically interesting – is that there exists at least one external factor that contributes to performance on both working memory and fluid intelligence tasks. Theoretical positions vary as to the identity of this external factor (for a review, see Engle & Kane, 2004); the next sections will review some of the possible candidates.

### **3.2. Task-specific skills**

Some have argued that working memory tasks correlate with high-level cognitive tasks inasmuch as both tasks require the manipulation of the same type of material. For

example, the reading span task would be predictive of verbal comprehension tasks because both paradigms involve the manipulation of verbal material. The initial research in working memory had a particular focus on verbal working memory and its relationships with verbal comprehension (e.g. Baddeley & Hitch, 1974), which may help explain the emergence of this hypothesis. The task-specific hypothesis was the original view of Daneman and Carpenter (1980). These authors worked on the assumption that the reading span actually measured individual differences in reading ability; good readers would be able to devote less resources to reading sentences in the task and more resources to memorizing the final words. In this view, both reading comprehension tasks and the reading span task would have indexed reading ability. This hypothesis can be extended to fluid intelligence tasks: a visuo-spatial fluid intelligence test would primarily correlate with visuo-spatial working memory tasks such as the symmetry span, because of their common content.

Although this hypothesis was historically important in working memory research, it was contradicted by a large number of ulterior results and may be safely discarded as incorrect. Turner and Engle (1989) constructed the operation span task and showed that it is a good predictor of reading comprehension, despite not being based on verbal processing; as a methodological control, the authors even had participants listen to a recorded voice reading out the stimuli during the operation span task so as to ensure that reading ability did not factor in working memory performance. Later studies consistently demonstrated that working memory tasks predict high-level cognitive tasks independently of the type of material being manipulated; for example one classic study (Kane et al., 2004) related three verbal and three visuo-spatial working memory tasks to five verbal and five visuo-spatial reasoning tasks, and observed that all working memory tasks tend to correlate with all reasoning tasks; the data was best summarized by a general working memory factor being related to a general reasoning factor. This is not to say that task-specific skills don't play a role in the relationship – for example, verbal working memory tasks are more related to verbal reasoning tasks and visuo-spatial working memory tasks to visuo-spatial reasoning tasks (e.g. Süß et al., 2002; see Kane et al., 2004 for a review) – but the predictive value of working memory capacity clearly goes beyond these task-specific aspects.

### ***3.3. The processing speed hypothesis***

Processing speed, an especially ill-defined notion (debate still rages about the unity of processing speed as a construct and the tasks that can be used to measure it; see Danthiir, Roberts, Schulze, & Wilhelm, 2005), may be conceptually viewed as the speed at which

mental operations can be completed. It has been proposed that a high processing speed may help participants score higher in working memory tasks, because completing the processing demands in the task faster would leave more time for attentional refreshing of the to-be-memorized stimuli (A. R. Jensen, 1998; Engle & Kane, 2004). As for intelligence, processing speed may function as a general marker of information processing efficiency, this efficiency being itself a determinant of general intelligence (A. R. Jensen, 1998). This hypothesis is often expressed in reference to neural efficiency: faster participants would have a more efficient neuronal substrate leading to a higher intelligence (Danthiir et al., 2005). In another view, processing speed may determine working memory capacity and in turn the ability to complete a reasoning task before the required mental representations have decayed (Fry & Hale, 2000). These arguments have led to the proposal that processing speed is a possible substrate for the relationship between working memory capacity and fluid intelligence (A. R. Jensen, 1998; see also Engle & Kane, 2004).

This hypothesis is partially supported by the data. Working memory capacity is often claimed to correlate with processing speed (Kyllonen & Christal, 1990; Fry & Hale, 2000; Ackerman et al., 2002), but this is not always the case (Redick, Unsworth, Kelly, & Engle, 2012). Additionally, it has been argued that the observed relationships between working memory and processing speed are largely artifactual and can be explained by the use of speeded tasks to measure working memory (Engle & Kane, 2004). There is some evidence that processing speed is mildly related to general intelligence (for a review, see A. R. Jensen, 1998); on the other hand, it is also observed that complex processing speed tasks correlate more with *g* than more simple tasks (Danthiir et al., 2005), which suggests that the relationship may be due to other factors than processing speed, such as memory or attention. Besides, the intra-individual variability in response times is a better predictor of fluid intelligence than mean response times (e.g. Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007; Unsworth, Redick, Lakey, & Young, 2010), which is difficult to explain in terms of processing speed. In any case, it seems unlikely that processing speed fully explains the relationship between working memory and fluid intelligence, whether it is actually related to these constructs or not. This conclusion is supported by several studies using latent variable analyses; these studies observed various patterns of correlations between the three constructs, but processing speed never accounted for the relationship between working memory capacity and fluid intelligence (Ackerman et al., 2002; Conway et al., 2002; Redick, Unsworth, Kelly, & Engle, 2012).

### **3.4. Motivation**

A simple and appealing explanation for the relationship between working memory and fluid intelligence relies on the idea of motivation, or mental effort invested in a task. It is obvious that the amount of mental effort exerted by a participant influences his performance in a complex task. As a consequence, participants may score higher in a working memory task because they are more motivated, or exert more effort; one experiment systematically measuring motivation to perform a working memory task through self-report supported this idea (Brose, Schmiedek, Lövdén, & Lindenberger, 2012). Logically, the same should hold true for any high-level cognitive task; in particular, motivation has a well-known effect on intelligence testing (Duckworth, Quinn, Lynam, Loeber, & Stouthamer-Loeber, 2011). As a result, motivation could create a spurious correlation between working memory capacity and every task where the amount of exerted mental effort is a factor of performance: those participants who are more motivated would score higher on all tasks and those who are less motivated would score lower on all tasks (Engle & Kane, 2004).

This elegant hypothesis is generally discarded with three counter-arguments. First, working memory is not a predictor of performance in certain simple tasks, such as the ability to direct one's gaze towards a target (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004). If working memory was dependent on mental effort, it would be expected to correlate with any speeded task. Second, no correlation emerges between working memory capacity and very simple questions about motivation (e.g., "how motivated were you to do well on the task?", Unsworth & McMillan, 2013). The third argument is based on a study using pupillometric dilation as a marker of mental effort (Heitz, Schrock, Payne, & Engle, 2008). In this study, the authors assumed that if working memory capacity is related to the amount of mental effort, then incentivizing performance should have more effect on pupil dilation for participants with low working memory capacity than for the already motivated participants with high working memory capacity. The study found no correlation between working memory capacity and phasic changes in pupillometric contraction as a function of the level of incentive, which the authors interpreted as evidence that working memory is not related to mental effort.

### **3.5. Short-term storage of information**

As we have seen, working memory can be thought of as the association of short-term storage and control processes. As a consequence, short-term storage is one possible candidate for a shared process between working memory and fluid intelligence. The corresponding

interpretation is that solving a complex problem requires one to memorize information, such as the rules of the problem. Forgetting this information mid-trial would naturally lead to a lower performance. This interpretation is close to the hypothesis that working memory is required to complete a high-level cognitive task, yet subtly different in its rationale: in this case, working memory is viewed neither as a special construct, nor as a workspace for cognition. Instead, the idea would be that working memory tasks are predictive of fluid intelligence only insofar as they involve short-term storage of information. A corollary of this hypothesis is that short-term memory tasks should be correlated with fluid intelligence, just like working memory tasks.

This hypothesis is incompatible with three main findings in the literature. The first is the consistent observation that short-term memory does not mediate the relationship between working memory and fluid intelligence, and that short-term memory is a poorer predictor of fluid intelligence than working memory (Engle et al., 1999; Conway et al., 2002; Kane et al., 2004; Colom, Abad, et al., 2005). In fact, the disappointing predictive value of short-term memory was actually the whole reason behind the development of the working memory construct (Baddeley & Hitch, 1974): Baddeley and Hitch based their work, among other results, on the observation that brain-lesioned patients with a critical short-term memory deficit demonstrate normal performance in high-level cognitive tasks (see Baddeley & Hitch, 1974). The second problem stems from experimental studies on Raven's advanced progressive matrices (APM), a fluid intelligence task requiring that participants find the missing piece to complete a matrix of geometrical patterns in accordance with a variable number of logical rules (Raven, Raven, & Court, 1998). The data show that working memory capacity is equally related to performance on problems with a low or large number of rules to memorize (Salthouse, 1993; Unsworth & Engle, 2005). The third problem is, conversely, the observation that all trials in a working memory task are predictive of fluid intelligence, independently of their working memory load (Salthouse & Pink, 2008). As an example, the authors reported that trials of length two in a symmetry span task (trials with two stimuli to hold in working memory) correlated .57 with fluid intelligence; the correlation was .61 for trials of length five.

On the other hand, a few clues do point towards a role of memory storage. Participants with low working memory capacity demonstrate a lower ability to recognize information presented earlier in a problem solving task (Salthouse, 1993); this lower memory for previous information may hinder their ability to adapt to the task. A few studies using latent variable analyses did report significant relationships between short-term memory and high-level

cognition (Colom, Abad, et al., 2005; Colom, Flores-Mendoza, Quiroga, & Privado, 2005; Unsworth & Engle, 2007b; Colom et al., 2008; Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014). Additionally, reanalyses of previous studies suggested that some of the frequently reported non-significant relationships between short-term memory and fluid intelligence could actually appear significant under certain circumstances, such as when using different scoring methods or different analysis procedures (Colom, Rebollo, Abad, & Shih, 2006; Unsworth & Engle, 2007b). It is difficult to take a definitive stance on the question of short-term memory: the few recent articles pointing towards a role of short-term storage may not quite offset the two decades of contrary results, and no easy answer seems really able to reconcile these contradicting views. A tentative explanation could be that short-term memory tasks and working memory tasks share several component processes and are both related to fluid intelligence, but that short-term storage does not fully drive the predictive value of working memory (Shipstead et al., 2014; Unsworth et al., 2014).

### **3.6. *The cognitive control hypothesis***

The final hypothesis that we wish to develop is related to the notion of cognitive control. The main line of reasoning is as follows. We have seen that working memory involves control processes related to the selection, coordination and manipulation of information (p. 6). These cognitive control processes may very well be required in other complex tasks as well, which includes fluid intelligence tasks. Thus, the relationship between working memory and fluid intelligence could be explained by their common reliance on cognitive control processes: participants with highly efficient cognitive control processes would tend to score higher on both working memory tasks and fluid intelligence tasks (e.g. Engle & Kane, 2004).

Among all the hypotheses attempting to explain the relationship between working memory and fluid intelligence, the cognitive control hypothesis is certainly the one that has drawn the most attention over the past decade and a half. We believe it is also one of the most interesting: this hypothesis allows for an elegant interpretation of the data, while providing a unified approach to three of the most discussed constructs in play in complex human cognition, in a way reminiscent of Blair's (2006) view of fluid cognitive functioning. The cognitive control hypothesis is the main focus of the present work; we will review this hypothesis in detail in the next chapter.



***In summary***

- It is important to work out why working memory and fluid intelligence are related, since the answer has significant implications for our understanding of human cognition.
- A wide range of different explanations have been proposed to account for this relationship. Some are generally discarded, some are difficult to test, and some lack empirical evidence. Most of them are essentially unconvincing.
- One hypothesis in particular proposes that working memory and fluid intelligence both rely on cognitive control, and that this common reliance explains their relationship. This hypothesis is the focus of the present work and will be developed in the next chapter.

## CHAPTER 2. COGNITIVE CONTROL AS AN EXPLANATORY FACTOR

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### **Objectives**

In the previous chapter, we have seen that working memory is related to high-level cognition and to fluid intelligence in particular, and that cognitive control may explain this relationship. This chapter focuses on this possible explanatory role of cognitive control. Our first step is to delineate cognitive control as a construct, and to review a few relevant accounts of its functioning. The next two sections provide indirect arguments in favour of the explanatory role of cognitive control by highlighting its ties, first with working memory, and second with fluid intelligence. In the final part of this chapter, we review the existing evidence in favour of an explanatory role of cognitive control and discuss the major limitations of this evidence.

### **1. The theory of cognitive control**

#### **1.1. What is cognitive control?**

##### *1.1.1. An overview of cognitive control*

Cognitive control as a construct refers to the broad notion of regulating behaviour to achieve a particular goal (see E. K. Miller & Cohen, 2001; Stuss & Levine, 2002; Schneider & Chein, 2003; Koechlin & Summerfield, 2007; Gazzaley & D'Esposito, 2007; Braver, 2012). In other words, cognitive control is the cognitive function dealing with the organization of behaviour in reference to a specific objective. Cognitive control is often described within an evolutionary perspective: while simple animals are limited to following simple associations between stimuli and responses, higher mammals benefit from the ability to select which actions they carry out according to internal goals or plans (E. K. Miller & Cohen, 2001; Koechlin & Summerfield, 2007). This ability to select and perform a specific action in order to achieve a goal, rather than simply react to stimuli with automatic responses, is the defining feature of cognitive control (Kimberg, D'Esposito, & Farah, 1997; Koechlin &

Summerfield, 2007). As can be seen, cognitive control is heavily dependent on the notion of following a goal; it is sometimes referred to as "goal-driven behaviour".

Because it relies on response selection, the definition of cognitive control draws on the classic distinction between automatic and controlled processes (Schneider & Shiffrin, 1977; Schneider & Chein, 2003). Some cognitive processes are automatic, which means they always trigger in response to a particular stimulus and activate without a need for active control or even for conscious awareness; by contrast, controlled processes are not automatically triggered by a stimulus, and are instead activated by the subject through conscious awareness (Schneider & Shiffrin, 1977). Cognitive control refers to this type of controlled processing: one could say that control is engaged whenever an action is non-automatically selected according to a specific goal. In this view, cognitive control is often described as a willed, effortful, and conscious process (K. B. MacDonald, 2008), in contrast with the quick and relatively effortless automatic processing.

A myriad of terms have been used to refer to cognitive control. These include, among others, "effortful control", "executive control", "executive functioning", "executive attention" and "controlled attention". These terms have been used by different authors and may allude to slightly different assumptions; however, they all refer to the same general notion of applying cognitive control to non-automatically select an action, and may be viewed as equivalent for our purposes<sup>4</sup>. In the same fashion, refinements are sometimes added to the general definition of cognitive control; for example, some authors may describe it as the ability to regulate behaviour according to a goal *in the face of interference*; or the ability to *formulate goals, plan how to achieve them*, and to regulate behaviour according to these goals. Again, these subtleties do not change the fundamental nature of the construct, which still refers to the non-automatic selection of an action according to a goal.

As could be expected for such a broad function, cognitive control relies on an extensive neural substrate (e.g. Collette, Hogge, Salmon, & Van der Linden, 2006; Braver, Gray, & Burgess, 2007). This substrate prominently includes regions of the prefrontal cortex, the cingulate cortex, and the dopaminergic system. It has been known for quite some time that the prefrontal cortex in particular is central to cognitive control (e.g. Luria & Tsvetkova, 1964); virtually all researchers agree on this matter (e.g. E. K. Miller & Cohen, 2001; Stuss &

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<sup>4</sup> The term *cognitive control* will be used throughout this work to refer to the broad notion of non-automatically selecting an action to achieve a particular goal. *Goal-driven behaviour* will also be used to refer to cognitive control, and more specifically to top-down cognitive control (see p. 40). The term *executive function* will be used to refer to specific functions assigned to cognitive control by certain authors, such as inhibition or shifting.

Levine, 2002; Koechlin & Summerfield, 2007; Gazzaley & D'Esposito, 2007). Several lines of evidence converge towards this conclusion: neuroimaging studies show reliable activations in the prefrontal cortex during tasks that require cognitive control (e.g. E. E. Smith & Jonides, 1999; Collette et al., 2006), while patients with a prefrontal lesion show marked impairments of goal-driven behaviour, which leads to an array of deficits often termed "dysexecutive syndrome" (Stuss & Levine, 2002). The dorsolateral part of prefrontal cortex seems especially involved in cognitive control (Kane & Engle, 2002).

### *1.1.2. The functions of cognitive control*

What does cognitive control do? Numerous conflicting accounts exist for the various functions performed by cognitive control (see V. Anderson, 2008). A first example is Lezak's model, in which cognitive control is said to perform four distinct functions: formulating goals, planning actions according to these goals, implementing these actions in practice, and doing so effectively (Lezak, 1982). Barkley's model also proposes that cognitive control encompasses four functions, albeit different ones (Barkley, 1997): self-regulation of emotion, motivation and arousal; internalization of speech; analyzing and synthesizing a situation to generate new responses; and working memory. These functions are all hypothesized to rely on a general ability to implement behavioural inhibition. In an influential study, Miyake and colleagues identified three executive functions through factor analysis of classic executive tasks: updating of previous representations, shifting between tasks or between mental sets, and inhibiting prepotent responses (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). These authors tentatively proposed that coordinating dual task performance constitutes a fourth function. Various other functions of cognitive control are frequently mentioned in the literature such as planning, selective attention, verbal or behavioural fluency, and problem solving (V. Anderson, 2008).

While they may be heuristically interesting, all these accounts of cognitive control are plagued by the same problem: they do not offer an integrative conceptual framework of cognitive control, but only a collection of arbitrarily defined functions. In some cases, these functions are defined via a bottom-up process on the sole basis of the tasks that are used to measure them: for example, Miyake and colleagues defined three executive functions by interpreting the patterns of correlations between several executive tasks (Miyake et al., 2000). This approach is not necessarily an efficient way to distinguish independent executive functions: the fact that performance on one task correlates with another does not mean that there exists one common underlying function since the correlation may be caused by several

unrelated factors, and conversely, two tasks may be uncorrelated despite requiring the same function if this function is not a primary driver of performance. Another problem is that using different tasks could have yielded entirely different results and led to the definition of different functions (Rabbitt, 1997; P. W. Burgess, Alderman, Evans, Emslie, & Wilson, 1998). In other models (e.g. Lezak, 1982), the classification of executive functions is purely theoretical and relies on the preconceptions of the researchers rather than on empirical data. Unfortunately, these preconceptions heavily influence research on cognitive control in ways that are not always entirely justified. For example, inhibition is certainly the most ubiquitous executive function in the literature; regardless, the results attributed to inhibition can be entirely reinterpreted within an activation account, completely removing the need for this function (MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). Actually, there seems to be no reason to believe in the existence of an inhibition function other than the biases of researchers (MacLeod et al., 2003). In other words, even the functions that generally achieve unanimous consensus are rather arbitrary, and all the separable functions attributed to cognitive control seem to individually suffer from poor construct validity.

In summary, there is general agreement that cognitive control performs a range of very important functions, but no consensual classification of these functions currently exists. As a consequence, we believe that the wisest course of action is to avoid relying on the existing classifications altogether: rather than using any one list of executive functions in particular, it seems that the most parsimonious view is to just stick to our original definition and to simply consider that cognitive control refers to the non-automatic regulation of behaviour according to a goal. This definition suggests that cognitive control may be required whenever it is necessary to implement goal-driven behaviour; actually, some have argued that cognitive control is involved in any task where the participant has to follow instructions (see V. Anderson, 2008). In this view, cognitive control encompasses all of the proposed executive functions, from inhibition to updating through dual task coordination. Importantly, this definition includes control processes associated with working memory – the controlled selection, coordination and manipulation of information – in the list of functions requiring cognitive control.

This view leaves open the question of the unitary nature of cognitive control. A number of clues point towards a separability of cognitive control processes; these clues include in particular the different brain activations elicited by different executive functions (Collette et al., 2005), the variability of deficits in patients with dysexecutive syndrome (V. Anderson, 2008), the different developmental trajectories of the various executive

functions (V. Anderson, 2008), and the different factors appearing in factor analysis studies (V. Anderson, 2008). At the same time, however, most authors seem to consider that cognitive control relies on one or several general mechanisms; this is the case even for those authors who argue that there exist separable control processes (e.g. Miyake et al., 2000; V. Anderson, 2008). Just like for working memory (see p. 9), the best answer is likely to lie between the two extremes: cognitive control probably corresponds to the association of domain-specific processes restricted to one or several tasks, and domain-general processes common to all situations requiring control. Because these general processes are likely to be both the closest to our original definition of cognitive control, and its most heuristically interesting component, it seems sensible to consider cognitive control as an essentially unitary construct for our purposes.

## **1.2. How does cognitive control work?**

### *1.2.1. Triggering cognitive control*

As we have seen, cognitive control may be engaged in any task where non-automatic response selection is required. This definition encompasses a wide range of situations; for example, it includes tasks that require complex planning or decision making, tasks that require troubleshooting, tasks that are novel or otherwise not learned well enough to allow for automatic processing, tasks that are dangerous or difficult, and tasks that require the overriding of an automatic response (Norman & Shallice, 1986). In order to accurately understand how cognitive control works, it seems important to understand how it comes to be recruited in these situations (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Two main accounts of how cognitive control is triggered coexist.

A first hypothesis is that control is actively recruited before it is needed, in a top-down fashion. According to this account, cognitive control originates with an internal goal or intention at the "top" level; this intention is then implemented to regulate behaviour (see E. K. Miller & Cohen, 2001). In this view, cognitive control is a sustained process that begins at the onset of a task. This account confers a critical role to the dorsolateral prefrontal cortex, whose role is to maintain internal goals and use these goals to regulate behaviour. One of the conceptual bases of this hypothesis is the well-documented observation that certain neurons in the dorsolateral prefrontal cortex demonstrate a pattern of sustained activity during the delay of a task when an intention has to be actively maintained (Fuster & Alexander, 1971; Goldman-Rakic, 1995; Kane & Engle, 2002). For many authors, this sustained activity reflects the active maintenance in the prefrontal cortex of the task goal that serves as the basis

for top-down cognitive control (e.g. Kimberg et al., 1997; Kane & Engle, 2002). This account is also congruent with the observation that the prefrontal cortex exerts top-down modulation of neural activity in other cortical regions via long-range neuronal projections (for a review, see Gazzaley & D'Esposito, 2007).

Contrasting with this top-down mechanism of cognitive control recruitment, there is also evidence that cognitive control can be triggered by signals within a situation in a bottom-up manner (Botvinick et al., 2001). In view, the basis of control is not an internal goal: on the contrary, it is a feature of the situation that signals the need for cognitive control. For example, cognitive control may be selectively triggered as a function of the amount of conflict within a task (Botvinick et al., 2001). A significant amount of conflict between two representations (for example, two possible responses to a situation) or two processes (for example, two tasks that should be performed simultaneously) would function as a marker that cognitive control needs to be implemented. A critical cerebral region for cognitive control in this account is the anterior cingulate cortex, whose role would be to monitor the amount of conflict in a task, or more generally to index the need for control. Congruent with this idea, activations are selectively observed in the anterior cingulate cortex when a participant detects that he has just made a mistake in a task, or when he detects the occurrence of conflicting stimuli (Bush, Luu, & Posner, 2000).

The bottom-up regulation of control seems to hold several advantages over top-down control (Botvinick et al., 2001): it allows for "on the fly" triggering of cognitive control when no intention exists in advance, makes it possible to adjust the amount of effort invested in control when the difficulty of the task varies, and also to detect when control is no longer required. Importantly, however, the bottom-up and top-down accounts of cognitive control are in no way contradictory; the coexistence of both mechanisms is well documented in certain situations such as visual processing (Desimone & Duncan, 1995). It is therefore likely that both mechanisms are used in practice (Braver et al., 2007), an idea that will be extensively developed in the next chapter.

### *1.2.2. Implementing cognitive control*

We have reviewed what cognitive control is, which functions it performs, and how it is triggered; another critical question is how it operates in practice to regulate behaviour. As we have seen, early models attempting to describe cognitive control were largely homuncular in nature. The processing system, or office worker, in Broadbent's model (1984) and the central executive in Baddeley's model (2003a) both represent a black box system, whose functioning

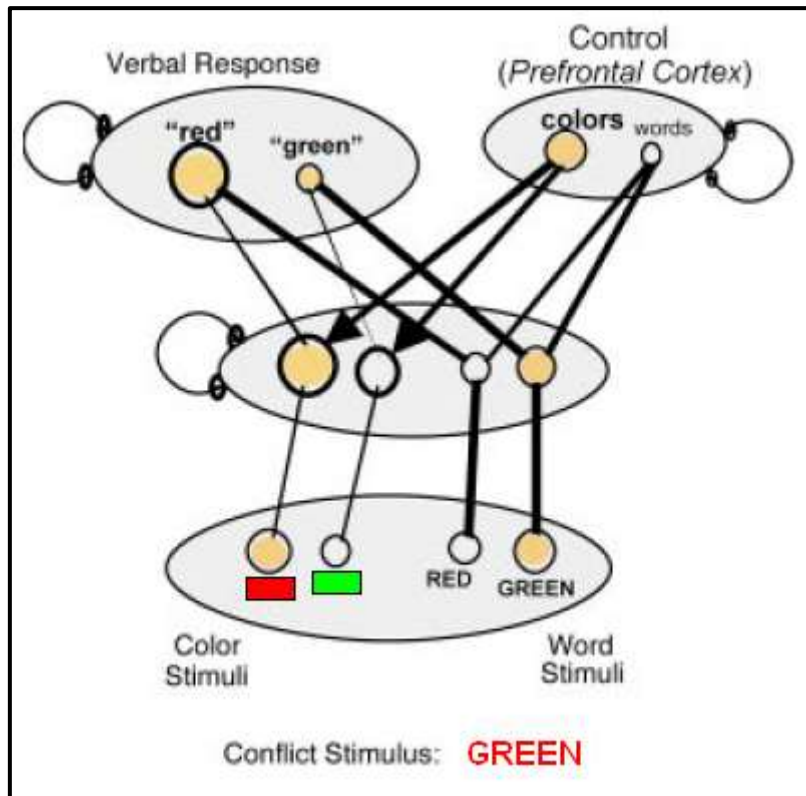
is essentially magical: it "just knows" when to implement control (Botvinick et al., 2001) and "just does it". While very economical, this is not really a sound scientific basis for further theorizing.

Several authors have proposed that the cognitive control system does not directly carry out intended actions; instead, control may be implemented by selecting which actions are performed among possible alternatives in a situation (e.g. Kimberg et al., 1997). This view echoes the definition of cognitive control as the mechanism allowing to select which actions to perform according to a goal. However, this definition simply states that the *role* of cognitive control is response selection; this role could be performed through an infinite number of elementary mechanisms (such as planning which actions to perform, inhibiting irrelevant responses, and so on). In contrast, the idea suggested here is that cognitive control directly *operates* through response selection. In this view, no mechanism other than response selection is needed to account for the whole range of functions of cognitive control: for example, the executive functions of "planning" and "inhibition" can be viewed in terms of selecting a response other than the first one that comes to mind (see Kimberg et al., 1997).

The idea that cognitive control operates through response selection was already present in the supervisory attentional system model (Norman & Shallice, 1986; Shallice & Burgess, 1996). Recall that in this model, behaviour is controlled through learned schemata; whenever a new situation is encountered, the corresponding schema is automatically activated and the associated behaviours are triggered. Cognitive control, in the form of the supervisory attentional system, is required when a situation cannot be solved using the automatically selected schema; critically, the supervisory attentional system only acts by helping select another schema or response (Norman & Shallice, 1986; Shallice & Burgess, 1996). In other words, there is no need for cognitive control to directly intervene in the system other than by regulating which schemata are activated.

This response selection view was famously summarized in an integrative theory of cognitive control (E. K. Miller & Cohen, 2001). The authors claimed that cognitive control acts by biasing processing in a task, rather than by directly triggering the intended action. This theory was illustrated with a neural network model of the Stroop task, depicted in Figure 2 (see also Cohen, Dunbar, & McClelland, 1990).





*Figure 2.* Schematic of the neural network model for cognitive control in the Stroop task. Grey ovals represent layers in the model. Circles represent individual units; larger circles represent more activated units. Lines represent connections, with larger lines representing stronger connections, and looped lines with small black circles representing mutual inhibition among units within a layer. Adapted from "An integrative theory of prefrontal cortex function" by E. K. Miller and J. D. Cohen, 2001, *Annual Review of Neuroscience*, 24, p. 183. Copyright 2001 by Annual Reviews Inc.

This model includes four layers of units: one layer coding for the features of incoming stimuli, one layer coding for possible responses, one hidden layer connecting stimuli to responses, and a fourth set of units representing rule representations (whose storage is ensured by the prefrontal cortex). In the Stroop task, participants have to name the colours in which colour name words are printed; thus, stimuli all have two features – the identity of the word and the colour of the ink. The incoming stimuli layer is accordingly divided into two sets of units: one set coding for words and one set coding for colours. Each stimulus elicits activation in one unit per set. The natural response in the task is reading the word; as a consequence, the connections between the word units and the corresponding responses are stronger than the connections between the colour units and the corresponding responses. Because of this imbalance, in the absence of cognitive control an incoming stimulus would elicit more activation in the response units associated with the word than with the colour, leading to the network "reading" the word. Critically, cognitive control is implemented in the form of units

coding for the rule of the task. These units bias processing in the network by modulating the relative strength of connections between features and responses. If the rule is to name the colour rather than read the word, the corresponding rule unit is activated in the layer representing the prefrontal cortex; this rule unit selectively strengthens the connection between the colour units and the responses, allowing these colour units to elicit more activation than the word units. Thus cognitive control is not itself directly associated with stimuli-responses mappings; it is implemented in the network purely as a biasing mechanism. This model provides an interesting example that cognitive control may be viewed as a biasing mechanism indirectly influencing response selection. Importantly, it also confers a central role to the rules or goals that are used to bias behaviour in a task: in this model, cognitive control is successful insofar as the task goal is appropriately maintained and implemented.

***In summary***

- Cognitive control may be defined as the non-automatic regulation of behaviour according to a goal.
- Many different functions are assigned to cognitive control, but no taxonomy of these functions seems truly convincing. It seems best to view it as an essentially domain-general ability, at least for our purposes.
- Cognitive control may be triggered by top-down or bottom-up mechanisms; these two solutions are not mutually exclusive.
- Rather than directly carry out intended actions by itself, cognitive control may operate by biasing the relative strengths of stimuli-responses mappings on the basis of a task goal.

## **2. Proximity between cognitive control and working memory**

Now that we have examined the nature and functioning of cognitive control, let us turn our attention to the hypothesis that cognitive control drives the relationship between working memory and fluid intelligence. One prerequisite for this hypothesis to be valid is that cognitive control should be related to working memory. Several pieces of evidence suggest that this prerequisite is met in practice; the next sections will review this evidence in more detail.

## **2.1. Conceptual argument**

A first argument that relates cognitive control to working memory is conceptual; in other words, it is based on the theory of both constructs rather than on empirical evidence. First, a role of cognitive control is implied in working memory. As we have seen in the previous chapter (p. 6), working memory may be viewed as the association of short-term storage and control processes akin to cognitive control. Cognitive control plays a prominent role in many important models of working memory, under the guise of the office worker in Broadbent's model, the central executive (or the supervisory attentional system) in Baddeley's model, and controlled attention in Engle's model. In the latter case, cognitive control is even viewed as the primary driver of individual differences in working memory. A contribution of cognitive control could be pinpointed at many levels within a working memory task: for example, a complex span task requires the coordination of storage and processing, the implementation of complex encoding strategies, as well as attentional refreshing of to-be-remembered stimuli. Cognitive control may also be required to prevent the processing and subsequent memorization of stimuli irrelevant to the task, thus ensuring that working memory is not overloaded by superfluous items (Gazzaley & D'Esposito, 2007; Fukuda & Vogel, 2009).

Interestingly, this theoretical relationship is not unidirectional: working memory is sometimes hypothesized to be required for cognitive control functioning. As reviewed in the previous section, cognitive control may be described as the biasing of task-related processing by rules maintained in the prefrontal cortex. Because these task rules have to be actively maintained over a time period during which concurrent processing takes place, it is often said that they are stored in working memory (e.g. Desimone & Duncan, 1995; Kimberg et al., 1997). Certain authors accordingly describe working memory as the basis of cognitive control (Kimberg et al., 1997). For example, it has been proposed that cognitive control does not rely on any control processes, but entirely on working memory: in practice, cognitive control would emerge whenever working memory is used to implement schemata over time (see Kimberg et al., 1997). This may be going a little too far, as the system maintaining task rules for cognitive control might be distinct from working memory for external stimuli (D'Esposito & Postle, 1999; Postle, Berger, & D'Esposito, 1999). However, this reasoning does illustrate the conceptual proximity between the two constructs.

This proximity sometimes even leads to confluence between the two constructs. Anecdotally, the term "dysexecutive syndrome" was initially coined by Baddeley; the syndrome was interpreted within the context of his working memory model and attributed to a

failure of the central executive. Working memory is also sometimes described as an executive function (Barkley, 1997). Although this seems really difficult to justify in relation to the definition of working memory, it helps illustrate the degree of similarity of the constructs in the minds of many researchers.

## **2.2. Psychometric evidence**

### *2.2.1. Miscellaneous assessments of cognitive control*

A substantial number of studies converge to suggest that working memory is related to cognitive control. For example, dual task experiments show that having participants complete a secondary task that taxes cognitive control decreases performance in a concurrent working memory task (Vandierendonck, De Vooght, & Van der Gote, 1998), suggesting that cognitive control is required for successful working memory performance. Participants with high working memory capacity are typically better at processing relevant stimuli and ignoring irrelevant stimuli in attentional tasks (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Fukuda & Vogel, 2009). They are also better at resisting proactive interference, a finding that is often attributed to a more efficient cognitive control (Kane & Engle, 2000).

Various studies have demonstrated that working memory capacity correlates with performance in cognitive control tasks. In one classic study using the dichotic listening paradigm, Conway and colleagues had participants listen and attend to a continuous verbal stream presented in one ear, while an irrelevant message was presented in the other ear (Conway, Cowan, & Bunting, 2001). After a variable period of time, the participant's own first name was presented amid the irrelevant message. Participants with low working memory capacity were significantly more likely to detect their name in the irrelevant message, suggesting that they had more trouble implementing the task goal of focusing the attention on the relevant auditory stream. Another study has shown that participants with high working memory capacity are also better at producing sequences of random numbers, another task thought to involve cognitive control (Miyake et al., 2001). Working memory capacity correlates with performance in verbal fluency tasks (Rosen & Engle, 1997; Schelble, Therriault, & Miller, 2012), a paradigm frequently used as a test of executive functioning. One study (Redick, Calvo, Gay, & Engle, 2011) related working memory capacity to performance in a go/no-go task, often used to assess inhibition; the study found a correlation between working memory capacity and performance, although the conclusion is debatable because the authors used a conditional go/no-go task imposing a significant load on working memory. A high working memory capacity is sometimes associated with better performance

in the flanker task, where participants have to indicate the orientation of a central arrow while ignoring the orientation of conflicting flanker arrows (Redick & Engle, 2006; Unsworth, Redick, Spillers, & Brewer, 2012; but see Keye, Wilhelm, Oberauer, & van Ravenzwaaij, 2009; Wilhelm et al., 2013); critically, working memory only predicts the ability to respond selectively to the central arrow while ignoring the flankers, not the ability to quickly detect the target or the ability to orient attention towards the spatial location of the stimuli (Redick & Engle, 2006). A couple of studies have also tested the relationship between working memory and cognitive control using latent variable analyses. One study (McVay & Kane, 2012a) observed a significant correlation between working memory and a cognitive control variable estimated from the antisaccade task, the Stroop task and a modified go/no-go task; another study (McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010) observed a significant correlation between working memory capacity and a cognitive control factor estimated with measures such as the Wisconsin card sorting test and a verbal fluency task. In summary, all these studies converge to show that working memory capacity is related to performance on a variety of cognitive control measures.

### *2.2.2. Working memory and goal-driven behaviour*

A few studies on the relationship between working memory and cognitive control deserve special attention because they directly studied the ability to maintain and implement a task goal, a critical notion for cognitive control. For example, several studies have shown that participants with high working memory capacity perform significantly better in the towers of Hanoi task (Welsh, Satterlee-Cartmell, & Stine, 1999; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Zook, Davalos, DeLosh, & Davis, 2004) and its variant, the towers of London task (Gilhooly, Wynn, Phillips, Logie, & Della Salla, 2002). These two tasks involve planning the movement of disks across a series of wooden pegs; they are classically used to assess the planning executive function, but they also rely on a very important goal management component (Carpenter, Just, & Shell, 1990).

Another series of studies has been carried out in the context of the controlled attention framework (Engle & Kane, 2004), in which controlled attention is viewed as the determinant of individual differences in working memory and goal maintenance is viewed as one of the two critical functions of controlled attention. One classic study (Kane et al., 2001) used the antisaccade paradigm, in which a flashing cue is presented on either side of a computer screen; participants are required to make an eye movement either in the direction of the cue (prosaccade condition) or in the opposite direction (antisaccade condition). The antisaccade

condition is thought to require more cognitive control because the natural tendency is to look in the direction of the target. Participants with high working memory capacity were more efficient than their counterparts in the antisaccade condition, but no difference emerged in the prosaccade condition. These results suggest that participants do not differ in their basic ability and speed to perform saccades, but only in their ability to implement cognitive control. This result was replicated several times (e.g. Unsworth et al., 2004; McVay & Kane, 2012a; Unsworth, Redick, et al., 2012). In a follow-up experiment (Unsworth et al., 2004), the lateral flashing cue was replaced by an arrow presented at the fixation point and indicating the direction of the required saccade; this manipulation presumably required participants to voluntarily trigger an eye movement, rather than simply let their gaze get captured by the flashing cue. Interestingly, working memory capacity was predictive of performance in the prosaccade condition in this experiment, suggesting that working memory is not related to the ability to refrain from following an external signal, but rather to the ability to endogenously generate a behaviour on the basis of an internal goal.

A second classic study (Kane & Engle, 2003) used a modified version of the Stroop paradigm, in which the proportion of congruent stimuli varied. The stimuli were either mostly congruent, a condition that presumably requires active maintenance of the task goal to remember that one is to name the colours rather than read the word, or mostly incongruent, a condition that places less emphasis on goal maintenance. Working memory capacity was predictive of performance in the task, but only when most stimuli were congruent; the authors concluded that working memory capacity is related to the ability to actively maintain the goal of the task. This result was also replicated in a number of later studies (e.g. Hutchison, 2011; Unsworth, Redick, et al., 2012). Conceptually similar to this Stroop study, other experiments used a go/no-go task with only 10% of no-go trials (McVay & Kane, 2012a; McVay & Kane, 2012b); because most trials simply elicited a "go" response, participants were rarely reminded that the task sometimes required no response at all. Working memory capacity showed an inverse correlation with the number of no-go errors on this paradigm; this suggests that a high working memory capacity is associated with a higher ability to actively maintain and implement the goal throughout the task (McVay & Kane, 2012).

These studies directly indicate that working memory is related to the ability to maintain a task goal. This conclusion is also indirectly supported by a series of studies investigating working memory capacity in relation with response time distributions, and more specifically very slow response times (as estimated by the tail of the distribution, or *tau* parameter; see Schmiedek et al., 2007). Because very slow response times may reflect a

temporary failure of maintaining the task goal on a trial, they can be viewed as an indirect index of cognitive control. Analyzing response time distributions reliably yields a higher tau parameter for participants with low working memory capacity; in other words, a low working memory capacity is associated with a larger number very slow response times (Schmiedek et al., 2007; Unsworth et al., 2010; Unsworth, Redick, et al., 2012; McVay & Kane, 2012b). Importantly, the tau parameter is a better predictor of working memory capacity than the mean response time. These results are observed not only in tasks that require cognitive control (Unsworth, Redick, et al., 2012; McVay & Kane, 2012b), but also in simple reaction time tasks (Schmiedek et al., 2007; Unsworth et al., 2010). Very slow response times for participants with low working memory capacity are also associated with more frequent self-reports of mind-wandering (McVay & Kane, 2012b). Taken together, these results suggest that participants with low working memory capacity fail more frequently to maintain the task goal.

Two studies are especially interesting in that they have attempted to extend these results to a more ecological setting. In a first study (Kane, Brown, et al., 2007), the participants were given personal digital assistants that randomly beeped eight times a day for one week. Participants were asked to report whether they were focused on their current task or daydreaming whenever they heard the personal assistant beep. Participants with high working memory capacity were more likely to report that they were focused on their current task when the personal assistant beeped. A second study asked participants to keep a diary of their attentional failures over a week (Unsworth, McMillan, Brewer, & Spillers, 2012); working memory capacity predicted certain mind wandering indices, such as the rate at which participants were distracted while studying.

### **2.3. Neurologic evidence**

Another argument for the proximity between cognitive control and working memory stems from their largely common neural substrate. As we have seen, the dorsolateral prefrontal cortex is central to cognitive control; this is also the case for working memory (a very exhaustive review is presented in Kane & Engle, 2002). Neuropsychological studies show that patients with a lesion in the prefrontal cortex demonstrate marked impairments in working memory tasks (for a meta-analysis see D'Esposito & Postle, 1999; see also Kane & Engle, 2002). Working memory capacity in healthy older adults is slightly correlated with the volume of the dorsolateral prefrontal cortex, but not other brain regions (Raz, Briggs, Marks, & Acker, 1999). Neuroimaging data also converge to show that the prefrontal cortex, and

especially its dorsolateral region, is activated during working memory tasks (E. E. Smith & Jonides, 1997; Kane & Engle, 2002; Kane, 2005). This involvement of the dorsolateral prefrontal cortex has been reliably observed across a variety of tasks, such as the *n*-back task (Owen, McMillan, Laird, & Bullmore, 2005) and delayed-memory paradigms (Kane & Engle, 2002).

What is the role of the prefrontal cortex in working memory tasks? Because single-cell recordings show that certain neurons in the prefrontal cortex exhibit sustained activation throughout delay tasks involving memory, some have concluded that the prefrontal cortex is involved in the short-term storage of information (Fuster & Alexander, 1971; Goldman-Rakic, 1995). However, these delay tasks also involve cognitive control in that they require goal-driven behaviour (see Kane & Engle, 2002); furthermore, the prefrontal cortex does not typically demonstrate particular activations during short-term memory tasks involving only storage (Postle et al., 1999), and lesions in this region do not lead to impairments in short-term memory tasks either (D'Esposito & Postle, 1999). A plausible interpretation is that sustained neuronal activity in the prefrontal cortex only reflects the maintenance of internal task goals subtending cognitive control, as described in the previous sections, but that it is not needed for simple storage of exogenous stimuli. If this view is correct, the prefrontal cortex is required in working memory tasks inasmuch as it subtends the operation of control processes in working memory (e.g. Postle, 2006). This would explain why this region is not required in simple short-term memory tasks, which do not place a strong emphasis on control processes.

***In summary***

- Cognitive control is conceptually very close to working memory: working memory might be required to implement cognitive control and cognitive control may help achieve a higher working memory capacity.
- Many studies have showed that a high working memory capacity correlates with an efficient cognitive control, and especially with the ability to maintain and implement a task goal.
- Cognitive control and control processes in working memory share a common neural substrate in the prefrontal cortex, as evidenced by neuroimaging and lesion studies.



### **3. Proximity between cognitive control and fluid intelligence**

The fact that working memory is related to cognitive control is a first element in favour of the hypothesis that cognitive control drives its relationship with fluid intelligence. On the other hand, for this hypothesis to be valid, a second prerequisite must be met: cognitive control also has to be related to fluid intelligence. Evidence that this is the case will be reviewed in the next section.

#### **3.1. Cognitive control involvement in fluid intelligence tasks**

The idea that intelligence is related to cognitive control is not exactly a novel one. Spearman postulated that  $g$  indexed a form of mental energy broadly equivalent with attentional resources, and the ability to appropriately direct this mental energy was discussed in several of his works on general intelligence (see Messick, 1996). More formally, recall that fluid intelligence refers to « the use of deliberate and controlled mental operations to solve novel problems that cannot be performed automatically » (McGrew, 2009, p. 5). If it were not for the name of the author and the context, one could believe that this definition refers to cognitive control rather than fluid intelligence: it includes the notion of controlled processing as well as the notion of non-automatic processing, both critical to cognitive control. As we have seen, cognitive control should be involved at various degrees in any task that is sufficiently complex to preclude automatic processing; in practice, no cognitive task is more complex than fluid intelligence tests. In fact, it seems unlikely that a situation as complex as understanding and solving a novel problem could be performed through fully automatic processes, without resorting to cognitive control (Ackerman et al., 2005).

How exactly is cognitive control required in a fluid intelligence task? Carpenter and colleagues (1990) studied which processes are used to solve problems in Raven's APM test, and subsequently proposed an interesting account of cognitive control involvement. In an experiment using verbal report and eye tracking, the authors observed that participants typically work their way through a problem in a very systematic manner. The typical sequence of gazes depicted in Figure 3 illustrates this process. As can be seen, participants tend to compare the first two elements in the top row, presumably to contrast their attributes, then compare the second and the third elements. These pairwise comparisons are followed by several scans of the complete row. This process is then repeated on the second and third row.

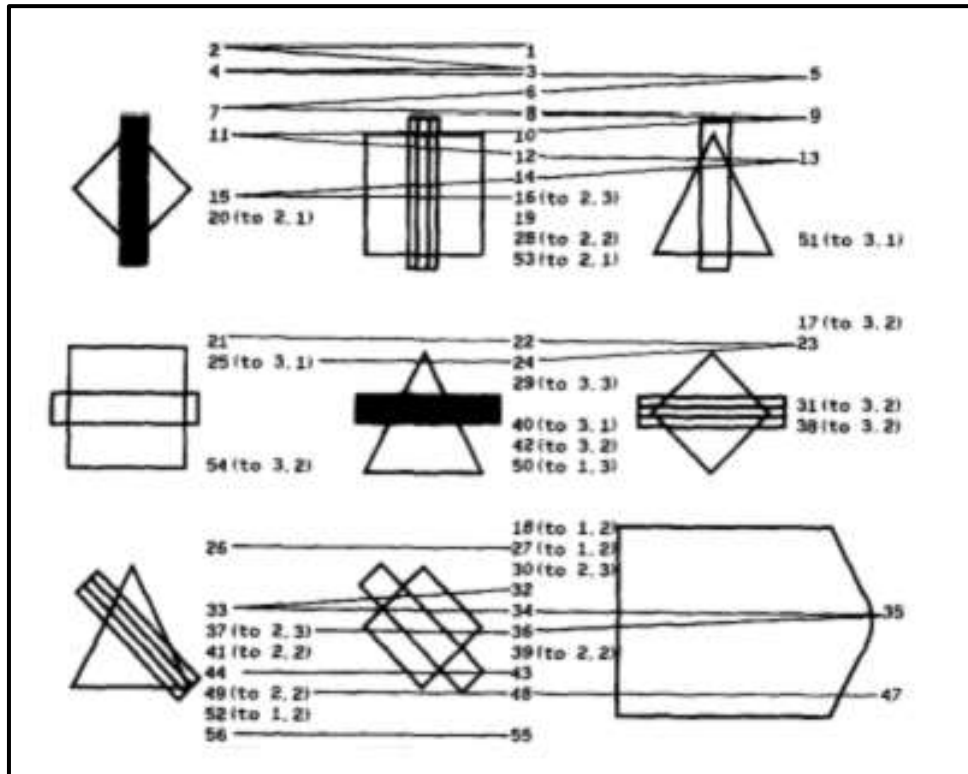


Figure 3. Typical sequence of gazes in one problem of Raven's advanced progressive matrices. Increasing numbers represent the successive locations that were fixated by the participant. Straight lines indicate eye movements within the same row. From "What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices Test." by P.A. Carpenter, M.A. Just and P. Shell, 1990, *Psychological Review*, 97(3), p. 412. Copyright 1990 by the American Psychological Association.

Based on these observations, the authors suggested that participants work their way through the problem with an incremental procedure: they break the problem down into a hierarchy of goals and sub-goals, and then proceed to solve each sub-goal successively. In other words, the task seems to be solved through a series of elementary goal-driven behaviours. The authors provided an example of a possible goals hierarchy:

**Top goal:** Solve problem

**Sub-goal 1:** Find all rules in the top row

**Sub-goal 2:** Do a first scan of top row

**Sub-goal 3:** Compare adjacent entries

**Sub-goal 4:** Find what aspects are the same or different or have no relation.

Because this account completely relies on goal-driven behaviour, it makes the involvement of cognitive control directly apparent. Carpenter and colleagues additionally tested their interpretation with simulation models of APM performance. A first model was programmed to solve the task through simple perceptual and conceptual analysis; a second model was mainly identical to the first one with one major difference: it incorporated a goal monitor module, aiming to decompose the problems into a sub-goals structure and regulate the behaviour of the model as a function of these goals. This second model demonstrated much better performance than the first one, both in terms of overall accuracy and in terms of the complexity of the rules it was able to follow. Overall, this work illustrates that the involvement of cognitive control in one test of fluid intelligence may be viewed simply in terms of regulating behaviour according to a series of incremental goals.

### **3.2. Psychometric evidence**

#### *3.2.1. Miscellaneous assessments of cognitive control*

The relationship with cognitive control has been less studied for fluid intelligence than for working memory, and these studies have yielded less unanimous results. The data tend to point towards a correlation between measures of fluid intelligence and cognitive control (see Chuderski & Nęcka, 2010), but the results are often mixed. Fluid intelligence is predictive of performance in certain tasks that require resistance to interference, such as the Stroop test, but not in other interference tasks (for a review, see Dempster & Corkill, 1999). Fluid intelligence correlates with the number of perseverative errors on the Wisconsin card sorting test in certain studies, but not in others (Dempster & Corkill, 1999). Similarly, fluid intelligence demonstrates a correlation with dual task coordination in certain studies, but not in others (Chuderski & Nęcka, 2010); interestingly, the relationship has been observed to be higher in conditions emphasizing the need for cognitive control, such as when the stimuli for the two both tasks appeared simultaneously (Chuderski & Nęcka, 2010).

Other measures seem consistently related to fluid intelligence. One study (Cowan, Fristoe, Elliott, Brunner, & Saults, 2006) observed a correlation between a general estimate of intelligence and the ability to control attention, calculated as the benefit in recall performance when specifically focusing attention on a series of stimuli. The same study observed that participants with a low fluid intelligence were able to recall more of the stimuli that should have been ignored, conceptually similar to the earlier experiment relating working memory to dichotic listening (Conway et al., 2001). Fluid intelligence seems to correlate with performance on the Towers of Hanoi task (Carpenter et al., 1990; Zook et al., 2004); in one

study (Colom, Rubio, Shih, & Santacreu, 2006), this correlation appeared even higher than the correlation between fluid intelligence and working memory and increased with the complexity of the fluid intelligence task.

Several studies have tried to use latent variable analyses to obtain a more accurate measure of cognitive control so as to estimate its relationship with fluid intelligence. Friedman and colleagues found a correlation between latent variables representing fluid intelligence and the updating executive function (N. P. Friedman et al., 2006), but this result is not really informative since they assessed updating with working memory tasks. The same study did not find a relationship between fluid intelligence and latent variables representing the functions of inhibition or shifting; on the other hand, the authors reported a statistically significant bivariate correlation between Raven's progressive matrices and the antisaccade task, as well as between measures of *g* and several other cognitive control tasks. Another study (Chuderski, Taraday, Nęcka, & Smoleń, 2012) found a correlation between latent variables representing fluid intelligence and cognitive control, as assessed by the antisaccade task and variants of the Stroop task. The same study reported a correlation between Raven's progressive matrices and a go/no-go task. A third study (Paulewicz, Chuderski, & Nęcka, 2007) found a relationship between fluid intelligence and cognitive control measured with a goal monitoring task, a dual task coordination paradigm, and various executive function tasks. Another study (Schweizer, Moosbrugger, & Goldhammer, 2005) also found a relationship between fluid intelligence and a cognitive control latent variable, estimated with various attentional tasks assumed to involve control to some extent. Lastly, Unsworth and colleagues completed two similar studies (Unsworth et al., 2010; Unsworth & Spillers, 2010) where they tested the correlation between latent variables representing fluid intelligence and cognitive control; their cognitive control assessment included an antisaccade task, a flanker task (Unsworth et al., 2010; Unsworth & Spillers, 2010), and a mostly congruent Stroop task (Unsworth & Spillers, 2010), among others. Both studies reported a significant relationship between the fluid intelligence and cognitive control latent variables; however, the bivariate correlations between the individual cognitive control tasks and the individual fluid intelligence tasks were very low and generally non-significant.

Overall, these results suggest that fluid intelligence is moderately related to cognitive control; although this relationship seems relatively task-dependent and less universally observed than the relationship between working memory and cognitive control, it is still found in a significant number of studies.

### 3.2.2. *Fluid intelligence and goal-driven behaviour*

Several of the aforementioned studies have used tasks that can be seen as particularly reliant on goal-driven behaviour. Two studies have evidenced a relationship between fluid intelligence and the antisaccade task (N. P. Friedman et al., 2006; Chuderski et al., 2012), which Kane and colleagues have argued depends primarily on the ability to maintain a task goal. Three studies demonstrated that fluid intelligence correlates with performance on the towers of Hanoi task (Zook et al., 2004; Carpenter et al., 1990; Colom, Rubio, et al., 2006); in the latter two cases, the results were particularly interesting because the authors trained all participants to use a goal-recursion strategy beforehand, resulting in even more emphasis on the goal management aspect of the task.

As for indirect results, a few studies have observed a negative correlation between fluid intelligence and the tau parameter in response time distributions (Schmiedek et al., 2007; Unsworth et al., 2010); as we have seen, the tau parameter may be used as an index of goal maintenance. As was already the case for working memory, the tau parameter seems to be a better predictor of fluid intelligence than mean response times, suggesting that reasoning is more related to the ability to maintain a task goal than to processing speed itself. Two studies reported that reading comprehension correlates with mind wandering during cognitive control tasks (McVay & Kane, 2012a), and that attentional failures self-reported in a diary over the course of a week predict scores on the scholastic assessment test (Unsworth, McMillan, et al., 2012). Even though they are not directly related to fluid intelligence, these two studies suggest that the role of cognitive control is not limited to fluid intelligence tasks, but may be observed in other high-level cognitive tasks too.

A series of particularly influential studies have shown a relationship between fluid intelligence and a phenomenon termed *goal neglect* (Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan et al., 2008). Duncan and colleagues defined goal neglect as the phenomenon observed when participants disregard a task requirement despite perfectly understanding and remembering this requirement (Duncan et al., 1996); this concept constitutes a direct operationalization of cognitive control and more specifically goal-driven behaviour. The authors give the example of patients with frontal lesions, who often disregard task instructions, acknowledge their own failure to fulfill the task goal, but do not make any attempt to modify their behaviour. A psychometric task was used by the authors to assess goal neglect: participants had to attend one of two visual streams of letters presented on each side of a screen. They were sometimes required to change the attended side; the number of failures to comply was recorded as a measure of goal neglect. Participants were then asked which side

they were supposed to attend and which side they had actually attended. In a series of studies, goal neglect was shown to be widespread in non-pathological samples; critically, goal neglect was much more common in participants with a low fluid intelligence score (Duncan et al., 1996; Duncan et al., 2008; Paulewicz et al., 2007). The performance of these participants even appeared similar to patients with a frontal lesion (Duncan et al., 1996). Interestingly, participants who neglected the goal demonstrated perfect understanding of the task instructions and could repeat them accurately on demand; in many cases, they were able to immediately correct their mistake whenever prompted to do so (Duncan et al., 1996). A related point is that the goal neglect rate increased with the complexity of the task, but also when the instructions were made more complex without changing the task itself (Duncan et al., 2008). These results suggest that participants with low fluid intelligence have more trouble forming a mental representation of the task goal and implementing this goal in practice to regulate their behaviour.

### **3.3. Neurologic evidence**

Just like working memory, fluid intelligence seems to share a neural substrate with cognitive control in the prefrontal cortex (for a review, see Gray & Thompson, 2004; Kane & Engle, 2005). Neuroimaging studies consistently evidence activations in the prefrontal cortex during fluid intelligence tasks (e.g. Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997; Duncan et al., 2000). One study in particular contrasted brain activations in very different spatial and verbal fluid intelligence tasks, and found that only the lateral prefrontal cortex was reliably activated by all tasks (Duncan et al., 2000). While other studies have reported mixed results involving activations of more diffuse neural networks (e.g. Prabhakaran et al., 1997; see Gray & Thompson, 2004), virtually all these studies conclude that the prefrontal cortex is recruited by fluid intelligence tasks. Various studies also found a correlation between the volume of the prefrontal cortex and general intelligence (e.g. Reiss, Abrams, Singer, Ross, & Denckla, 1996; see also Gray & Thompson, 2004).

Although a number of neuropsychological studies have failed to demonstrate impairments in performance on intelligence tasks after a prefrontal lesion (Kane & Engle, 2005), most of these studies have used tests of crystallized intelligence rather than fluid intelligence (Duncan, Burgess, & Emslie, 1995). This distinction is critical because crystallized intelligence is dependent on acquired knowledge more than on reasoning, which means crystallized intelligence tasks probably have lesser requirements in the way of adapting to a novel situation. When actual fluid intelligence tasks are used, impairments in fluid

intelligence do appear after a prefrontal lesion (Duncan et al., 1995). Another study concluded that patients with a prefrontal lesion were impaired in deductive reasoning tasks such as syllogistic reasoning (Waltz et al., 1999). Interestingly, the same patients were impaired in Raven's progressive matrices, but only on problems requiring the application of more than one rule; they demonstrated normal performance on single-rule problems (Waltz et al., 1999). In other words, a prefrontal lesion seems to only hinder performance in problems requiring that patients follow a hierarchy of goals to solve a complex task.

***In summary***

- Because cognitive control is supposed to be involved in all complex tasks that cannot be solved automatically, it should play a role in fluid intelligence tasks.
- The contribution of cognitive control to intelligence may be described in terms of regulating behaviour according to a hierarchy of goals and sub-goals necessary to solve the task.
- Fluid intelligence correlates with various measures of cognitive control and especially goal-driven behaviour, although this relationship seems less reliable and more task-dependent than for working memory.
- Fluid intelligence shares a neural substrate with cognitive control in the prefrontal cortex, as evidenced by neuroimaging and lesion studies.

## **4. Assessing the role of cognitive control**

### ***4.1. Empirical tests of the cognitive control hypothesis***

As we have seen in the previous two sections, an impressive number of researchers agree that cognitive control seems related to working memory and fluid intelligence, both conceptually and empirically. These twin relations make cognitive control an eligible candidate as the basis of the correlation between working memory and fluid intelligence. However, the observation that cognitive control is related to both constructs is not, in and of itself, sufficient grounds to consider that it drives their correlation. Several studies have attempted to test this hypothesis more directly by evaluating the three-way relationship between estimates of cognitive control, working memory and fluid intelligence.

#### *4.1.1. Cognitive control as residual variance*

A first group of studies attempted to test the hypothesis by measuring fluid intelligence, and then estimating the respective contributions of short-term storage and cognitive control processes in working memory to this measure. All these studies used the same rationale: if working memory is the association of short-term storage and control processes and if short-term storage does not explain the relationship between working memory and fluid intelligence, then cognitive control processes must contribute to this relationship. In other words, these studies did not attempt to directly measure cognitive control; instead, they considered that the residual variance remaining in a measure of working memory capacity after controlling for short-term storage reflected the role of control processes, and that a significant correlation between this residual variance and a measure of fluid intelligence would indicate a role of cognitive control.

Most of these studies used latent variable analyses to assess the different constructs. In four such studies, short-term storage was defined as the shared variance between working memory and short-term storage tasks, while cognitive control was defined as the residual variance unique to working memory tasks. With this procedure, two studies reported that cognitive control predicted fluid intelligence, and that the relationship between short-term storage and fluid intelligence was non-significant once cognitive control was accounted for (Engle et al., 1999; Conway et al., 2002). Two other studies concluded that both short-term storage and cognitive control were predictors of fluid intelligence (Colom, Flores-Mendoza, et al., 2005; Colom, Abad, et al., 2005); in one case, the unique variance predicted by cognitive control was especially small (Colom, Flores-Mendoza, et al., 2005).

Another study (Kane et al., 2004) used a similar rationale, but estimated cognitive control in a slightly different way. If working memory is constituted of domain-specific storage processes and domain-general control processes, the variance common to working memory tasks using different types of materials should uniquely reflect cognitive control. The authors elected to divide working memory tasks into two groups, spatial tasks and verbal tasks. The model included one latent variable for spatial short-term storage and one variable for verbal short-term storage; a third variable representing cognitive control was defined as the variance common to all working memory tasks. Cognitive control was a better predictor of fluid intelligence than the two short-term storage variables, although spatial short-term storage retained a significant relationship with fluid intelligence.

In summary, all these studies suggest that cognitive control explains part of the relationship between working memory and fluid intelligence, whereas short-term storage is



sometimes, but not always, a significant predictor. Unfortunately, this conclusion has been challenged by re-analyses of some data sets in subsequent studies (Colom, Rebollo, et al., 2006; Unsworth & Engle, 2007b); for example, a re-analysis of Kane et al. (2004) suggested that the working memory residual did not account for any supplementary variance in fluid intelligence when short-term storage was accounted for (Colom, Rebollo, et al., 2006), and a re-analysis of Engle et al. (1999) suggested that the working memory residual extracted after controlling for short-term storage was not a significant predictor of fluid intelligence either.

Not all studies using this approach worked with latent variable analyses; one author (Embretson, 1995) elected to directly assess the separate contributions of storage and cognitive control within a fluid intelligence task. The author constructed a series of 130 problems mimicking Raven's progressive matrices. The problems were matched on most dimensions such as their structure and distractors, but they systematically varied in terms of memory load (operationalized as the number and complexity of logical rules within a problem). The author considered that the difference in performance between items of different memory loads would reflect the contribution of storage to performance, whereas the difference in performance between items with the same memory load would reflect the contribution of cognitive control. The results indicated that both storage and cognitive control contributed to performance in the task.

#### *4.1.2. Mediation by cognitive control measures*

A second group of studies tried to test the cognitive control hypothesis by directly measuring all three constructs – working memory capacity, fluid intelligence, and cognitive control – and then assessing the relationships between these three measures. Several of these studies used a single measure of cognitive control to test the mediation. For example, one study measured cognitive control as the benefit in recall performance when specifically focusing attention on a series of stimuli (Cowan et al., 2006); a second measure was labeled "scope of attention" by the authors, but used a visual arrays comparison task conceptually similar to working memory tasks. The results indicated that both cognitive control and working memory were predictive of fluid intelligence. In another study, cognitive control was measured with the towers of Hanoi task after training the participants to use a goal recursion strategy based on the active maintenance and implementation of a hierarchy of task goals (Colom, Rubio, et al., 2006). Results showed that cognitive control did not mediate the relationship between working memory and fluid intelligence.

Two other studies used the *n*-back task to assess cognitive control. This task requires the participant to attend to a continuous series of sequentially presented stimuli, and to decide for each stimulus whether it is identical to the stimulus presented exactly *n* trials previously. In some trials, the stimulus may be identical to a stimulus previously seen by the participant, but not exactly *n* trials previously (for example, the participant may have seen this stimulus *n*+1 trials before); in this case, a non-target response is required. These trials are frequently labeled "lure trials" because the familiar stimulus elicits a much higher chance of error. Some researchers have proposed that lure trials require cognitive control to refrain from making a target response (e.g. G. C. Burgess, Gray, Conway, & Braver, 2011); in this view, accuracy on lure trials may be used as a measure of cognitive control. One study assessed cognitive control with this approach and estimated a working memory measure as the total number of correct hits in the *n*-back task (Chuderski & Necka, 2012). Cognitive control estimated with a combination of 1-back and 5-back tasks was not a significant predictor of fluid intelligence, contrary to working memory; on the other hand, this null result could be attributed to the low sensitivity of the 1-back (extremely easy) and the 5-back (extremely difficult) versions of the paradigm. Cognitive control was a better predictor when measured with a combination of 1-back and 3-back tasks or with a combination of 2-back and 4-back tasks. In both cases, it predicted a significant percentage of variance in fluid intelligence, but this percentage was very small and working memory was a much better predictor. Another experiment (G. C. Burgess et al., 2011) estimated a measure of cognitive control as the behavioural accuracy and neural activity on lure trials in a 3-back task, and elected to measure working memory with classic complex span tasks. The results indicated that both accuracy and neural activity on lure trials were correlated with fluid intelligence; furthermore, these two measures mediated part of the relationship between working memory and fluid intelligence.

Lastly, a few studies used latent variable analyses to extract a latent cognitive control factor. One study measured cognitive control with performance on a "keep track" task based on the simultaneous storage and processing of information, performance on a shifting task, and global accuracy in a *n*-back task (Colom et al., 2008); the relationship between working memory and fluid intelligence was primarily mediated by short-term storage, although cognitive control also explained a small percentage of variance. Another study measured cognitive control with the antisaccade task, the flanker task and two verbal fluency tasks (Unsworth et al., 2010); working memory was highly correlated to fluid intelligence even when controlling for cognitive control. A third study used a wide variety of interesting executive tasks and concluded that they did not mediate the relationship between working

memory and fluid intelligence (Krumm et al., 2009); however, its results are particularly difficult to interpret because the authors considered that various complex tasks (including the trail-making test, the d2 test and a task-switching paradigm, among others) actually assessed mental speed rather than cognitive control, that a task requiring the participant to keep track of at least nine items regularly changing within a grid did not measure any sort of control processes in working memory beyond short-term storage, and that tasks such as the go/no-go, the antisaccade and the Stroop test, despite having been completed by the participants, did not need to be included in the analyses.

#### **4.2. The problem with current data**

In summary, all the studies that we have reviewed in this section converge to one of two conclusions: either cognitive control is not involved in the relationship between working memory and fluid intelligence (as suggested by the studies reporting that only short-term storage correlates with fluid intelligence and by the studies that do not observe a link between cognitive control measures and fluid intelligence); or cognitive control mediates part of the relationship between working memory and fluid intelligence, but only explains a very limited part of the shared variance (as suggested by the studies reporting that both cognitive control and variance attributed to other constructs are predictive of fluid intelligence). None of these studies reported a full mediation by cognitive control. This conclusion stands in contrast with the cumulative evidence that cognitive control is related to working memory and fluid intelligence; despite these strong theoretical roots, it seems that the cognitive control hypothesis does not survive direct empirical evaluation.

However, virtually all the studies testing this hypothesis are crippled by the exact same shortcoming: their cognitive control estimates are entirely unsatisfying. Assessing cognitive control poses a number of very important psychometric problems; among these problems, even those that are common to the assessment of other cognitive constructs tend to be much harder to avoid when it comes to cognitive control. Listing *all* the problems related to the measurement of cognitive control may not be a desirable endeavour, but it is perhaps useful to point out the most impeding of these problems.

First, cognitive control is not a binary construct that is either required or not required in a task; instead, it is likely that all cognitive tasks require cognitive control to some extent given that they require the participant to act according to a goal (V. Anderson, 2008). In other words, the efficiency of cognitive control may be a factor of performance in all possible tasks. This idea poses an obvious problem to studies attempting to assess cognitive control

separately from other constructs: if cognitive control factors in all possible tasks, then it is impossible to test its independent contribution to performance. Studies assessing cognitive control as the residual variance after controlling for short-term storage (e.g. Engle, 1999; Conway, 2002; Kane, 2004) are particularly at risk because cognitive control is certainly required in short-term memory tasks, although not necessarily as much as in working memory tasks. In other words, the correlation between short-term memory and fluid intelligence may reflect a contribution of cognitive control. This also means that the correlation sometimes observed between short-term memory (e.g. spatial short-term memory in Kane et al., 2004) and fluid intelligence could also reflect common reliance on cognitive control. Similarly, Embretson (1995) attributed the difference in performance between problems of varying memory load to a role of short-term storage; but this variance could also reflect a differential contribution of cognitive control on items with different numbers of rules. This is all the more true that the author considered rule complexity as a component of memory load, and that problems with more rules tend to be the most difficult.

Second, the role of cognitive control is to regulate the functioning of other cognitive processes; it is sometimes described as an orchestra conductor. Consequently, it is impossible to measure cognitive control in isolation because any task involving cognitive control will also involve other cognitive abilities (Rabbitt, 1997; V. Anderson, 2008). For example, the *n*-back task used in several studies also relies on motivation (to maintain a high level of vigilance throughout the task), short-term memory (to actively maintain and rehearse recent stimuli), long-term memory (to recognize stimuli that are no longer present in short-term memory), and processing speed (simply because the task is speeded and stimuli appear at a sustained pace). A participant might fail on lure trials because he has poor cognitive control, because he is not really motivated to succeed, or because his slow processing speed means he does not have the time to rehearse all stimuli in short-term memory and instead has to retrieve them in long-term memory, which makes him more vulnerable to lure trials. This problem becomes particularly worrying when one considers that working memory is related to motivation, short-term memory, retrieval in long-term memory, and processing speed all at once: the relationship between working memory capacity and performance in cognitive control tasks may be explained by a contribution of factors entirely distinct from cognitive control. Of course, the same is true for the relationship between fluid intelligence and cognitive control. This problem makes it difficult to assess the correlations between the three constructs because these correlations may be driven by another process entirely than the one being measured. For example, the antisaccade task (e.g. Unsworth et al., 2010) requires

processing speed; verbal fluency (e.g. Unsworth et al., 2010) requires retrieval from long-term memory; and the benefit in recall performance when focusing attention on a specific channel (Cowan et al., 2006) obviously relies on memory as much as cognitive control. Studies assessing cognitive control as the residual variance after controlling for short-term storage also have a serious problem, since their cognitive control estimate may include contributions from an infinite number of other factors; in this view, these studies do not show that both short-term storage and cognitive control contribute to fluid intelligence, but they merely state that short-term storage does not fully explain fluid intelligence and that the residual variance is significantly different from zero.

Third, a related problem is that the fact that a task requires cognitive control does not mean that performance on this task is primarily driven by cognitive control. This problem can be best explained with an analogy: all visual short-term memory tasks require vision, but this does not imply that individual differences in visual acuity are an important factor of performance, even though blind participants are clearly going to fail the task. For example, many of the tasks used in the various studies we have reviewed have been selected because they show sensitivity to prefrontal lesions; but individual differences in performance in these tasks may not reflect individual differences in the efficiency of cognitive control in non-lesioned samples. Instead, performance may be driven by some of the confounds: processing speed, sustained attention or short-term memory for example. Certain tasks used to assess cognitive control, such as verbal fluency tasks or the towers of Hanoi, are also very sensitive to the type of strategy being used (see Miyake et al., 2001; Schelble et al., 2012); in non-lesioned samples, strategic behaviour may be more influential in determining performance than the efficiency of cognitive control. Again, this problem is compounded that the fact that working memory is predictive of processing speed, short-term memory and strategic behaviour.

Fourth, cognitive control may not be adequately assessed by cognitive control tasks at all. For example, cognitive control deals with the organization of behaviour in complex situations, but the laboratory setting provides artificial order and structure which necessarily reduces the demand on cognitive control (V. Anderson, 2008). Therefore, laboratory tasks may not be an adequate indicator of the underlying cognitive control ability. Another example is that cognitive control is required when a task is novel; after a period of learning, automaticity takes place, the role of cognitive control becomes much less salient, and performance becomes driven by other factors (Rabbitt, 1997). However, many tasks used to assess cognitive control include a large number of trials, sometimes in the hundreds.

Performance on these tasks may reflect learning rate or resistance to fatigue more than cognitive control. Along the same lines, one could wonder whether studies training participants to perform an executive task with a specific strategy in advance (e.g. Colom, Rubio, et al., 2006) are measuring cognitive control at all.

Fifth, these various difficulties do not take into account the amount of overlap between working memory, cognitive control and fluid intelligence, which may lead to critical operationalization problems. Many researchers have measured cognitive control with tasks that obviously tap working memory: for example, the *n*-back task and the keep-track task used to measure cognitive control in certain studies (e.g. Colom et al., 2008; Chuderski & Necka, 2012) are basically two working memory tasks. It is not overwhelmingly surprising that cognitive control as assessed with working memory tasks does not explain any variance in fluid intelligence above and beyond working memory tasks.

Sixth, all these problems are compounded by the fact that all studies concluding that cognitive control does not mediate the relationship between working memory and intelligence are obviously testing the null hypothesis. Given the difficulty in obtaining adequate measures of cognitive control, the lack of a relationship may simply mean that cognitive control has not been correctly assessed. As a sidenote, most cognitive control tasks have poor psychometric properties (Rabbitt, 1997) which necessarily limits their correlations with other measures and may help explain their lack of predictive validity.

In short, all these criticisms ultimately come down to a single problem: it is really, really hard to operationalize and measure cognitive control in isolation. Performance in a cognitive control task may be driven by factors other than cognitive control efficiency, whereas non-cognitive control tasks certainly require cognitive control to some extent. All the studies that we have reviewed are critically impacted by at least one of these problems. In other words, it seems that one cannot place too much trust into the existing studies testing the mediating role of cognitive control. This does not mean, however, that all studies on cognitive control are doomed to fail. Instead, we believe that many of these problems stem from the fact that most studies have adopted a largely homuncular view of cognitive control as "the thing that carries out cognitive control tasks". As stated by Underwood (1975, p. 131): « A single-process theory must always be isomorphic to empirical relationships. [...] As a theoretical concept, it is superfluous and has no predictive power ». Because we consider cognitive control as a unidimensional ability whose efficiency is always positively related to working memory and fluid intelligence, the only prediction we can make is that the various tasks should be positively correlated. However, because we can never be certain that performance

in a cognitive control task is actually driven by cognitive control, and because both fluid intelligence and working memory capacity tend to be positively correlated with the efficiency of many cognitive abilities, all results can be interpreted at will: if a cognitive control measure is related to working memory or fluid intelligence, we are free to attribute this finding to cognitive control or to any other ability such as processing speed; conversely, if our measure is not related to either construct, we are free to believe that the task did not truly index cognitive control efficiency, a form of "No True Scotsman" fallacy. We argue that the lesson here is that we need a more accurate operationalization of cognitive control if we are to disentangle its relationships with other constructs. In the next chapter, we will see how the Dual Mechanisms of Control (DMC) framework constitutes one possible answer to this problem.

***In summary***

- Several studies have directly tested the mediating role of cognitive control, either by considering cognitive control as the residual variance in a measure, or by using one or several cognitive control tasks.
- Cognitive control is especially difficult to measure: it may play a role in non-cognitive control tasks and may not drive performance in cognitive control tasks. This problem impacts virtually all existing studies on the mediating role of cognitive control.
- Getting around this measurement problem requires a more accurate operationalization of cognitive control.

# CHAPTER 3. THE *DMC* FRAMEWORK APPLIED TO WORKING MEMORY

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## ***Objectives***

We have seen in the previous chapter that our hypothesis that cognitive control holds an explanatory role is difficult to test in the absence of an accurate operationalization of the construct. This chapter aims to present the Dual Mechanisms of Control (*DMC*) framework of cognitive control, and to show how it can be fruitfully applied to the understanding of working memory and its relationship with fluid intelligence. We first describe in detail the *DMC* framework and the experimental studies supporting this framework. We then synthesize the existing evidence in favour of a relationship between working memory and proactive control. We conclude this introduction by showing how the *DMC* framework allows for an operationalization of cognitive control that can be directly tested in relationship with other constructs, and by presenting the rationale for our experimental work.

## **1. The dual mechanisms of control framework**

### ***1.1. Presentation of the framework***

As described in the previous chapter (pp. 40-41), cognitive control may be recruited via either a top-down or a bottom-up process. The *DMC* framework (Braver, Gray, & Burgess, 2007; Braver, 2012) proposes that the two solutions coexist and correspond to different mechanisms, respectively labeled proactive control and reactive control. Both mechanisms rely on a top-down biasing role of contextual representations (such as task goals), whose storage is ensured by the prefrontal cortex, to drive action selection in a task. The critical difference between the two mechanisms resides in how they are recruited. Proactive control constitutes an anticipatory mechanism; it is implemented in advance, before control is actually required in a situation. In other words, engaging in proactive control to regulate behaviour relative to a particular event means implementing control before the event occurs. As a consequence, proactive control may be described as a continuous process



sustained throughout the task. Importantly, this mechanism requires some predictive contextual representation about the nature of the action that will have to be performed in order to proactively bias cognitive processing.

By contrast, the reactive control mechanism is only implemented after the occurrence of the event requiring control. In other words, reactive control gets selectively engaged after the need for control relative to an event is detected. Only at this point in time is the contextual representation reactivated and used to bias processing; this contextual information decays quickly and must be reactivated each time a demanding event takes place. As a result, response selection remains relatively unbiased before the occurrence of the event that triggers reactive control. Prior to this event, cognitive processing is essentially unaffected by cognitive control; stimuli are processed based on their features in a bottom-up manner.

The functioning of reactive and proactive control is sometimes illustrated with the example of prospective memory tasks (e.g. Braver, 2012). Imagine that you are to make an important phone call after you finish reading this paragraph. There are two possible ways for you to remember your task. With a proactive control strategy, you will implement the objective in advance by actively reminding yourself of the goal as you read these words. By contrast, with a reactive control strategy you will not use a sustained process to actively remind yourself of the goal; instead, you will only reactivate your goal when confronted with some salient event acting as a trigger – for example when you see that piece of paper with a phone number on your desk<sup>5</sup>.

Interestingly, each control mechanism is thought to be associated with its own costs and benefits (Braver et al., 2007). Proactive control is by nature a non-selective mechanism, impacting all trials within a task whether required or not. As a sustained process maintained over a significant period of time, it is also more costly in terms of metabolic resources. Because contextual information is required to implement control ahead of time, proactive control is sensitive to the validity of this information, with invalid contextual cues leading to processing errors. By contrast, reactive control can be selectively applied only when required, leading to more flexibility and a lesser cost in resources; it is also relatively unaffected by erroneous predictive cues. On the other hand, reactive control is dependent on stimulus-specific features and tends to fail when stimulus-driven processing is not efficient; the fact that it is recruited after the occurrence of a demanding event also necessarily leads to slower response times and lower performance in many situations. Because both mechanisms have their shortcomings, they are not to be seen as one "efficient" and one "inefficient" mechanism;

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<sup>5</sup> Go ahead, look around you: have you *actually* forgotten to do something important?

the preferred view is that they are complementary mechanisms with different cost/benefit tradeoffs (Braver, 2012).

As we have seen in the previous chapter (pp. 40-41), bottom-up and top-down mechanisms may be associated with different neural activations. Proactive control is heavily dependent on the active maintenance of contextual information in the dorsolateral prefrontal cortex; as a result, it is associated with sustained activations in this region (Braver et al., 2007). Reactive control, on the other hand, is engaged whenever a need for control is detected; as we have seen, the anterior cingulate cortex is thought to be a critical region for conflict detection (e.g. Botvinick et al., 2001). As a result, reactive control places more emphasis on the role of the anterior cingulate cortex. Of course, this does not mean that either mechanism recruits only one brain region: reactive control still depends on the dorsolateral prefrontal cortex for storage and implementation of contextual information, but this activation is more transient than for proactive control and only emerges after a demanding event has occurred. Conversely, proactive control may require the anterior cingulate cortex (Braver et al., 2007). Both mechanisms are also associated with a range of other brain regions: proactive control is thought to require the dopaminergic system to regulate the active maintenance of contextual information in the prefrontal cortex, while the stimulus-driven nature of reactive control means it can be expected to recruit more extensive neural networks (Braver et al., 2007). However, the important point here is that the two mechanisms are separable in terms of the neural activations they elicit and the time dynamics of these activations.

In summary, the DMC framework proposes that there exist two distinct mechanisms of cognitive control; a critical characteristic of this framework is that the two mechanisms are separable in terms of temporal dynamics, in terms of efficiency in different tasks, in terms of sensitivity to situational features, and in terms of neural activations, among other things. This separability of control mechanisms marks a departure from simpler models presenting cognitive control as a general ability that is either efficient or not. This feature of the framework is especially interesting because it allows for more fine-grained testing of cognitive control engagement in a task: rather than simply check whether performance in the task is high or low, the DMC framework makes it possible to test whether participants use reactive or proactive control.

Importantly, the model also predicts that there exist individual differences in the use of proactive and reactive control (Braver et al., 2007): because it requires sustained activation of the dorsolateral prefrontal cortex and consumes more metabolic resources, proactive control is presumably more vulnerable to neural dysfunction and can also be expected to develop later

than reactive control in children (Brahmbhatt, White, & Barch, 2010) and to be relatively more impaired by normal ageing (Braver et al., 2007). Since proactive control is more oriented towards performance at a greater cost than reactive control, it may also be sensitive to individual differences in personality, such as the tendency to maximize external rewards (Braver et al., 2007). Lastly, it is not absurd to consider that individual differences in the use of proactive and reactive control may also be associated with individual differences in working memory capacity (Braver et al., 2007).

## **1.2. Testing the DMC framework**

### *1.2.1. A paradigmatic task: the AX-CPT*

The DMC framework has often been studied with one paradigmatic task, the AX-CPT. Every trial in the task confronts the participant with a first letter, the cue; this letter is followed by a short delay, typically around five seconds, and then by a second letter, the probe. The objective for the participant is to detect one sequence of letters in particular: an A cue followed by an X probe. There are four types of trials in the task: AX trials (the target sequence), AY trials (an A followed by any letter other than an X), BX trials (any letter other than an A followed by an X), and BY trials (any sequence of two letters other than A and X). Participants are expected to make a target response on AX trials, and a non-target response in the three other cases. The four trial types appear with different frequencies: in the original version of the task, there are 70% of AX trials and 10% of each other trial type (e.g. Braver et al., 2007). These unbalanced frequencies mean that whenever the cue is an A, there is a high probability that the probe will be an X, requiring a target response.

This task is particularly interesting in the context of the DMC framework because it is well suited to contrast the two control mechanisms. This is the opportunity for us to take a rough example. Say that Pierre implements proactive control. When Pierre detects an A as the cue, he stores this contextual information in the dorsolateral prefrontal cortex. During the five seconds delay, Pierre uses this contextual information to actively prepare for a target response, since it is very likely that the A will be followed by an X. When the X appears, Pierre only has to execute the target response that he has prepared in advance. If the cue is not an A, Pierre can safely prepare for a non-target response during the delay because whatever the identity of the cue, a non-target response will be required. Now say that Rachel implements reactive control. When Rachel detects an A as the cue, she also stores this contextual information in the dorsolateral prefrontal cortex. During the five seconds delay, however, Rachel does not use this contextual information to prepare a response; instead, she

waits for the probe to appear. When the *X* appears, Rachel selectively reactivates the contextual information concerning the identity of the cue, decides that a target response is required, and executes this response. Another way to summarize this account is to say that Pierre implements control driven by contextual information in the form of the cue, whereas Rachel implements control driven by the probe information.

Importantly, proactive and reactive control are associated with different patterns of performance relative to the different trial types. Since he prepares for a target response during the delay, Pierre should be faster than Rachel on AX trials. Rachel should also be slower and make more mistakes than Pierre on BX trials, because stimulus-driven processing is dominant in reactive control and the *X* tends to elicit a target response. Pierre shouldn't have this problem with BX trials since he uses contextual information to prepare for a non-target response. However, Pierre should be slower and make more errors than Rachel on the infrequent AY trials, because the target response that he has prepared turns out to be incorrect. When it comes to BY trials, both control mechanisms should lead to a comparable performance since both the cue and the probe are associated with a non-target response; BY trials are sometimes used as a sort of control condition (e.g. Barch et al., 2001).

### *1.2.2. Validation studies*

The individual differences approach is a prime tool to oppose proactive and reactive control; this approach has often been used in conjunction with the AX-CPT. As we have seen, it can be hypothesized that older adults should use proactive control relatively less than younger participants. In a series of studies, it was observed that the pattern of performance of older adults in the AX-CPT is congruent with this prediction (e.g. Braver et al., 2001). More specifically, older adults tend to be slower and make more errors than younger adults on AX and BX trials. In particular, older adults are disproportionately slower than younger adults on BX trials when compared to BY trials. Importantly, however, they tend to respond more accurately than younger adults on AY trials. These results are extremely interesting in that they are very difficult to explain with classic accounts of cognitive control: for instance, most simple models of executive functioning would only predict that older adults should be less efficient on all trials "because the task requires cognitive control and they have poor cognitive control". The fact that older adults actually make less errors on AY trials is best explained if one considers that younger adults, but not older adults, incorrectly prepare a target response on these trials. The fact that older adults are disproportionately slower on BX trials also suggests that they do not actively prepare a non-target response during the delay period. Other

studies replicated and extended these observations (Braver, Satpute, Rush, Racine, & Barch, 2005; Paxton, Barch, Storandt, & Braver, 2006). Critically, one study demonstrated that keeping the cue displayed on screen throughout the delay period did not influence the results (Paxton et al., 2006). This suggests that the differences between younger and older adults do not stem from an inability of older adults to remember or maintain the identity of the cue in (working) memory; instead, they seem to be due to the way the cue information is used to prepare a response.

Interestingly, these behavioural results were also complemented through the use of neuroimaging. One study (Paxton, Barch, Racine, & Braver, 2008) using functional magnetic resonance imaging (fMRI) compared the activation in the lateral prefrontal cortex for older adults and younger adults. Older adults demonstrated reduced activation at the time of the cue and during the delay period, but increased activation at the time of the probe. The study also varied the length of the delay between the cue and the probe; younger adults, but not older adults, demonstrated increased activation in the dorsolateral prefrontal cortex for longer delays. Taken together, these results suggest that younger adults have a higher tendency to recruit the dorsolateral prefrontal cortex to actively maintain contextual information concerning the cue during the delay period; in other words, younger adults are more prone to using proactive control.

Another interesting feature of these results is that they can be manipulated. For example, a behavioural study tried to train older adults to use proactive control in the AX-CPT; more specifically, the authors informed participants that most A cues were followed by X probes, and asked them to try to prepare for a target response whenever they saw an A cue (Paxton et al., 2006). The results suggested that the training made the performance of older adults closer to that of younger adults, as their error rates decreased on BX trials and increased on AY trials. However, the effects were small and the trained group did not prove to be overly different from the control group. A second study partly resolved this problem (Braver, Paxton, Locke, & Barch, 2009). The authors replicated the same behavioural results on the AX-CPT; using fMRI they also observed that after the training older adults showed increased activations in the dorsolateral prefrontal cortex at the time of the cue and reduced activations at the time of the probe, consistent with a higher tendency to use proactive control. Interestingly, the same study (Braver et al., 2009) also suggested that proactive control can be manipulated in younger adults. The authors added no-go trials to the AX-CPT, in the form of infrequent trials where the participants had to refrain from responding to the probe entirely; monetary penalties were given for errors on these no-go trials. Since this manipulation

incentivizes away from actively preparing a response before the probe appears, it was hypothesized to favour reactive control. The results showed that younger adults were disproportionately slowed on BX trials, while there was little difference on other trial types. These participants also demonstrated reduced activation in the dorsolateral prefrontal cortex at the time of the cue and increased activation at the time of the probe. Because they are very consistent with the predictions of the DMC framework, all these results contribute to the validation of the model.

As we have seen, the DMC framework predicts that proactive control should develop later than reactive control in children. A couple of studies have directly tested this prediction (e.g. Chatham, Frank, & Munakata, 2009; Brahmabhatt et al., 2010). For example, Chatham et al. (2009) compared 3.5-year-old children with 8-year-old children on the AX-CPT, under the hypothesis that 8-year-olds should show a pattern of results more consistent with proactive control. This study reported that 8-year-olds were slower on AY trials than on BX and BY trials; on the contrary, 3.5-year-olds were not slowed on AY trials. The same study used pupillometric dilation as a measure of invested effort; 8-year-olds showed greater pupil dilation, indicating more effort, during the delay period; by contrast, 3.5-year-olds showed greater pupil dilation at the time of the probe. These results are interesting both in that they validate the predictions of the DMC framework in children, and in that they demonstrate that fMRI is not the only tool that can pick up individual differences in the use of proactive control.

The DMC framework predicts that neural dysfunction, in particular at the level of the dorsolateral prefrontal cortex, should be more of a problem for proactive control. In one study, patients suffering from an Alzheimer-type dementia in an early stage were found to have impaired proactive control (Braver et al., 2005), which could be attributed to neural dysfunction. Because schizophrenia is associated with prefrontal dysfunction (see Braver et al., 2007), a series of studies have also attempted to assess reactive and proactive control in schizophrenic patients. These studies used methods and yielded results very close to the studies in older adults that we have reviewed; the results were compatible with a lower tendency to use proactive control in schizophrenic patients. These patients made more errors than controls on BX trials but less errors on AY trials, consistent with the use of reactive control (Barch et al., 2001); they were also slower on BX trials, but not on AY trials. In several fMRI studies, schizophrenic patients demonstrated reduced delay-related activation in the dorsolateral prefrontal cortex (Barch et al., 2001; A. MacDonald & Carter, 2003; Edwards, Barch, & Braver, 2010): relative to controls, they showed less activation during the

delay period in the AX-CPT (A. MacDonald & Carter, 2003; Edwards et al., 2010), and this activation did not increase when the delay was lengthened (Barch et al., 2001). Similar to older adults, it seems that proactive training can shift the results pattern of schizophrenic patients towards proactive control, both in terms of behavioural performance and in terms of neural activity in the prefrontal cortex (Edwards et al., 2010).

Lastly, it should be noted that not all studies on the DMC framework have used the AX-CPT paradigm. For example, one study tested the implication of proactive control in the *n*-back task as a function of age (Brahmbhatt et al., 2010). When memory load increased in the task, children demonstrated a lesser increase in sustained activity in the frontal cortex when compared to adults, consistent with a more reactive control strategy. Not all studies on the DMC framework have used an individual differences approach either. Another study used the *n*-back task and manipulated the amount of interference participants expected to encounter; participants were hypothesized to engage in more proactive control when interference expectancy was high (G. C. Burgess & Braver, 2010). Congruent with this hypothesis, the high interference expectancy condition was associated with more sustained activation in the dorsolateral prefrontal cortex during the inter-stimulus interval (ISI). An elegant study (Speer, Jacoby, & Braver, 2003) used the Sternberg task, a paradigm requiring that participants memorize a set of stimuli such as words and then decide, after a delay, whether a target word was present in this set. According to the DMC framework, a proactive control strategy would consist in actively maintaining and re-encoding the words during the delay period; reactive control would be implemented by waiting for the target word to appear and then selectively retrieving the corresponding information in memory. A related prediction is that proactive control should constitute a more relevant strategy when there are few words to remember, since active maintenance presumably becomes prohibitively difficult for longer sets. The authors manipulated the expected memory load by presenting trials with six stimuli to memorize within blocks of trials where the average number of words to memorize was either nine or three. Trials with a low expected memory load elicited higher activity in the prefrontal cortex at the start of the trial and lower activity at the time of the probe than trials with a high expected memory load, congruent with the idea that trials with a low expected memory load were associated with more proactive control. Although this last set of results can also be interpreted in terms of differential reliance on short-term and long-term memory (Speer et al., 2003), it does contribute to show that the DMC framework can be applied to the understanding of varied experimental situations.

***In summary***

- The DMC framework proposes that cognitive control can be recruited through either a proactive mechanism, implemented in advance, or a reactive mechanism, implemented after a demanding event.
- Each control mechanism has its own neural and behavioural signature.
- The DMC framework is often tested with the AX-CPT.
- A series of studies have validated the DMC framework with several different tasks, often using an individual differences approach.

## **2. Working memory, fluid intelligence, and the DMC framework**

### ***2.1. Relating working memory and fluid intelligence to proactive control***

We know that working memory is related to cognitive control; how does this theoretical conception translate to the context of the DMC framework? Proactive control leads to higher performance in most situations, both because its implementation ahead of time elicits faster response times and because sustained cognitive control leaves less room for errors. Since participants with high working memory capacity are hypothesized to benefit from a more efficient cognitive control, a logical corollary is that participants with high working memory capacity should be more prone to using proactive control. This idea is consistent with various aspects of the framework, such as the fact that proactive control is used less by children, older adults and schizophrenic patients, three populations that also tend to demonstrate lower working memory capacity.

Establishing a link between working memory, fluid intelligence and the use of control mechanisms defined by the DMC framework is not an overwhelming theoretical leap: the princeps article for the framework (Braver et al., 2007) presented it as a paradigm for understanding working memory. The authors proposed that a high working memory capacity should be associated with a stronger tendency to use proactive control, with the idea that « individuals possessing greater cognitive resources will be those most willing and able to adopt a proactive mode [...] the construct of cognitive resources may index the same underlying mechanism indexed by the constructs of WM capacity and fluid intelligence » (Braver et al., 2007, p. 88).



Although intuitively appealing, one problem with the formulation of this hypothesis is that it relies on so-called cognitive resources; the precise nature of these cognitive resources is unclear. After putting so much effort into avoiding a homuncular view of cognitive control, it would be somewhat unfortunate to resort to yet another nondescript cognitive entity. It is however possible to propose explanations for a relationship between working memory and proactive control using concepts we already know; three main interpretations seem plausible.

Firstly, since proactive control depends on the active maintenance of a task goal and since working memory consists in actively maintaining information, an efficient working memory might be required to maintain the contextual cue used to bias behaviour in proactive control. Put differently, working memory may factor in proactive control in the form of the system used to actively maintain contextual information throughout the task. As mentioned earlier, however (p. 45), the maintenance of stimuli in working memory and the maintenance and implementation of task goals may reflect independent cognitive systems; in other words, maintaining the perceptual identity of stimuli in working memory may be different from maintaining a contextual representation used to bias behaviour. The interpretation that working memory does not in fact play a role in proactive control is supported by two observations: first, working memory and cognitive control depend on partly independent neural networks, because the dorsolateral prefrontal cortex is not thought to perform storage functions (Kane & Engle, 2002) whereas working memory recruits additional regions specifically associated with short-term storage (e.g. Postle, 2006; Owen et al., 2005); second, keeping the cue accessible throughout the delay period in the AX-CPT does not shift the performance of older adults towards proactive control (Paxton et al., 2006). In short, the idea that working memory is required for proactive control does not seem very convincing.

A second possibility is that both working memory capacity and the ability to use proactive control reflect the same underlying construct: the ability to actively maintain mental representations. A very rough formulation of this view would be that both proactive control and working memory make use of the ability of the dorsolateral prefrontal cortex to maintain the activation of mental representations over a period of time, with working memory using this ability to maintain representations of to-be-memorized stimuli stored in other brain regions.

Interestingly, if we consider that control processes are involved in determining working memory performance, a third possibility exists: a preferential use of proactive control could lead to higher performance in working memory tasks and to a higher measured working memory capacity. This idea is indirectly supported by the observation that

differences in the use of proactive and reactive control can appear within memory tasks (Speer et al., 2003; Brahmhatt et al., 2010; G. C. Burgess & Braver, 2010) and impact performance (Speer et al., 2003). In this view, it is not even necessary to posit that there are differences in cognitive efficiency between participants with a high and low working memory capacity; a thrilling alternative is that participants with low working memory capacity are just those who tend to use reactive control more than proactive control, which impacts their performance both in working memory tasks and other high-level cognitive tasks.

All three solutions seem possible - a high working memory capacity could cause proactive control or the reverse, and it is even possible that the question is not meaningful and the two constructs are actually one and the same thing; data are as yet lacking to narrow down a definite hypothesis. In any case, if individual differences in working memory capacity are truly associated with a differential use of control mechanisms, the literature strongly suggests that proactive control should be associated with an efficient working memory; the opposite hypothesis seems hard to justify, since there is no obvious reason to believe that an efficient working memory could be associated with a reactive control mechanism that elicits suboptimal performance in most situations. Whatever the direction of causality, then, we can safely consider that participants with high working memory capacity should have a higher tendency to use proactive control.

If we consider that the more efficient cognitive control of participants with high working memory capacity is due to their preferential use of proactive control, it follows that their reliance on proactive control should also explain why they perform better in fluid intelligence tasks. In turn, this implies that using proactive control should lead to higher performance in fluid intelligence tasks. Do we have any arguments in favour of this idea? At this point we can again resort to the work of Carpenter and colleagues (1990), who demonstrated that completing a fluid intelligence task requires that participants maintain and implement a hierarchy of goals and sub-goals. In the context of the DMC framework, a participant using proactive control in a fluid intelligence task could implement these goals to regulate behaviour in a sustained manner throughout the task, ensuring that the logical hierarchy of goals and sub-goals is respected. Conversely, a participant using reactive control would tend to use stimulus-driven processing in the task, letting his attention be captured by salient stimulus features and only transiently reactivating goal representations. This reactive strategy would presumably lead to lower overall performance in tasks such as the APM. Thus, participants who tend to use proactive control should also perform better in fluid intelligence tasks.

In summary, scattered pieces of evidence in the literature converge to suggest that participants with high working memory capacity should have a higher tendency to use proactive control, and that this higher reliance on proactive control is what drives their higher performance in fluid intelligence tasks. The next two sections will review the existing evidence in favour of this idea.

## **2.2. Indirect evidence from individual differences studies**

Most of the studies showing a relationship between working memory capacity and individual differences in cognitive control efficiency are directly compatible with the DMC framework. However, certain studies among those that we have reviewed, in particular those relating working memory to goal-driven behaviour, fit particularly well with the idea that a high working memory capacity is associated with a higher tendency to use proactive control. It may be useful to briefly come back to these studies.

Experiments using a modified Stroop task (e.g. Kane & Engle, 2003; Hutchison, 2001) have demonstrated that participants with low working memory capacity make more errors on incongruent trials when most of the stimuli in the task are congruent. This finding is generally interpreted as evidence that participants with low working memory capacity have more trouble maintaining the task goal; the large number of congruent trials makes them "forget" the task goal that they are to name the colour rather than read the word, which elicits more errors on the rare incongruent trials. The same results can be reinterpreted in terms of proactive and reactive control: if participants with high working memory capacity use proactive control, then they actively maintain the task goal throughout the test whether most trials are congruent or not. This facilitates performance on incongruent trials because these participants actively bias processing in favour of naming the colour before they even read the incongruent stimulus. In contrast, if participants with low working memory capacity use reactive control, then they only transiently reactivate the task goal after they have encountered an incongruent stimulus, which logically increases the risk of error.

In the antisaccade task, participants with low working memory capacity had more trouble averting their eyes from a visual cue, but all participants performed equivalently in a prosaccade condition (Kane et al., 2001; Unsworth et al., 2004; McVay & Kane, 2012a; Unsworth, Redick, et al., 2012); these results give rise to a similar interpretation. Because the antisaccade and the prosaccade conditions are tested in separate task blocks, participants know in advance whether the next trial is going to require that they ignore the cue. Using proactive control means that a participant with high working memory capacity can implement

the task goal in advance, before the cue even appears; this makes it logically easier to look away from the visual cue. Conversely, using reactive control means that a participant with low working memory capacity waits before the visual cue appears to reactivate the task goal. At this point, the participant's gaze may already have been captured by the cue through stimulus-driven processing. Critically, both control mechanisms should lead to comparable performance on prosaccade trials, because stimulus-driven and goal-driven processing elicit the same response; this is exactly what is observed in practice.

Although it is less directly obvious, results from other studies also fit well within the DMC framework. It is for example the case with the dichotic listening task (Conway et al., 2001), where participants with low working memory capacity are more efficient at detecting their name presented amid an irrelevant message. Using reactive control, a participant with low working memory capacity should implement mainly stimulus-driven processing, which could mean a higher probability to detect his own name in the irrelevant message. In contrast, a participant with high working memory capacity using proactive control should implement sustained cognitive control throughout the task, which means the irrelevant message should receive less processing time, decreasing the probability of detection. Another example is the observation that participants with low working memory capacity tend to demonstrate a higher tau parameter in a variety of tasks. Since reactive control is only implemented after the event requiring control has occurred, it may be associated with more variable and possibly very long response times because much of the required cognitive processing has to be completed during the time window in which the participant is supposed answer. If participants with high working memory capacity use proactive control, then they are able to carry out much of the required cognitive processing before the event occurs, which may reduce and smooth their response times.

The results from the study relating working memory capacity and performance on a conditional go/no-go task (Redick et al., 2011) are also noteworthy because they are sometimes interpreted in terms of proactive and reactive control (e.g. Redick, 2009). In this study, participants viewed a continuous series of letters; they had to make a target response when confronted with either a *M* or a *W*, but only if the last target they had seen was not the same letter. For example, in the series *M...F...K...W...J...W...*, participants were supposed to make a target response on the first *M* and on the first *W*, but not on the second *W* because the last target they had seen was also a *W*. This task is conceptually close to the AX-CPT: it involves making a target response when confronted with certain stimuli as a function of the identity of the previous stimuli; proactive control may benefit performance through active

maintenance of the identity of the previous target to be seen. Participants with high working memory capacity make less errors on this task, consistent with our hypothesis. On the other hand, this result should not be seen as direct evidence in the context of the DMC framework because it poses one major problem. This conditional go/no-go task differs from the AX-CPT in one critical way: it directly places a heavy demand on working memory, because making a correct response requires remembering the identity of a letter throughout the processing of multiple following stimuli, rather than throughout an unfilled delay period. Thus, the higher performance of participants with high working memory capacity may simply be attributed to their greater ability to remember the identity of the previous target.

What about individual differences in fluid intelligence and cognitive control? A few pieces of evidence also relate fluid intelligence and proactive control: studies showing a relation between fluid intelligence and performance in the antisaccade task (N. P. Friedman et al., 2006; Chuderski et al., 2012; Unsworth et al., 2010), as well as studies showing an inverse correlation between fluid intelligence and the tau parameter (Schmiedek et al., 2007; Unsworth et al., 2010), may be interpreted in the same way. Studies on the goal neglect phenomenon (Duncan et al., 1996; Duncan et al., 2008) can also be interpreted within the DMC framework. Goal neglect is observed when participants fail to dynamically change the side of the screen they attend in a task; if participants with low fluid intelligence tend to engage in reactive control, they should only transiently reactivate the new task goal, leaving them more vulnerable to neglecting it.

As we have mentioned, it may be the case that proactive control provides an advantage in fluid intelligence tasks because it helps participants structure their behaviour as a function of the hierarchy of task goals (as per Carpenter et al., 1990). One piece of evidence points to a direct role of proactive control in fluid intelligence tasks in a way that is compatible with this account, despite being described at a higher level of abstraction. Behavioural and eye-tracking data suggest that participants use two main strategies in Raven's progressive matrices : constructive matching and response elimination (see Vigneau, Caissie, & Bors, 2006). Constructive matching consists in carefully decomposing the matrix, trying to form a mental representation of what the missing piece should look like, and only then looking at the possible answers to decide whether one of them matches the representation that has been constructed. By contrast, response elimination consists in getting a rough view of the matrix, then looking at the possible answers and selecting one of these by an elimination process; participants who use this strategy spend less time looking at the matrix and toggle more often between the matrix and the distractors. These two strategies are not directly equivalent to

proactive and reactive control, but cognitive control mechanisms may be related to strategic behaviour. The constructive matching strategy may be viewed as a direct implementation of the goals and sub-goals hierarchy as described by Carpenter and colleagues; it is also consistent with a proactive control strategy, wherein processing is guided by internal goals actively maintained and implemented throughout the task. On the contrary, a reactive control strategy wherein processing is guided by features of the stimuli is more consistent with response elimination. In practice, it is observed that the constructive matching strategy leads to higher performance in the task (Vigneau et al., 2006), which suggests that proactive control can help performance in a fluid intelligence task. Interestingly, participants with low working memory capacity seem more prone to using a response elimination strategy and to allocating more attention to salient distractors in the task (Jarosz & Wiley, 2012); this may well be evidence that these participants use reactive control and favour stimulus-driven processing over goal-driven processing.

### ***2.3. Direct assessments of the relationship***

All the aforementioned studies can be interpreted with a DMC view, but this is not quite convincing: because these studies used a variety of tasks that were not designed to explicitly assess proactive and reactive control, they do not rule out alternative explanations based on other mechanisms. For example, results from the dichotic listening study (Conway et al., 2001) could be reinterpreted by stating that participants with high working memory capacity were more efficient at "blocking interference" or "inhibiting irrelevant information". So as to get reliable evidence of the link between working memory and mechanisms of the DMC framework, what we need is experiments using tasks designed to test these two mechanisms. Of course, the AX-CPT is a prime candidate to assess the DMC framework; in light of the previous studies using this task, the hypotheses are straightforward: participants with high working memory capacity should perform better on BX trials and secondarily on AX trials, whereas participants with low working memory capacity should perform better than their counterparts on AY trials. All participants should demonstrate comparable performance on BY trials. As it turns out, four studies related working memory capacity to the AX-CPT.

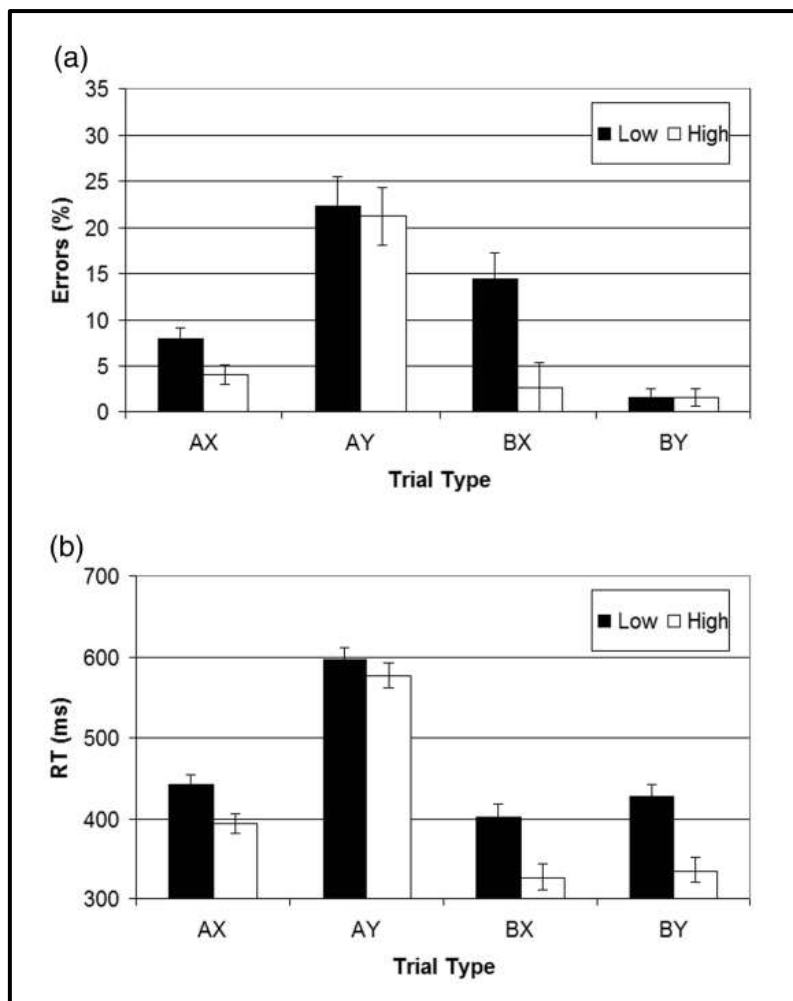
One study in older adults (Braver et al., 2005) tried to correlate performance on the AX-CPT with various executive control tasks; one of these tasks was a backward digit span, often used as a working memory measure because it involves both storage and processing of information. The results did not demonstrate a significant correlation between performance on

the backward digit span task and performance on the AX-CPT; numerically, span scores were negatively related to the number of errors on both BX and AY trials, contrary to our predictions. On the other hand, this analysis included only a very small sample ( $n = 33$ ); the sample was constituted of older adults who tend to use proactive control less often, which could mask any effect of working memory capacity; and the backward digit span is universally recognized as a poor working memory task (e.g. Conway et al., 2005). As a consequence, it is probably best not to put too much trust into this result.

More interestingly, a second study had participants complete complex span tasks as well as the classic version of the AX-CPT (Redick & Engle, 2011). Participants with high working memory capacity were both faster and more accurate on AX trials and BX trials, and they were also faster on BY trials; however, there was no difference on AY trials as a function of working memory capacity (see Figure 4). According to the authors, these results indicated that participants with high working memory capacity had a higher tendency to actively maintain the identity of the cue during the delay period: they were more efficient on AX and BX trials because maintaining the identity of the cue is critical to selecting a response in these cases, but this benefit was eliminated on AY trials where the cue is not a valid predictor.

However, there is a major problem with this interpretation. The strength of the DMC framework applied to the AX-CPT is the observation that proactive control is a hindrance on AY trials, which leads participants with neural dysfunctions or generally lower cognitive control abilities to actually perform better on these trials. This, along with the fact that BY trials serve as a sort of control condition where all participants demonstrate comparable performance, is what allows to explain the results in terms of proactive and reactive control, rather than simpler interpretations describing cognitive control as a unitary mechanism leading to overall better performance. In this experiment, unfortunately, participants with high working memory capacity instead performed better on all trial types including both AY and BY trials. Although the difference in performance between the two groups was not significant for AY trials, the analyses only included eight AY trials, in contrast with the seventy AX trials; with such a small number of data points, behavioural indices typically demonstrate low reliabilities and high standard deviations, which necessarily decreases the significance level of statistical tests. In other words, these results do not allow to rule out the alternative explanation that participants with high working memory capacity simply performed better throughout the task because of any mechanism other than proactive control. In particular, the hypothesis put forth by the authors – that participants with high working memory capacity performed better on AX and BX trials because they were more efficient at actively

maintaining the identity of the cue over the delay period – does not actually depend on proactive control. In this view, the advantage of participants with high working memory capacity in the task does not stem from any tendency to actively prepare a response as a function of the cue, but from their ability to actively maintain the identity of the cue. One could simply rephrase this hypothesis to state that participants with high working memory capacity were better at maintaining the identity of the cue in working memory, a relatively underwhelming conclusion. As a consequence, this study does not unambiguously point towards a link between working memory and the DMC framework.



*Figure 4.* Mean percentage of errors (A) and mean RTs (B) in the AX-CPT as a function of working memory capacity. Low = participants with low working memory capacity. High = participants with high working memory capacity. Error bars represent the standard error of the mean. Adapted from "Integrating working memory capacity and context-processing views of cognitive control" by T. S. Redick and R. W. Engle, 2011, *The Quarterly Journal of Experimental Psychology*, 64(6), pp. 1052-1053. Copyright 2011 by The Experimental Psychology Society.



On the other hand, these results do not necessarily mean that our hypothesis regarding proactive control and working memory is erroneous, either. Similar results have been observed in a study in schizophrenic patients (A. MacDonald & Carter, 2003): the patients performed lower than control participants on all trials, including AY trials. Despite these unsatisfactory behavioural results, the schizophrenic patients demonstrated reduced neural activity during the delay period of the task, which unambiguously indicated a lower tendency to use proactive control. In the same fashion, it is possible that participants with high working memory capacity have a higher tendency to use proactive control and are actually more impeded on AY trials, but that this lower performance is masked by their generally higher "cognitive efficiency" (e.g. higher processing speed).

Do other empirical results allow us to resolve this ambiguity? The third study (Redick, 2009, republished in Redick, 2014) yielded very similar results (see Figure 5). Participants with high working memory capacity made less errors on AX, BX and BY trials, although the difference was only significant at the trend level for BX trials; working memory capacity was not related to performance on AY trials. Additionally, participants with high working memory capacity had faster response times on BY trials. Thus, this experiment suffers from the same problem as the previous one: participants with high working memory capacity had overall better performance on all trial types, although the difference was again not significant for AY trials. The problem actually seems worse in this third experiment: it is quite obvious in Figure 5 that participants with high working memory capacity simply performed better on all trials. Although descriptive statistics were not provided by the author, the difference in response times as a function of working memory capacity seems quite close in magnitude across AX and AY trials, and the same is true for the percentage of errors (see Figure 5). Besides, the rest of the results pattern is not in complete adequation with the DMC framework either. The only significant difference in response times emerged on BY trials, where all participants are supposed to perform equivalently. For error rates, the effect size of working memory capacity was descriptively larger on BY trials than on BX trials, despite BX trials being supposedly the one condition where proactive control should be the most beneficial. Again, these results do not unambiguously indicate a link between proactive control and working memory.

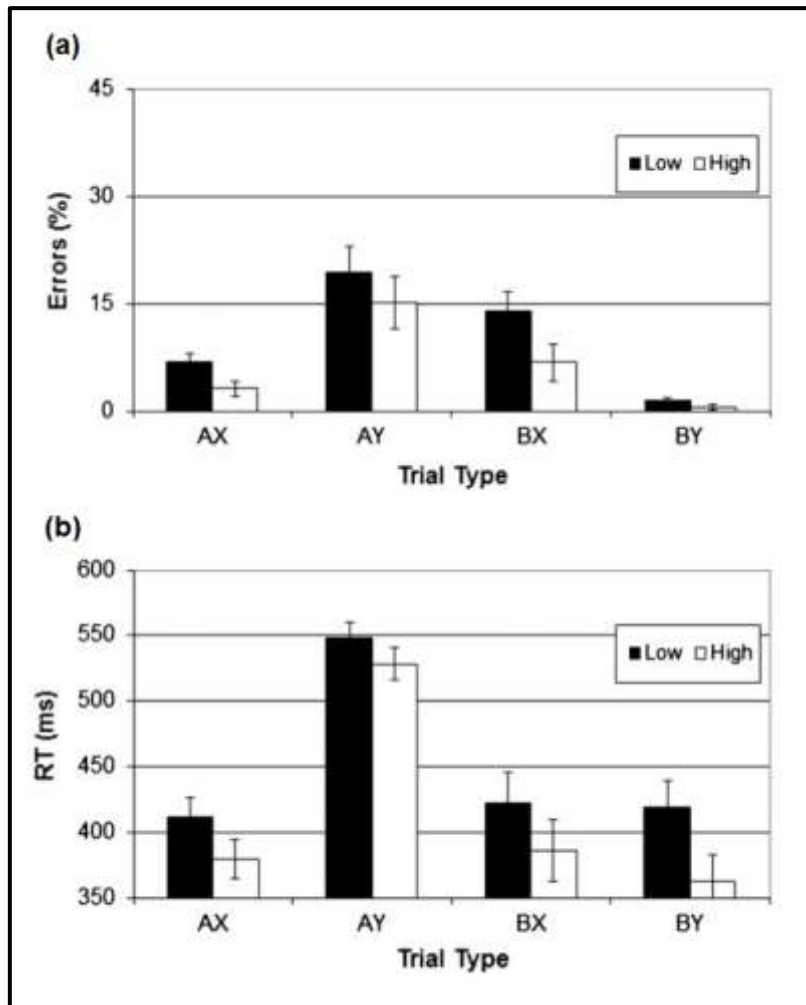


Figure 5. Mean percentage of errors (A) and mean RTs (B) in the AX-CPT as a function of working memory capacity. Low = participants with low working memory capacity. High = participants with high working memory capacity. Error bars represent the standard error of the mean. Adapted from "Cognitive control in context: Working memory capacity and proactive control" by T. S. Redick, 2014, *Acta Psychologica*, 145, pp. 5-6. Copyright 2014 by Elsevier B. V.

In a second experiment, the same study (Redick, 2009; Redick, 2014) had participants complete a version of the AX-CPT with different trial frequencies: 10% of AX trials, 70% of AY trials, 10% of BX and 10% of BY trials. The author expected that participants with high working memory capacity would use proactive control to prepare a nontarget response on all trials with an A cue; thus, they predicted better performance for these participants on the frequent AY trials, but impaired performance on the rare AX trials requiring a target response. In fact, all participants demonstrated comparable performance on AY trials, but participants with high working memory capacity made less errors on AX trials. The author retroactively explained these results with the observation that 90% of trials in the task required making a nontarget response, and that participants using reactive control would be biased towards not

actively maintaining the identity of the cue and simply making nontarget responses, resulting in more errors on the rare AX trials (Redick, 2009). This interpretation is plausible, and pretty close to previous research using modified Stroop (e.g. Kane & Engle, 2003) and modified go/no-go tasks (McVay & Kane, 2012a; McVay & Kane, 2012b), where participants with low working memory capacity tend to make more errors on the rare trials requiring actively goal-driven behaviour. As a result, this study might indicate a link between working memory capacity and proactive control. However, the strength of this conclusion is limited by several important points: the fact that the results were reinterpreted a posteriori by the author, the fact that two antagonistic results patterns in this task could both be fitted to the DMC framework, the fact that the only significant difference in performance was again in favour of participants with high working memory capacity, and the fact that the conceptual equivalence between this version of the AX-CPT and previous work using nonspecific cognitive control tasks means it ceases to be a specific test of the DMC framework. In short, these results do suggest a difference of cognitive control efficiency as a function of working memory capacity, but they are not really convincing evidence in favour of a specific link between proactive control and working memory.

In a third experiment, the same study had participants perform yet another modified version of the AX-CPT with 40% of AX trials, 40% of AY trials, 10% of BX trials and 10% of BY trials (Redick, 2009; Redick, 2014). Since A cues were followed equally often by a target or a nontarget stimulus, the author expected that participants with high working memory capacity would tend not to engage in proactive control on AX and AY trials, and consequently that all participants would demonstrate comparable performance on these trials. However, they still predicted that participants with high working memory capacity would engage in proactive control and perform better on BX trials. In fact, the results indicated that participants with high working memory capacity made less errors on both AX and BX trials, but there were no differences on AY and BY trials. The author interpreted these results with the idea that participants with high working memory capacity were more efficient on the two trial types where maintaining the identity of the cue is beneficial to performance (similar to Redick & Engle, 2011). Again, this interpretation is not exactly incompatible with the DMC framework, but it suffers from the same weaknesses as above: the results were not predicted; the only significant differences in performance were in favour of participants with high working memory capacity; and above all, the results can be adequately explained without resorting to the notion of proactive control, using the idea that participants with high working

memory capacity were simply better at actively maintaining the identity of the cue in working memory.

A fourth and final study tested participants on both complex span tasks and the AX-CPT (Richmond, Redick, & Braver, 2013; Experiment 1). Contrary to all previous studies, the authors elected to control for performance on BY trials when testing the effect of working memory capacity; the objective of this statistical control was to remove any global effect of working memory capacity on performance. The results were more convincing in this study: after controlling for performance on BY trials, participants with high working memory capacity made less errors on both AX and BX trials, but they were also slower on AY trials than participants with low working memory capacity. A second experiment using a similar method reported similar results (Richmond et al., 2013; Experiment 2); in this second experiment, participants with high working memory capacity were slower and also made more errors on AY trials. These results are entirely congruent with our initial predictions.

Interestingly, the authors also tried to replicate the previous finding that proactive control can be manipulated through strategy instructions (Richmond et al., 2013; Experiment 3). In a second experiment, they trained another sample of participants to specifically use a proactive strategy in a first block of trials and a reactive strategy in a second block of trials. On the basis of the idea that differences in performance as a function of working memory capacity stem from a differential use of proactive and reactive control, these strategy trainings were expected to make all participants use the same mechanism of control and to erase these differences in performance. In the proactive training condition, working memory capacity was no longer related to performance on either AY or BX trials; in the reactive training condition, working memory capacity was no longer related to performance on AY trials although participants with high working memory capacity still performed better on BX trials. In both conditions, participants with high working memory capacity performed better on AX trials. According to the authors, the lack of a significant difference between participants on AY trials after strategy training meant that the previously observed difference was indeed due to their differential use of proactive and reactive control. While interesting, the problem with this conclusion is that it is essentially based on a null result: the fact that no difference appeared on AY trials as a function of working memory capacity in this experiment is taken as evidence that the difference observed in the first experiment was due to proactive control. This problem is compounded by the fact that the authors did not use a baseline condition to test the effect of working memory capacity on performance before the strategy training. It is also noteworthy that the results after strategy training were very similar to

previous studies: for example, in the reactive training condition, participants with high working memory capacity performed better on AX, BX and presumably BY trials (similar to Redick, 2009, and Redick & Engle, 2011). Thus, there is no way to know if the strategy training actually worked, or if these results are actually a simple replication of previous studies failing to demonstrate an effect of working memory capacity in AY trials.

In summary, only four studies have directly tested the relationship between working memory capacity and the tendency to use proactive control (Braver et al., 2005; Redick & Engle, 2011; Redick, 2009, 2014; and Richmond et al., 2013). These studies have yielded mixed results. As expected, participants with high working memory capacity seem to have more difficulties on AY trials, where proactive control is a hindrance more than a help to performance. On the other hand, participants with high working memory capacity tend to perform better overall in the AX-CPT, and this better performance is also observed on BY trials where proactive control should not represent an advantage. The critical *impairment* in performance expected on AY trials, with working memory being negatively related to performance, has only been observed in two unpublished experiments (Richmond et al., 2013). Additionally, the results are not excessively stable from one study to another (for example, participants with high working memory capacity are sometimes faster on all trials, sometimes not). These results are not completely contradictory with our hypothesis and can be interpreted in a way that fits the framework, but they are not entirely satisfying either.

One last study did not measure working memory capacity at all, but still deserves careful examination because it assessed the relationship between fluid intelligence and the DMC framework. As we have seen, the AX-CPT is not the only available paradigm to test the mechanisms of the DMC framework: sustained neural activity during a delay period in any task may be indicative of proactive control. Using fMRI, one study investigated sustained neural activity during a *n*-back task as a function of fluid intelligence (G. C. Burgess & Braver, 2010; see also G. C. Burgess & Braver, 2004). During the delay period between two stimuli, participants with a high fluid intelligence demonstrated higher activity than participants with a low fluid intelligence in regions of the frontal cortex, including the dorsolateral prefrontal cortex. Conversely, participants with a high fluid intelligence demonstrated lower activity at the times when stimuli were presented when compared to participants with a low fluid intelligence. Interestingly, increasing the amount of interference in the task increased stimulus-related neural activation, but only for participants with a low fluid intelligence. These results are consistent with the idea that participants who use reactive control also tend to score lower in fluid intelligence tasks; hence, this study constitutes direct

evidence in favour of the idea that mechanisms in the DMC framework are differentially related to fluid intelligence.

***In summary***

- A high working memory capacity should be associated with a higher tendency to use proactive control, and this tendency to use proactive control should explain the relationship between working memory and fluid intelligence.
- This hypothesis is consistent with various individual differences studies on working memory and fluid intelligence, which indirectly suggest that both participants with a high working memory capacity and participants with a high fluid intelligence have a higher tendency to use proactive control.
- Only four studies have directly tested the relationship between proactive control and working memory, with mixed results. Their results are not entirely incongruent with the DMC account, but they do not allow to specifically conclude to a link between working memory capacity and proactive control.

### **3. Rationale and introduction to the experimental section**

Let us take a moment to synthesize the previous chapters. In Chapter 1, we saw that working memory may be defined as the association of short-term storage and cognitive control processes; that working memory is predictive of high-level cognition and especially fluid intelligence; and that a solid hypothesis is that this relationship is due to a joint role of cognitive control processes. Testing this hypothesis constitutes the focus of the present work. In Chapter 2, we reviewed evidence that cognitive control is conceptually and empirically very close to both working memory and fluid intelligence, congruent with our hypothesis. On the other hand, we also found out that there is little direct evidence that cognitive control actually explains the relationship between working memory and fluid intelligence. We attributed this lack of evidence to the difficulty in accurately measuring cognitive control, due to the absence of a testable operationalization of the construct. Finally, in Chapter 3, we described the DMC framework, and we saw how this framework allows for a precise operationalization of cognitive control through the idea of two distinct control mechanisms. We proposed that a high working memory capacity is related to a higher tendency to use proactive control, and that this higher reliance on proactive control explains why these

participants tend to perform better in fluid intelligence tasks. We saw that both direct and indirect evidence suggest that this hypothesis may be correct; however, the existing direct evidence does not prove quite satisfying.

The picture emerging from this literature review seems pretty straightforward. Our thesis is that a high working memory capacity is related to an efficient cognitive control in the form of a higher tendency to use the proactive control mechanism, and that this tendency to use proactive control leads to higher performance in fluid intelligence tasks.

As we have seen, relating both working memory and fluid intelligence to cognitive control is a classic proposition, and several authors have also extended this hypothesis to proactive control in particular; these two ideas are not new. To the best of our knowledge, no researcher has tried to apply the notion of proactive control to the correlation between working memory and fluid intelligence, but this idea follows logically from the aforementioned arguments and does not constitute a theoretical revolution either. However, despite the fact that this thesis seems entirely consistent with the literature, there is surprisingly little evidence that it is correct. Direct studies of the relationship between working memory capacity and proactive control are scarce and the results fragile; the same is true for direct studies of the explanatory role of cognitive control; and no study has tested the relationship between working memory and fluid intelligence with a DMC perspective. Thus, the rationale for this work was to extend the existing evidence in favour of our thesis. Our theoretical objectives were twofold:

- To test the relationship between working memory capacity and the tendency to use proactive control;
- To apply the DMC framework to the understanding of the correlation between working memory capacity and fluid intelligence.

Our work had two main distinctive features. The first one was, of course, using the DMC framework to operationalize cognitive control. As we have seen, the main problem in testing the relationship between working memory and cognitive control is that cognitive control is very difficult to operationalize and to measure. We argue that the DMC framework constitutes a partial solution to this problem, because the two mechanisms it describes are associated with distinct and separable signatures. For example, we know that proactive control should be associated with sustained neural activity during a delay and that it should be more influenced by contextual information. The specificity of this signature makes it relatively easy to test whether participants are engaged in proactive control: if they

demonstrate sustained neural activity and if their answers are driven by contextual information, then the answer is yes. By contrast, simple models along the lines of "an efficient cognitive control gives a higher performance in cognitive control tasks" cannot be directly translated into a mechanistic account of what happens in a cognitive control task, which makes them very difficult to test.

A related advantage of the DMC framework over these simple models is the possibility of predicting results in terms of characteristic patterns rather than in terms of overall performance. As we have seen, cognitive control tests necessarily rely on a wide range of abilities, including for example processing speed and short-term memory, not to mention working memory itself. Since participants with high working memory capacity also tend to possess higher processing speed and short-term memory, it is often difficult to tell if they perform better in cognitive control tasks because of an efficient cognitive control or because of one of the other component abilities factoring in overall performance on the task. Interestingly, the DMC framework does not require that overall performance be used as a dependent variable. Instead, it is possible to use behavioural indices that are not tied with performance: for example, if the responses of a participant are more influenced by contextual information than by the features of the stimulus, he can be said to use proactive control, independently of any performance index. It is even possible to predict that the use of proactive control will be associated with poor performance, as we have seen with the example of AY trials in the AX-CPT. Thus, the DMC framework also constitutes an excellent tool to disentangle cognitive control from its confounding variables.

Another related advantage of the DMC framework over unidimensional models is its falsifiability. We have attributed the ambiguous conclusions of many of the studies attempting to evidence the role of cognitive control to the fact that they used a unidimensional, or homuncular view of cognitive control. We have also quoted (see p. 64) Underwood, who stated that single-process theories are superfluous and have no predictive validity. This quotation has a second part, which perfectly illustrates the interest of the DMC framework in this context:

« The theory must assume at least two intervening processes, and these processes must interact in some way to relate the independent variables to the dependent variable. [...] The moment we propose two intervening processes that, for at least one independent variable, have different functions and hence interact, we begin to get predictive power. » (Underwood, 1975, p. 131)



For these reasons, the present work was entirely grounded on the DMC framework: experimental procedures were designed to test various predictions related to the behavioural and neural signatures of proactive and reactive control, and the results patterns were interpreted in relation to the operation of the two control mechanisms.

The second defining feature of this work was the systematic adoption of an individual differences approach. Of course, our thesis is best phrased as an individual differences question: individual differences in working memory capacity should be related to individual differences in fluid intelligence because of individual differences in the tendency to use proactive control. This interest in individual differences is not mandatory in working memory research: some of the most popular theories, such as Baddeley's model (1986) do not address normal individual differences at all, which does not prevent them to test the relationship between working memory and cognitive control. However, we believe that the existence of individual differences demonstrating stable relationships with other abilities is not only an interesting characteristic of working memory, but also a critical aspect of the data that must be addressed for a theory of working memory to adequately represent natural phenomena (see also Underwood, 1975).

Besides an interesting research topic, individual differences are also a prime research tool to investigate the functioning and the interrelations of the various constructs in play. As we have seen, the individual differences approach has been fruitfully applied to the understanding of working memory (e.g. Engle & Kane, 2004), cognitive control (e.g. Braver et al., 2007), and of course fluid intelligence. The main point of using this approach in this work is that comparing individuals with different levels of ability is a way to obtain a source of variation when direct experimental manipulation of the constructs is not possible (De Ribaupierre & Pascual-Leone, 1984). In the case of the working memory and cognitive control constructs, this feature is especially useful since we do not have at our disposal a lot of experimental procedures that could change the level of one without affecting the other in a task. As a consequence, individual differences were both the focus and the research tool of the present work.

We put our thesis to the test through four main axes of research.

- As we have seen, studies relating working memory to performance in the AX-CPT posed several problems. In a first line of research, we tried to develop new behavioural measures of the tendency to use proactive control, so as to test the correlation between these measures and working memory capacity. Experiments described in Chapter 4

assessed the tendency to use proactive control as the tendency to prepare cognitive processing ahead of time; experiments presented in Chapter 5 assessed the tendency to use proactive control as the tendency to use contextual information to guide behaviour in a task.

- A second line of research, described in Chapter 6, aimed to replicate and extend existing evidence of the relationship between working memory and proactive control using more classic cognitive control tasks, such as the AX-CPT.
- We have reviewed evidence that neuroimaging is a powerful tool to investigate proactive and reactive control mechanisms; in Chapter 7, we present three neuroimaging experiments trying to take advantage of this tool to test the relationship between working memory capacity and proactive control.
- In a final series of studies, presented in Chapter 8, we tested the second part of our thesis, related to the explanatory role of cognitive control in the relationship between working memory and fluid intelligence. To this end, we attempted to directly manipulate the relationship between working memory and fluid intelligence through a combined experimental-correlational approach based on the DMC framework.

A prerequisite for testing our thesis was the availability of a valid working memory task. This task had to take the form of a complex span so as to facilitate comparison with the literature; it also had to yield a domain-general measure of working memory capacity (as per Kane et al., 2004), and to have been validated in a French sample. Unfortunately, no existing task matched these three criteria. Thus, an additional aspect of our work was to develop and validate a working memory task suitable for the assessment of working memory capacity in French-speaking samples. We constructed the Composite Complex Span (CCS), a composite working memory task designed to obtain a domain-general measure of working memory capacity. The CCS comprised three short versions of the three most common complex span tasks (Redick et al., 2012): the reading span, symmetry span and operation span. All three subtests were closely based on their classic full-length versions (Unsworth et al., 2005). The CCS was used in all experiments presented in this work; a full description of the task is presented in Appendix A, along with an examination of its psychometric properties.

***In summary***

- The present work aimed to extend existing evidence in favour of two hypotheses: working memory is related to the tendency to use proactive control; and this relationship explains the correlation between working memory capacity and fluid intelligence.
- This work had two main features: it used the DMC framework to operationalize cognitive control, so as to bypass the usual measurement problems associated with this construct; and it relied on an individual differences approach, both as a way to frame our research question and as a research tool to investigate the relationships between the constructs in play.



# EXPERIMENTAL SECTION

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# CHAPTER 4. PROACTIVE CONTROL AS PREPARATORY PROCESSING

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## 1. Overview

The objectives of this chapter were twofold: developing new behavioural measures of the tendency to use proactive control, and testing the relationship between these measures and individual differences in working memory capacity. The choice to develop new measures was mainly motivated by the limits that we have outlined in studies using the AX-CPT (pp. 81-87). As we have seen, the expected pattern of results as a function of working memory capacity was not observed in the task; participants with high working memory capacity instead performed better on all trial types. Rather than obtaining new data with the same task, a process that would presumably have led to the same problems, it seemed sensible to turn to other experimental paradigms. Other tasks have been used in the past to assess mechanisms of the DMC framework, mainly the *n*-back and the Sternberg task (Speer et al., 2003; Brahmhatt et al., 2010; G. C. Burgess & Braver, 2010). However, using these two tasks was not an option either because they both measure short-term or working memory; this would necessarily have biased their observed relationship with working memory capacity. The best solution therefore seemed to be developing new experimental paradigms altogether. A secondary motivation for the development of new measures was the observation that all the existing evidence supporting the DMC framework has been gathered using only a handful of tasks; extending this evidence with different paradigms could only strengthen the construct validity of proactive and reactive control.

The two studies presented in this chapter have in common the way they operationalized the notion of proactive control. One of the central characteristics of proactive control is that it is implemented as a preparatory process, before the event requiring control actually takes place; this characteristic of proactive control is observable for example as sustained neural activity during the delay period of a task before a target event takes place (e.g. Paxton et al., 2008; Brahmhatt et al., 2010; G. C. Burgess & Braver, 2010). As a consequence, finding that a participant carries out task-related preparatory cognitive processing during a delay period should unambiguously indicate that this participant is using proactive control. In turn, the tendency to implement preparatory processing should be positively correlated with working memory capacity.

## **2. Study 1 – Prospective memory**

### **2.1. Experiment 1a**

#### **2.1.1. Rationale**

The ability to successfully remember to perform an intended action in the future has been termed prospective memory. Prospective memory demands are ubiquitous in everyday situations; as a result, the processes that underlie performance in this type of memory tasks have received considerable attention over the years (e.g. McDaniel & Einstein, 2007a). Prospective memory is generally tested with paradigms in which participants have to complete a main task (or "cover task") while remembering to perform a particular action, such as pressing a key on a keyboard, in response to a specific trigger. A distinction is generally drawn between two main types of prospective memory tasks, depending on the nature of the trigger. A time-based prospective memory task requires the participant to perform an action after a certain amount of time has elapsed; an event-based prospective memory task requires the participant to perform an action whenever a specific cue event occurs.

Two mechanisms are thought to drive performance in prospective memory tasks. The first mechanism, spontaneous retrieval, relies on the formation of an association between the intended action and the specific event serving as a cue that the action should be performed (McDaniel & Einstein, 2007b). This association then elicits spontaneous retrieval of the intended action whenever the participant encounters the cue event. The spontaneous retrieval mechanism is mainly automatic and resource-free; in essence, the prospective intention "pops to mind" when the cue event is encountered (Einstein & McDaniel, 2005). The second mechanism relies on preparatory attentional processes to actively monitor the environment for the prospective memory trigger; the intended action is selectively retrieved whenever the monitoring process detects the trigger (R. E. Smith, 2003; R. E. Smith & Bayen, 2004), such as a cue event or the feeling that a certain amount of time has elapsed. In contrast with spontaneous retrieval, this second mechanism requires the allocation of attentional resources before the prospective memory cue event occurs.

These two mechanisms have been integrated within a multi-process view of prospective memory (McDaniel & Einstein, 2000; Einstein & McDaniel, 2005). According to the multi-process view, spontaneous retrieval and preparatory processes are complementary, and performance in a prospective memory task may rely on either mechanism. Importantly, these two mechanisms bear considerable conceptual similarity to proactive and reactive control: the spontaneous reactivation of task instructions when prompted by a cue event is



directly equivalent to reactive control, whereas the use of preparatory processes to actively maintain the task goal during the delay is equivalent to proactive control. This similarity between mechanisms of prospective memory and mechanisms of cognitive control has been emphasized in a recent review of the DMC framework, which actually used a prospective memory situation to explain the functioning of proactive and reactive control (Braver, 2012). Similar to proactive control, using preparatory processes in a prospective memory task should enhance performance by decreasing the probability that the prospective action is omitted (Braver, 2012).

This conceptual similarity raises a simple idea: it should be possible to assess the tendency of participants to use proactive control by examining performance in a prospective memory task. Those participants who rely on reactive control should be prone to omitting the prospective goal, while participants who use proactive control should more consistently manage to perform the prospective action when required. In this study, we considered prospective memory performance as a marker of the tendency to use proactive control; as a consequence, we hypothesized that prospective memory performance would be positively correlated with working memory capacity.

To the best of our knowledge, the relationship between working memory capacity and time-based prospective memory performance has only been tested in one study in young children; this study observed a positive correlation between working memory capacity and performance (Kretschmer, Voigt, Friedrich, Pfeiffer, & Kliegel, 2013). On the other hand, several studies have examined the relationship between working memory capacity and event-based prospective memory performance, with mixed results. Several studies reported that the two constructs were very weakly related (Cherry & LeCompte, 1999) or not related at all (Einstein, McDaniel, Manzi, Cochran, & Baker, 2000; Breneiser & McDaniel, 2006), whereas others reported that a high working memory capacity was related to higher prospective memory performance (Einstein et al., 2000; R. E. Smith, 2003; R. E. Smith & Bayen, 2005; Brewer, Knight, Marsh, & Unsworth, 2010; R. E. Smith, Persyn, & Butler, 2011). Importantly, these studies differed in the prospective memory tasks that they used, especially in terms of the amount of information that had to be held in working memory. For example, certain studies have used tasks where a prospective action had to be performed when detecting one of four targets (R. E. Smith & Bayen, 2005) or even one of six targets (R. E. Smith, 2003). These studies observed an effect of working memory capacity on performance, but this is not surprising since the tasks placed heavy demands on working memory: keeping four targets in mind is already at the limit of what participants with low working memory

capacity can handle (Cowan, 2001, 2010). Another study observed a relationship between working memory capacity and prospective memory performance, but only when participants had to wait for several dozens of seconds after detecting the event cue to perform the prospective action; this constraint means that participants had to hold an intention in mind while carrying out concurrent cognitive processing, which amounts to a working memory demand (Einstein et al., 2000). All these studies have in common the fact that their results may be interpreted in terms of the prospective memory task relying on working memory, rather than in terms of working memory being related to preparatory processes in the prospective memory task. Conversely, the few studies observing no relationship between working memory capacity and prospective memory performance used tasks with few prospective targets to hold in working memory: two studies used a task with two prospective targets (Einstein et al., 2000; Breneiser & McDaniel, 2006) and the other used a single prospective target (Cherry & LeCompte, 1999). Unfortunately, the latter study (Cherry & LeCompte, 1999) estimated working memory capacity with a set of tasks including the backward digit span, which casts doubt on the validity of their measure.

In short, working memory capacity is observed to be related to prospective memory performance in certain studies, but only when the prospective memory task imposes a working memory load. This observation contradicts our hypothesis that working memory is related to prospective memory performance because participants with high working memory capacity tend to implement preparatory processes in the task: the relationship between working memory and prospective memory should be entirely independent of the working memory demands of the task and should appear even in tasks with no particular working memory load. On the other hand, virtually no study has tested the relationship between working memory capacity and performance in an event-based prospective memory task designed to limit the role of working memory to a minimum. The sole exception seems to be the work of Cherry and LeCompte (1999), who used a prospective memory task with a single prospective target to hold in working memory; however, the use of the backward digit span as a working memory measure decreases the interpretability of their results.

In the present study, we sought to resolve this limitation by testing the relationship between working memory capacity, tested with complex span tasks, and a prospective memory task with a single target. Prospective memory was also assessed with a self-report questionnaire, so as to obtain a prospective memory measure as free as possible of working memory influence. We expected participants with high working memory capacity to perform

better in the task and report more efficient prospective memory in the questionnaire, as a consequence of their tendency to use preparatory processes.

Of secondary interest, we also expected the correlation between working memory capacity and prospective memory performance to be modulated by the difficulty of the main task. Increasing the difficulty of the main task should lead participants to invest more effort and attention in this task, which should make the use of preparatory processes in the prospective memory task impractical. Because participants with high working memory capacity were expected to perform better in the prospective memory task through the use of preparatory processes, their advantage was expected to decrease when the difficulty of the main task increased; in other words, the correlation between working memory capacity and prospective performance was expected to decrease when the difficulty of the main task increased.

### *2.1.2. Method*

#### *2.1.2.1. Participants.*

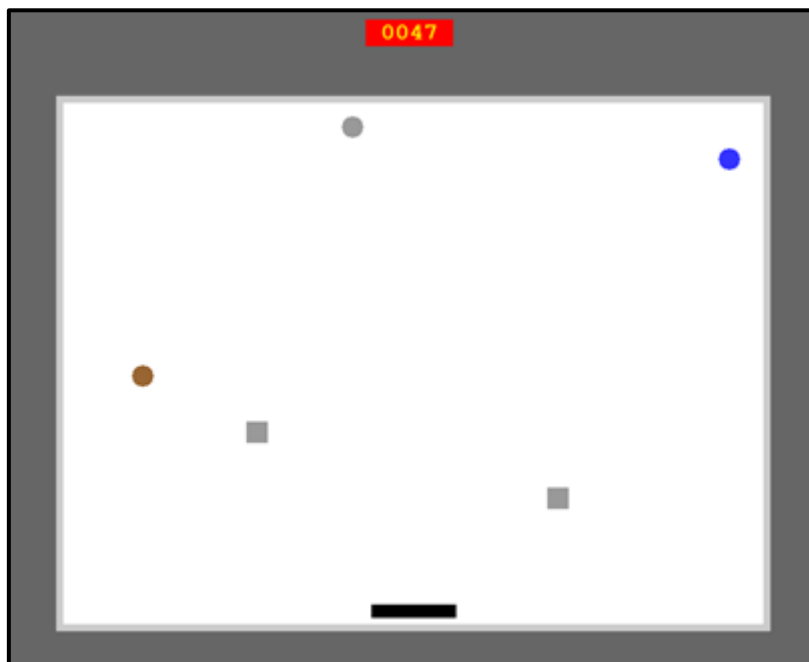
A sample of 89 participants completed the experiment (17 males and 72 females; age ranging from 17 to 32,  $M = 21.09$ ,  $SD = 2.45$ ). All participants were undergraduate students from the University of Savoy participating for course credit. Participants were included if they met the following criteria: native French speaker, no history of neurological disorders, and without psychoactive medication.

#### *2.1.2.2. Materials.*

**Working memory task.** Working memory capacity was measured with the CCS (see Appendix A). The dependent variable on the task was the composite working memory score.

**Prospective memory task.** An event-based prospective memory task was developed for this experiment. The structure of the task was similar to usual prospective memory assessments (see McDaniel & Einstein, 2007a): it was composed of a main task, on which participants were supposed to focus their attention, and an additional prospective memory requirement. Visually, the task resembled a "bat-and-ball" videogame; it included balls of various colours falling from the top of the screen, and a paddle placed at the bottom (see Figure 6). Participants could move the paddle laterally by pressing the arrow keys on a keyboard. The main goal of the task for the participants was to catch as many falling balls as possible with the paddle; the score was continuously displayed at the top of the screen, with caught balls adding two points and missed balls removing one point from the score. The additional

prospective instruction was to press the spacebar every time a red ball appeared on the screen. Thus, the task only included a single prospective memory target to hold in working memory capacity – the red ball. Three dependent variables were collected in the task: the total ball-catching score, the percentage of times when the spacebar was correctly pressed in response to a red ball, and the median response time (RT) when pressing the spacebar. The first dependent variable indexed performance in the main task and the two others indexed prospective memory performance. The difficulty of the ball-catching task was manipulated by changing the size of the paddle; participants completed both an easy version and a difficult version of the task.



*Figure 6.* Illustration of the visual display in the prospective memory task (easy version).

The ball-catching task used the following parameters. The paddle moved at a fixed speed; it could cross the entire width of the screen in 3.5 seconds. The size of the paddle was 100 pixels in the easy condition and 50 pixels in the difficult condition. There were at most six balls and at least two balls on the screen at all times. The balls fell in a straight line from a pseudo-random position, with two balls always being separated by at least 10% of the width of the screen; on average, the balls reached the bottom of the screen in 2000ms. Each ball could be one of six different colours chosen for their visual distinctivity (dark blue, grey, green, yellow, mauve, and red for the prospective target). So as to add some complexity to the visual display and reduce participant boredom, two irregularities were introduced: the falling balls could be either round or square, and their speed could vary by plus or minus 500ms to

reach the bottom of the screen. The red balls, or prospective memory targets, were always round; they always fell at the slowest speed, which means participants always had 2500ms to press the spacebar. Red balls appeared at pseudo-random intervals, between 20000ms and 30000ms after the previous red ball.

**Prospective memory questionnaire.** Participants reported their subjective perception of their prospective memory abilities in daily life with a self-report questionnaire, the Prospective and Retrospective Memory Questionnaire (PRMQ; G. Smith, Sala, Logie, & Maylor, 2000). The questionnaire was translated in French for this experiment. Participants completed the whole questionnaire, but only their answers on the prospective memory subscale were recorded.

#### *2.1.2.2. Procedure.*

Participants completed the experiment individually in a testing room equipped with a computer, a 19 inches LCD screen and headphones for phonic isolation. All participants provided written informed consent prior to the experimental session. They completed the prospective memory task and the CCS, in order. The whole process took approximately 45 minutes.

The experiment began with instructions for the prospective memory task. Participants were informed that there were two goals to the task – catching as many balls as possible and pressing the spacebar whenever a red ball appeared on the screen. Following these instructions, participants completed a short training session on the ball-catching task lasting 60 seconds. To prevent participants from placing too much emphasis on the prospective memory task, no prospective target appeared during the training session and they were not reminded of the prospective instructions after the training session (see e.g. R. E. Smith et al., 2011, for a similar procedure).

The training session was immediately followed by the actual task. The task was divided into six periods of 150 seconds. The difficulty of the ball-catching task systematically varied from period to period; the task began with the easy difficulty, then alternated between difficult and easy until the end of the test. Overall, the prospective memory task lasted for 15 minutes. On average, participants saw a total of 36 prospective memory targets throughout the task.

After the prospective memory task, participants completed the PRMQ, the CCS, and then received a short debriefing. The debriefing did not mention the prospective memory instructions at all, so as to avoid participants communicating the true purpose of the experiment to the rest of the sample.

### 2.1.3. Results

#### 2.1.3.1. Method of analysis.

Working memory capacity was treated as a continuous variable: the extreme groups approach frequently used in the working memory literature is not justified when a full sample of participants from all performance levels is available, as was the case here (Preacher, Rucker, MacCallum, & Nicewander, 2005). All analyses used the general linear model unless otherwise noted. After graphical inspection, the data were screened for outliers using Cook's distance for each analysis (see Stevens, 1984); data points with the highest Cook's distances and with distances greater than twice the preceding value were labeled as outliers. The outliers were selectively removed for the corresponding analysis; this procedure never resulted in excluding more than 5% of participants on any analysis. Homoscedasticity was checked for all analyses with either a Levene test (for categorical variables) or by plotting predicted values against the square root of residuals (for continuous variables); no major violation of this condition was detected unless specified.<sup>6</sup>

#### 2.1.3.2. Preliminary analyses.

Working memory scores were normally distributed ( $M = 0.23$ ,  $SD = 0.75$ , skewness =  $-0.49$ , kurtosis =  $-0.41$ ), although slightly above the population average<sup>7</sup>.

A series of analyses was performed to check the correct functioning of the experimental paradigm. Overall, the average performance in the ball-catching task was 51.77 ( $SD = 44.00$ ). Performance was higher in the easy condition ( $M = 97.17$ ,  $SD = 47.99$ ) than in the difficult condition ( $M = 6.38$ ,  $SD = 43.21$ ); this difference was significant,  $F(1, 88) = 1230.38$ ,  $MSE = 298.1$ ,  $p < .001$ ,  $\eta^2_p = .93$ . Performance in the ball-catching task was positively correlated with working memory capacity,  $F(1, 87) = 9.85$ ,  $MSE = 3519.1$ ,  $p = .002$ ,  $\eta^2_p = .10$ ,  $r = .26$ ; however, this correlation did not vary as a function of task difficulty,  $F(1, 87) = 1.69$ ,  $MSE = 295.8$ ,  $p = .198$ ,  $\eta^2_p = .02$ .

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<sup>6</sup> The same method of analysis was used in all studies presented throughout this work; this information will not be repeated for the next experiments.

<sup>7</sup> In this and all subsequent experiments, working memory scores were standardized in reference to the population parameters calculated in the validation sample of the CCS (see Appendix A). Because working memory scores are calculated as the average of three z-scores (see Appendix A), they have a mathematical expectation of zero at the population level. However, the fact that the three z-scores are correlated means the standard deviation of working memory scores should be less than one.

The internal consistency of accuracy in the prospective task was calculated with Cronbach's alpha, with the percentage of prospective actions correctly performed during each of the six task periods as measurement points; the task demonstrated excellent reliability ( $\alpha = .92$ ). On average, participants correctly performed the prospective action 66% of the time ( $SD = 35$ , range = 0 – 100). Contrary to our expectations, accuracy in the prospective memory task was slightly lower in the easy condition ( $M = 64$ ,  $SD = 36$ ) than in the difficult condition ( $M = 67$ ,  $SD = 35$ ) of the ball-catching task,  $F(1, 88) = 6.17$ ,  $MSE = 97.1$ ,  $p = .015$ ,  $\eta^2_p = .07$ . On average, participants pressed the spacebar 1300ms after the appearance of a red ball ( $SD = 432$ ). Response times were marginally slower in the easy condition ( $M = 1331$ ,  $SD = 517$ ) than in the difficult condition ( $M = 1231$ ,  $SD = 452$ ) of the ball-catching task,  $F(1, 76) = 3.08$ ,  $MSE = 124033$ ,  $p = .083$ ,  $\eta^2_p = .04$ . A total of 12 participants (13% of the sample) entirely disregarded the prospective memory task instructions and never pressed the spacebar throughout the task; a logistic regression indicated that the probability of forgetting the prospective instructions was not correlated with working memory capacity,  $\chi^2(1) = 0.56$ ,  $p = .455$ . Because our hypotheses concerned a relationship between working memory capacity and preparatory processes implemented during the task, rather than between working memory capacity and the ability to remember the existence of the prospective instructions, all participants who forgot the prospective memory task were excluded from analyses on prospective performance (see R. E. Smith et al., 2011, for a similar procedure).

Scores on the prospective memory subscale of the PRMQ were normally distributed, ( $M = 21.83$ ,  $SD = 4.72$ , skewness = 0.16, kurtosis = 0.65). Contrary to our expectations, scores on the prospective memory subscale did not correlate with performance in the prospective memory task,  $F(1, 87) = 0.21$ ,  $MSE = 22.479$ ,  $p = .647$ ,  $\eta^2_p = .00$ ,  $r = -.05$ .

### 2.1.3.3. Main analyses.

Our first hypothesis was that working memory capacity would correlate with self-reported prospective memory ability. This was not the case,  $F(1, 87) = 0.73$ ,  $MSE = 22.35$ ,  $p = .395$ ,  $\eta^2_p = .01$ ,  $r = .09$ . Our second hypothesis was that a high working memory capacity would be associated with better performance in the prospective memory task. This hypothesis was tested separately for accuracy and response times.

Working memory capacity was not correlated with accuracy in the prospective memory task,  $F(1, 71) = 0.79$ ,  $MSE = 48.34$ ,  $p = .377$ ,  $\eta^2_p = .01$ ,  $r = .11$  (see Figure 7). When controlling for performance in the ball-catching task, the correlation was still non-significant,  $F(1, 69) = 0.14$ ,  $MSE = 45.05$ ,  $p = .708$ ,  $\eta^2_p = .00$ ,  $r = .04$ . Also contrary to our hypotheses,

there was no two-way interaction between working memory capacity and task difficulty,  $F(1, 71) = 0.47$ ,  $MSE = 10.98$ ,  $p = .496$ ,  $\eta^2_p = .01$ : the correlations between working memory capacity and accuracy in the prospective memory task were similar in the easy condition ( $r = .04$ ) and in the difficult condition ( $r = .10$ ).

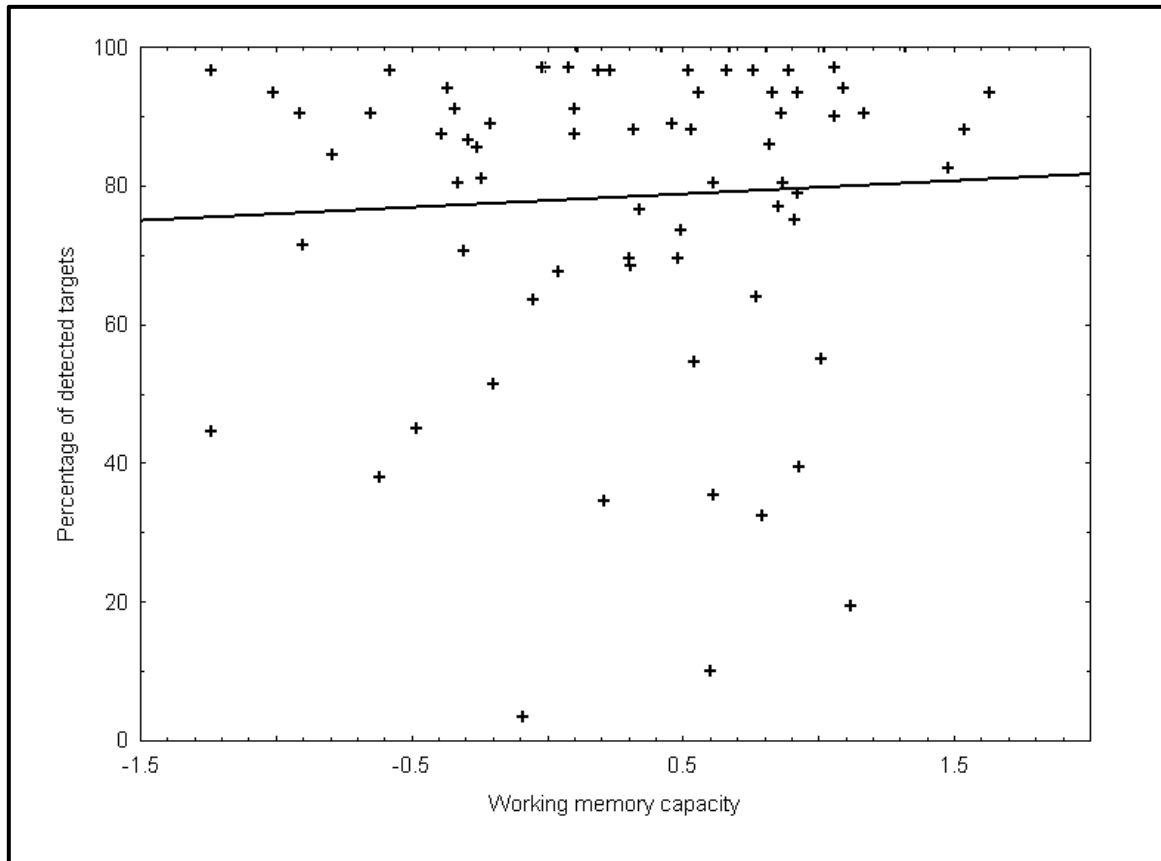


Figure 7. Correlation between working memory capacity and accuracy in the prospective memory task.

Working memory capacity was not correlated with response times in the prospective memory task either (see Figure 8),  $F(1, 73) = 0.45$ ,  $MSE = 158102$ ,  $p = .505$ ,  $\eta^2_p = .01$ ,  $r = -.08$ . Again, when controlling for performance in the ball-catching task the correlation was still non-significant,  $F(1, 73) = 0.21$ ,  $MSE = 157370$ ,  $p = .649$ ,  $\eta^2_p = .00$ ,  $r = -.06$ . Also contrary to our hypotheses, there was no two-way interaction between working memory capacity and task difficulty,  $F(1, 73) = 0.14$ ,  $MSE = 128580$ ,  $p = .711$ ,  $\eta^2_p = .00$ : the correlations between working memory capacity and response times in the prospective memory task were similar in the easy condition ( $r = -.03$ ) and in the difficult condition ( $r = .01$ ).



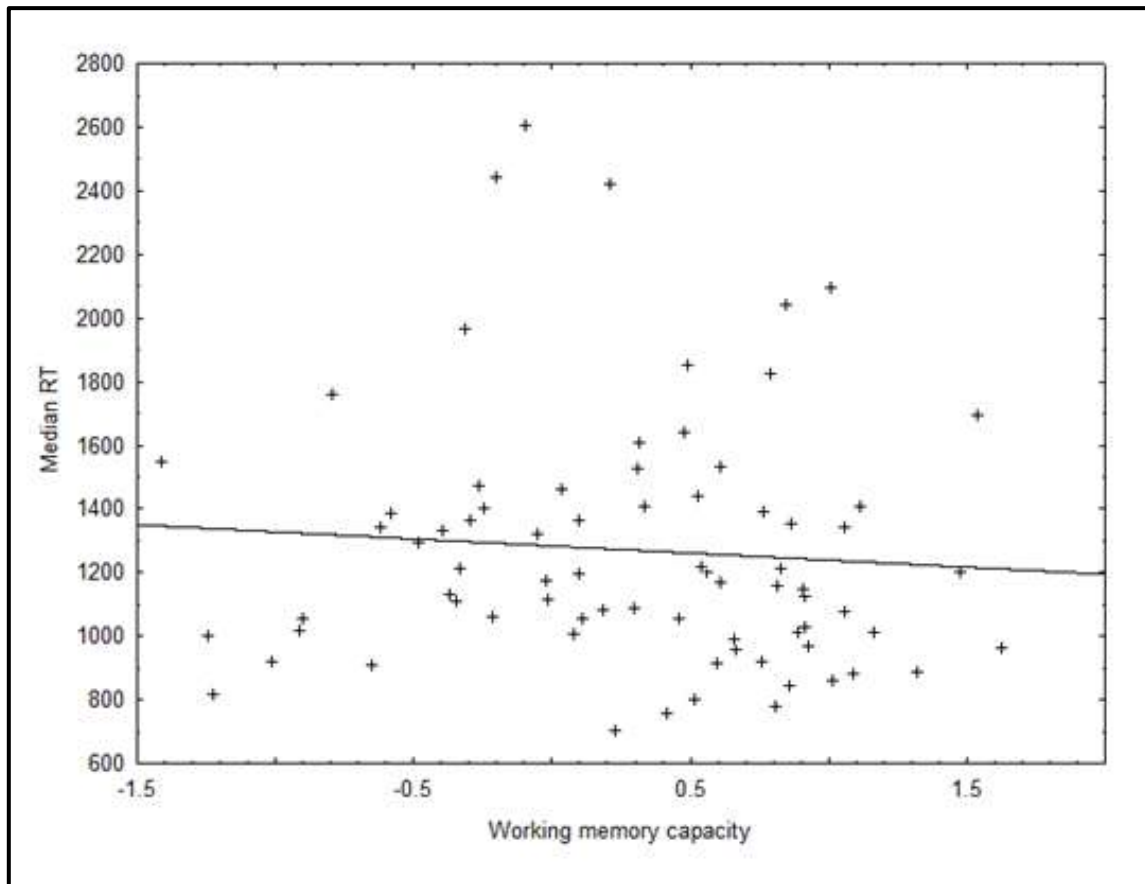


Figure 8. Correlation between working memory capacity and RTs in the prospective memory task.

#### 2.1.4. Discussion

Participants completed both a working memory task and an event-based prospective memory task; we expected participants with high working memory capacity to implement preparatory processes analogous to proactive control in the prospective memory task and consequently to perform better in the task. We also expected participants with high working memory capacity to report a higher subjective prospective memory ability in the PRMQ. The results did not support our hypotheses. Participants with high working memory task performed better in the main task, but did not perform the prospective action any more often than participants with low working memory capacity. Also contrary to our expectations, there was no two-way interaction between working memory capacity and task difficulty. Additionally, all participants reported a similar subjective estimation of their prospective memory ability in the PRMQ.

One possible explanation for these results would be that our prospective memory task was not valid and did not satisfyingly assess prospective memory ability. The fact that performance in the prospective memory task did not correlate with the PRMQ could be taken

as evidence that the task lacked convergent validity. However, a number of studies have observed that self-report measures tend to demonstrate weak correlations with objective assessments of prospective memory (Crawford, Henry, Ward, & Blake, 2006; Hertzog & Pearman, 2014). In other words, the fact that the prospective memory task did not correlate with a subjective measure of prospective memory does not necessarily indicate poor validity. Another important point is that the PRMQ was initially developed for use with older adults (G. Smith et al., 2000), who tend to demonstrate impaired prospective memory; the questionnaire may lack sensitivity in a sample of young university students. The same reason could explain why the PRMQ did not correlate with working memory capacity. In short, the absence of correlations between the PRMQ and other measures may be attributed to the PRMQ itself.

More worrying is the fact that performance in the prospective memory task did not correlate with working memory capacity. This is all the more surprising that working memory capacity tends to correlate with most high-level cognitive tasks. It is possible that all participants implemented preparatory processes in the task, contrary to our hypothesis. However, a more interesting alternative interpretation is also possible. The cue event in the prospective memory task was the appearance of a red ball on the screen; importantly, the red ball was highly visually distinctive. It is possible that the cue event was distinctive enough to elicit spontaneous retrieval of the prospective intention, thus serving as an efficient reminder for participants who used reactive control. In other words, it is possible that all participants were reminded of the prospective memory task when they saw the red ball on the screen. This idea means that implementing preparatory processes was not necessary to achieve efficient performance, and that both proactive and reactive control led to success in the prospective memory task (see Einstein & McDaniel, 1990). In fact, in a situation where the cue event is very distinctive, even participants with high working memory capacity may be expected to use reactive control rather than the more costly proactive control strategy (McDaniel & Einstein, 1990). In short, it is possible that no correlation emerged between working memory capacity and prospective memory performance because the event cue was so salient that it promoted the use of reactive control in all participants, even participants with high working memory capacity. This possibility means that our experimental paradigm may have actually prevented the emergence of a correlation between working memory capacity and performance by reducing individual differences in the use of control mechanisms.

Contrary to our expectations, manipulating the difficulty of the ball-catching task did not modulate the correlation between working memory capacity and prospective memory

performance. There are three likely explanations for this failure. The first possible explanation is based on the simple fact that working memory capacity had no main effect on performance in the prospective memory task; the fact that the relationship was not significant could explain why it was not modulated by the difficulty of the main task. The second possibility is that the difficulty manipulation was not successful in influencing the subjective difficulty of the task for participants, as suggested by the fact that prospective memory performance did not vary as a function of the difficulty condition. The third possibility is intimately tied with the idea that participants did not use preparatory processes to perform the prospective memory task. Contrary to preparatory processes, the spontaneous retrieval mechanism would not be expected to be affected by the difficulty of the main task: because this phenomenon is relatively automatic, it does not matter that participants invest more or less attention to the main task. Thus, if all participants used spontaneous retrieval, then changing the difficulty of the main task should not especially affect participants with high working memory capacity. If anything, increasing the difficulty should help all participants focus on the main task and increase their probability of detecting the event cue and perform the prospective action. In fact, this is exactly what we observed: participants were more efficient at performing the prospective action in the difficult condition of the ball-catching task. Thus, the fact that there was no two-way interaction between working memory capacity and task difficulty and that increasing the difficulty increased prospective memory performance was contrary to our expectations, but it is actually congruent with the interpretation that all participants used spontaneous retrieval rather than preparatory processes.

In summary, the results of Experiment 1a did not support our hypotheses; in particular, the correlation between working memory capacity and prospective memory performance was not significant. This failure may be attributed to the fact that the high distinctivity of the prospective cue event led all participants to rely on a spontaneous retrieval mechanism, a possibility that we chose to explore in Experiment 1b.

## **2.2. Experiment 1b**

### **2.2.1. Rationale**

Experiment 1b aimed to control the possibility raised in Experiment 1a that working memory capacity is related to the implementation of preparatory attentional processes in a prospective memory task, but that detecting this relationship requires a paradigm where using preparatory processes – rather than spontaneous retrieval – is mandatory for successful performance. To test this possibility, it was necessary to use an experimental paradigm where

participants using reactive control could not be reminded of the prospective instructions by a distinctive cue event. As we have seen (p. 98), there are two main types of prospective memory tasks: event-based and time-based tasks. The prospective memory task used in Experiment 1a was an event-based task: participants only had to perform the prospective action when confronted with a cue event – the appearance of a red ball. As for time-based tasks, they are less frequently used than event-based tasks and the question of their relationship with working memory capacity has seldom been raised. However, one interesting feature of time-based tasks is that they do not include cue events at all: instead, participants have to perform the prospective action after a fixed delay. In other words, there are no distinctive events in time-based prospective memory tasks that could serve to elicit spontaneous retrieval of the prospective instructions; instead, time-based tasks exclusively rely on preparatory processes (Einstein & McDaniel, 1990). Thus, participants who use proactive control should perform adequately in the task, because they tend to actively maintain the task goal and implement preparatory processes that do not depend on external cues to perform the prospective action. On the other hand, participants who use reactive control should consistently fail in time-based prospective memory tasks.

In this experiment, we tested this hypothesis with a time-based prospective memory task. We expected participants with low working memory capacity to use reactive control, to rely on spontaneous retrieval of the prospective instructions, and to fail the prospective memory task as a consequence; on the other hand, we expected participants with high working memory capacity to use proactive control, to implement preparatory attentional processes and to perform adequately in the task. In order to maximize comparability between Experiment 1a and Experiment 1b, the time-based prospective memory task used in this experiment was adapted from the event-based paradigm used in Experiment 1a.

This procedure raised a side concern. Participants with high working memory capacity are known to have better time estimation abilities than participants with low working memory capacity (Broadway & Engle, 2011); this could create a spurious correlation between working memory capacity and time-based prospective memory tasks, in that participants with low working memory capacity may perform worse due to a difficulty in estimating when exactly the prospective action should be implemented. To control for this possibility, a time estimation task was also included in the experimental session.

## 2.2.2. Method

### 2.1.2.1. Participants.

A sample of 62 participants completed the experiment (15 males and 47 females; age ranging from 17 to 25,  $M = 20.58$ ,  $SD = 1.99$ ). All participants were undergraduate students from the University of Savoy participating for course credit. The inclusion criteria were identical to Experiment 1a. None of the participants had participated in Experiment 1a.

### 2.1.2.2. Materials.

**Working memory task.** Working memory capacity was measured with the CCS (see Appendix A). The dependent variable on the task was the composite working memory score.

**Prospective memory task.** The main ball-catching task was identical to Experiment 1a, with the following exceptions. Instead of receiving instructions concerning the red balls, participants were instructed to press the spacebar every two minutes during the ball-catching task. A correct hit was scored whenever the participant pressed the spacebar within a time window of five seconds (i.e.,  $\pm 2500\text{ms}$ ) around the expected time (this procedure was similar to Kliegel, Martin, McDaniel, & Einstein, 2001). Participants were allowed to check the time during the experiment: pressing the A key displayed a clock indicating the amount of time that had elapsed since the beginning of the task. To prevent participants from keeping the clock consistently displayed throughout the task, it only remained on-screen for one second after pressing the A key and could not be displayed again for the next three seconds (see e.g. Kliegel et al., 2001, for a similar procedure). Two dependent variables were collected in the task: the total ball-catching score was recorded to index performance in the main task, and the percentage of times when the spacebar was correctly pressed served to index prospective memory performance.

As in Experiment 1a, we expected the correlation between working memory capacity and prospective memory performance to be modulated by the difficulty of the ball-catching task, as operationalized by the size of the paddle. However, manipulating difficulty in the same way as Experiment 1a – by having participants perform successive periods of easy and difficult conditions of the ball-catching task – was not an option: the scheduled alternation of phases would have provided participants with an external time cue, which could have interfered with the time-based prospective memory task. As a consequence, the difficulty of the ball-catching task was manipulated as a between-subjects variable in this experiment. Thus, the task only included a single continuous period of 15 minutes with constant difficulty

rather than alternating periods of 150 seconds as in Experiment 1a. In the final sample, 29 participants completed the easy condition and 33 participants completed the difficult condition.

**Time estimation task.** The time estimation task simply had participants press the spacebar every 2 minutes for 10 minutes. In order to prevent participants from focusing on the time estimation task and implementing strategies such as counting the seconds, they also completed a focal task during these 10 minutes. The focal task was the Mesulam continuous performance test (Mesulam, 1985), a simple symbol cancellation task. The task consisted of paper sheets with various printed symbols (such as uppercase letters); participants had to cross out all symbols of a given type on the sheet (for example, all instances of the letter A). This test was chosen to demand as little attention as possible so as not to bias time estimation performance. The dependent variable in this task was the median number of seconds between the moment when the participant should have pressed the spacebar and the moment when he actually pressed the spacebar.

#### *2.1.2.2. Procedure.*

The procedure was similar to Experiment 1a with the following exceptions. Participants completed the prospective memory task, the time estimation task and the CCS, in order. The whole procedure took approximately 45 minutes. The PRMQ was not included in Experiment 1b.

### *2.2.3. Results*

#### *2.2.3.1. Preliminary analyses.*

Working memory scores were normally distributed and close to the population average ( $M = -0.03$ ,  $SD = 0.71$ , skewness = 0.10, kurtosis = -0.59). One participant was excluded because of his performance in the processing tasks, yielding a total sample of 61 subjects.

A series of analyses was performed to check the correct functioning of the experimental paradigm. Performance in the ball-catching task was higher in the easy condition ( $M = 467.43$ ,  $SD = 229.20$ ) than in the difficult condition ( $M = 86.06$ ,  $SD = 184.80$ ); this difference was significant,  $F(1, 59) = 51.76$ ,  $MSE = 42563$ ,  $p < .001$ ,  $\eta^2_p = .47$ . As in Experiment 1a, performance in the ball-catching task was positively correlated with working memory capacity,  $F(1, 57) = 9.33$ ,  $MSE = 37778$ ,  $p = .003$ ,  $\eta^2_p = .14$ ,  $r = .27$ , but this

correlation did not depend on task difficulty,  $F(1, 57) = 0.41$ ,  $MSE = 3778$ ,  $p = .527$ ,  $\eta^2_p = .01$ .

On average, participants correctly performed the prospective action 32% of the time ( $SD = 23$ , range = 0 – 67). Contrary to Experiment 1a, performance in the prospective memory task was comparable in the easy condition ( $M = 34$ ,  $SD = 23$ ) and in the difficult condition ( $M = 30$ ,  $SD = 24$ ) of the ball-catching task,  $F(1, 59) = 0.30$ ,  $MSE = 551.55$ ,  $p = .583$ ,  $\eta^2_p = .01$ . A total of 8 participants (13% of the sample) entirely disregarded the prospective memory task instructions and never pressed the spacebar throughout the task; as in Experiment 1a, a logistic regression indicated that the probability of forgetting the prospective instructions was not correlated with working memory capacity,  $\chi^2(1) = 0.00$ ,  $p = .955$ . All participants who completely forgot the prospective memory task were excluded from analyses on prospective performance (see Experiment 1a, p. 105).

Scores on the time estimation task were normally distributed, ( $M = -0.47$ ,  $SD = 27.40$ , skewness =  $-0.23$ , kurtosis =  $0.69$ ). As expected, performance in the time estimation task was marginally correlated with performance in the prospective memory task,  $F(1, 58) = 3.02$ ,  $MSE = 535.29$ ,  $p = .087$ ,  $\eta^2_p = .05$ ,  $r = .22$ ; importantly, however, working memory capacity did not correlate with time estimation performance,  $F(1, 56) = 0.88$ ,  $MSE = 677.02$ ,  $p = .353$ ,  $\eta^2_p = .02$ ,  $r = .12$ .

### 2.2.3.2. Main analyses.

Our first hypothesis was that working memory capacity would be positively correlated with prospective memory performance. The correlation was significant,  $F(1, 49) = 9.42$ ,  $MSE = 352.44$ ,  $p = .003$ ,  $\eta^2_p = .16$ ,  $r = .40$  (see Figure 9), congruent with our expectations. The correlation was still significant when controlling for performance in the ball-catching task,  $F(1, 45) = 6.98$ ,  $MSE = 323.18$ ,  $p = .011$ ,  $\eta^2_p = .13$ ,  $r = .55$ , and when controlling for performance in the time estimation task<sup>8</sup>,  $F(1, 44) = 8.24$ ,  $MSE = 334.76$ ,  $p = .006$ ,  $\eta^2_p = .16$ ,  $r = .39$ .

Our second hypothesis was that the correlation between working memory capacity and prospective memory performance would be modulated by task difficulty; we expected the correlation to be lower in the difficult condition of the ball-catching task. Contrary to this hypothesis, the two-way interaction was not significant,  $F(1, 47) = 0.01$ ,  $MSE = 360.73$ ,

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<sup>8</sup> These two covariables were tested in two separate analyses because including both variables in the score model left too little unique variance in prospective memory scores.

$p = .920$ ,  $\eta^2_p = .00$ ; the correlation between working memory capacity and performance was similar for participants who completed the easy version ( $r = .46$ ) and participants who completed the difficult version of the ball-catching task ( $r = .37$ ).

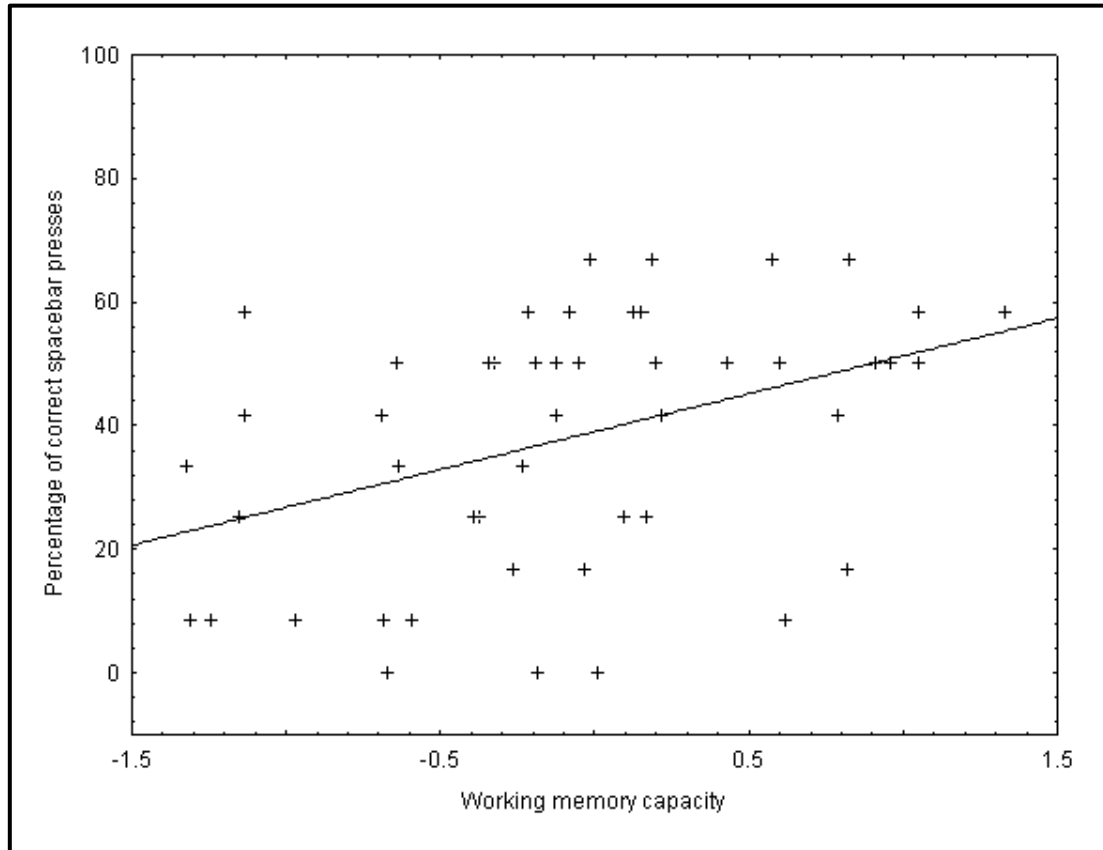


Figure 9. Correlation between working memory capacity and prospective performance.

#### 2.2.4. Discussion

In Experiment 1a, we did not observe the expected correlation between working memory capacity and performance in an event-based prospective memory task. We hypothesized that this null result was due to the nature of the prospective memory task, in which the salient event cue promoted the use of spontaneous retrieval mechanisms – or reactive control – in all participants. In Experiment 1b, we tested the same relationship with a time-based prospective memory task, designed to require preparatory processes and prevent the use of spontaneous retrieval mechanisms. This time, working memory capacity was related to performance in the prospective memory task; this relationship was not mediated by performance in the main task or by the time estimation abilities of participants. Thus, our results support the hypothesis that participants with high working memory capacity have a higher tendency to use proactive control, which elicits a higher performance in tasks where preparatory processes play a central role.



Interestingly, this conclusion allows for an elegant interpretation of results in the prospective memory literature. Recall that certain studies have observed a correlation between working memory capacity and prospective memory performance, while others observed no relationship (see pp. 99-100). Our results suggest that the correlation between working memory capacity and prospective memory performance depends on the degree to which the prospective memory task relies on preparatory processes. In other words, a prospective memory task would correlate with working memory capacity if the task cannot be solved with spontaneous retrieval, for example because there is no salient cue event to trigger the retrieval – which especially includes time-based prospective tasks. Conversely, an event-based prospective task including salient cue events would not correlate with working memory capacity. Of course, event-based prospective memory task with high working memory demands could also correlate with working memory capacity (which includes event-related paradigms requiring participants to detect one of six targets)

Overall, the literature seems to fit this interpretation. A single study tested the relationship between working memory capacity and time-based prospective memory and observed a significant correlation between the two variables (Kretschmer et al., 2013). One study observed a correlation between working memory capacity and event-based prospective memory performance, but only when participants had to wait for several dozens of seconds after they had detected the cue event to perform the prospective action; such a delay certainly required preparatory processes since it made the prospective action clearly separate from the cue that could have elicited spontaneous retrieval (Einstein et al., 2000). Other studies used prospective memory tasks associated with low working memory demands, but in which the cue event was not easily detected, which presumably makes spontaneous retrieval much less relevant and emphasizes the role of preparatory processes; these studies also observed a correlation with working memory capacity (Brewer, Knight, Marsh, & Unsworth, 2010).

The studies which used prospective memory tasks associated with high working memory demands also found a correlation with working memory capacity (R. E. Smith, 2003; R. E. Smith & Bayen, 2005; R. E. Smith, Persyn, & Butler, 2011). Conversely, the studies which used event-based prospective memory tasks with easily detected cue events, without working memory demands, and without an imposed delay between the cue and the prospective action to be performed reported a weak or non-existent correlation between prospective memory performance and working memory capacity. The latter finding is consistent with the idea that all participants resorted to spontaneous retrieval in these

situations, as in our own Experiment 1a (Cherry & LeCompte, 1999; Breneiser & McDaniel, 2006).

The fact that the two-way interaction between working memory capacity and task difficulty was non-significant was contrary to our predictions, but it does not significantly question this account of the results. Instead, it is likely that our difficulty manipulation simply did not alter the cognitive load imposed by the ball-catching task, as suggested in Experiment 1a (p. 109). This interpretation is supported by the fact that prospective memory performance was identical in both difficulty conditions.

Although these results fit nicely with the DMC framework, two problems remain with this study. First, our account relies on the null result observed in Experiment 1a; this is all the more problematic that this null result was not predicted and our interpretation of the results was entirely post-hoc. Second, participants with high working memory capacity again demonstrated better performance in the task. As was already the case for studies using the AX-CPT, this pattern of results does not constitute a definitive test of our thesis (see pp. 81-82): the superior performance of participants with high working memory capacity could be attributed to a number of variables other than cognitive control. For example, they could perform better due to their higher processing speed (for quickly processing the positions of the balls and deciding the trajectory of the paddle in the ball-catching task, which would leave more time for the prospective memory task itself), better coordinating skills (for simultaneously keeping track of the ball-catching task and the prospective instructions), more efficient sustained attention (for staying focused on the task), or even, as a far-fetched possibility, higher fluid intelligence (for understanding the importance of the prospective instructions in the experiment). In Study 2, we sought to control this problem by designing a study where the implementation of proactive control would not be reflected in a higher performance for participants with high working memory capacity.

### **3. Study 2 – Mental rotation**

#### **3.1. Experiment 2a**

##### *3.1.1. Rationale*

This second study was based on a straightforward idea. We know that there is a limit on the amount of information that can be attended to at once; this phenomenon is often described as an attentional bottleneck (e.g. Marti, Sigman, & Dehaene, 2012). The attentional bottleneck is thought to be the origin of performance decrements when performing two tasks at once, and of the difficulty to detect a stimulus immediately after another stimulus has appeared (Marti et al., 2012). Simply put, investing attention in one stimulus seems to decrease the amount of "attentional resources" available for the processing of another stimulus. Besides, we also know that cognitive control constitutes a controlled process, willed, effortful, and most importantly implemented through conscious awareness (Schneider & Shiffrin, 1977; K. B. MacDonald, 2008). Since proactive control refers to the implementation of cognitive control through preparatory processes, we can conclude that carrying out these preparatory processes should require active attention from the subject. These two observations suggest that a participant using proactive control should have reduced ability to attend to stimuli appearing at a time when he is engaged in preparatory processes.

In this study, we sought to take advantage of this idea to obtain a measure of the tendency to use proactive control. Participants completed a primary task where a target was preceded by a delay period; the delay period allowed for the implementation of preparatory processing. More precisely, the primary task was a mental rotation task (see Shepard & Metzler, 1971) where participants had to mentally rotate a first spatial shape to decide whether it was identical to a comparison shape. The mental rotation paradigm was chosen because it allowed for a simple account of the mechanisms playing a role during the task. In our version of the task, the first spatial shape appeared at the beginning of the trial and the comparison shape appeared after a delay period. There were two main approaches to solving the task: participants could either engage in preparatory mental rotation during the delay period to form a mental representation of the rotated first shape, so as to facilitate comparison with the second shape when it appeared; or they could wait for the comparison shape to appear and only then engage in comparison of the two shapes, a less costly but less efficient strategy (for a discussion of strategies in mental rotation tests, see e.g. Janssen & Geiser, 2010).

Irrelevant stimuli were also presented during the delay period. The irrelevant stimuli were auditorily presented words; the auditory modality was chosen to limit interference between the mental rotation task and the irrelevant stimuli, because participants with high working memory capacity are typically better at suppressing interference (Engle & Kane, 2004). At the end of the task, participants had to recognize the irrelevant stimuli among distractors in a surprise memory test. Our predictions were as follows: participants using proactive control should implement preparatory processes during the delay period and, consequently, devote less attention to irrelevant stimuli presented during the delay. In turn, these participants should be less efficient at recognizing the stimuli among distractors during the surprise memory test. Our thesis is that participants with high working memory capacity have a higher tendency to use proactive control. As a consequence, participants with high working memory capacity should engage in preparatory processing during the delay period, pay less attention to irrelevant stimuli presented at this time, and be less efficient at recognizing these stimuli later on. This hypothesis bears some conceptual similarity with the work of Conway and colleagues (Conway et al., 2001), who showed that participants with high working memory capacity were less efficient at detecting their own name presented amid an irrelevant message. A comparable mechanism should apply in our study: participants with low working memory capacity should outperform participants with high working memory capacity in memorizing irrelevant stimuli presented during the delay of the task.

One problem with this hypothesis is that participants with high working memory capacity tend to perform better overall in memory tasks. Therefore, simply comparing the amount of irrelevant stimuli correctly recognized by participants was not an option: even if participants with low working memory capacity implement less preparatory processing during the delay of a task and devote more attention to the irrelevant stimuli, there is a risk that they will recognize less of these stimuli in a subsequent memory test simply because they have lower memory abilities in general.

To control for this problem, we also presented irrelevant stimuli at the same time as the target of the primary task. The DMC framework predicts that both participants using proactive control and participants using reactive control should actively process the target of the task when it appears. As a consequence, for participants who use reactive control, irrelevant stimuli presented during the delay of the primary task should be memorized better than stimuli presented at the same time as the target because they should be able to devote more attention to the former than to the latter. For participants who use proactive control, irrelevant stimuli presented at the same time as the target should receive the same amount of

processing as stimuli presented during the delay, which means the recognition performance should be comparable for all irrelevant stimuli. In other words, a selective benefit in recognition performance should appear for irrelevant stimuli presented during the delay period preceding the target, but only for participants using reactive control. These predictions are summarized in Figure 10.

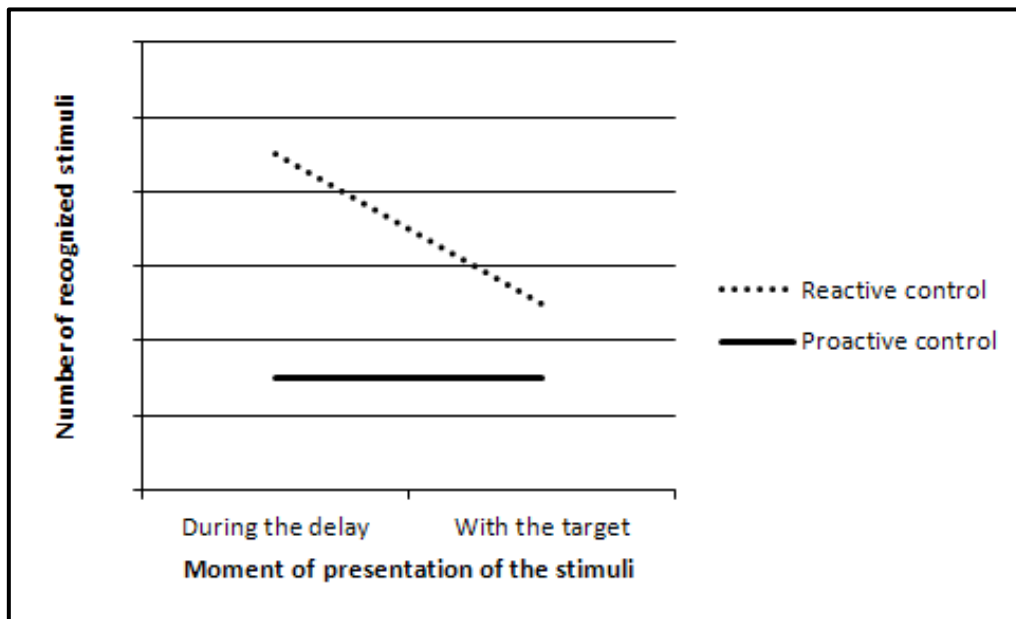


Figure 10. Hypothesized recognition performance for irrelevant stimuli as a function of the cognitive control mechanism and the moment of presentation.

Because of these predictions, the tendency to use proactive control in the task could be indexed by the difference in recognition performance between stimuli presented during the delay and stimuli presented concurrently with the target. Participants using proactive control were expected to recognize all irrelevant stimuli equally, yielding a null difference score, whereas participants using reactive control were expected to demonstrate better performance for irrelevant stimuli presented during the delay, yielding a non-zero difference score. In other words, the higher the tendency to use reactive control, the higher the benefit for stimuli presented during the delay period. The point of computing the proactive control index as a difference in memory performance is that this method is insensitive to baseline differences in mnemonic ability: if participants with high working memory capacity have a higher tendency to use proactive control, their difference score should be lower than that of participants with low working memory capacity, independently of the absolute number of stimuli that they manage to recognize. In this context, the DMC framework is directly useful in that it allows to predict a specific results pattern rather than simply a higher performance for participants using

proactive control; this feature is an excellent way to bypass the measurement problem due to the general advantage of participants with high working memory capacity, which constituted a critical issue in Study 1 and in prior studies using the AX-CPT.

### 3.1.2. Method

#### 3.1.2.1. Participants.

A sample of 77 participants completed the experiment (13 males and 64 females; age ranging from 18 to 31,  $M = 21.12$ ,  $SD = 2.36$ ). One participant was excluded because he did not understand the instructions of the task, yielding a total sample of 76 subjects. All participants were undergraduate students from the University of Grenoble 2 participating for course credit. Participants were included if they met the following criteria: native French speaker, right-handed, no history of neurological disorders and without psychoactive medication.

#### 3.1.2.2. Materials.

**Working memory task.** Working memory capacity was measured with the CCS (see Appendix A). The dependent variable on the task was the composite working memory score.

**Mental rotation task.** A mental rotation task was used as the primary task where participants could either implement proactive control or not. The objective of the task, as explained to the participants, was to decide whether one spatial shape was identical to another after rotation. A general outline of the task is presented in Figure 11.

At the beginning of each trial, a first spatial shape appeared on the left side of the screen. In order to help participants implement preparatory mental rotation, this spatial shape was accompanied by a centrally-presented arrow pointing either left or right to indicate in which direction to perform the rotation. The appearance of this first shape was followed by a 2500ms delay, during which the spatial shape remained visible at all times. At the end of the delay the comparison shape appeared on the right side of the screen and remained displayed for 4000 ms; during this delay the participant had to tell whether the second shape constituted a rotated version of the first shape by clicking on the appropriate button. On half the trials, the second shape was simply a rotated version of the first shape; on the other half, the second shape was a rotated mirror image of the first shape (Shepard & Metzler, 1971; see the example in Figure 11). The durations of the delay period and the response period were chosen so as to allow participants to complete the task either with or without preparatory processing during the delay. Trials were separated by a 1000ms inter-trial interval (ITI).

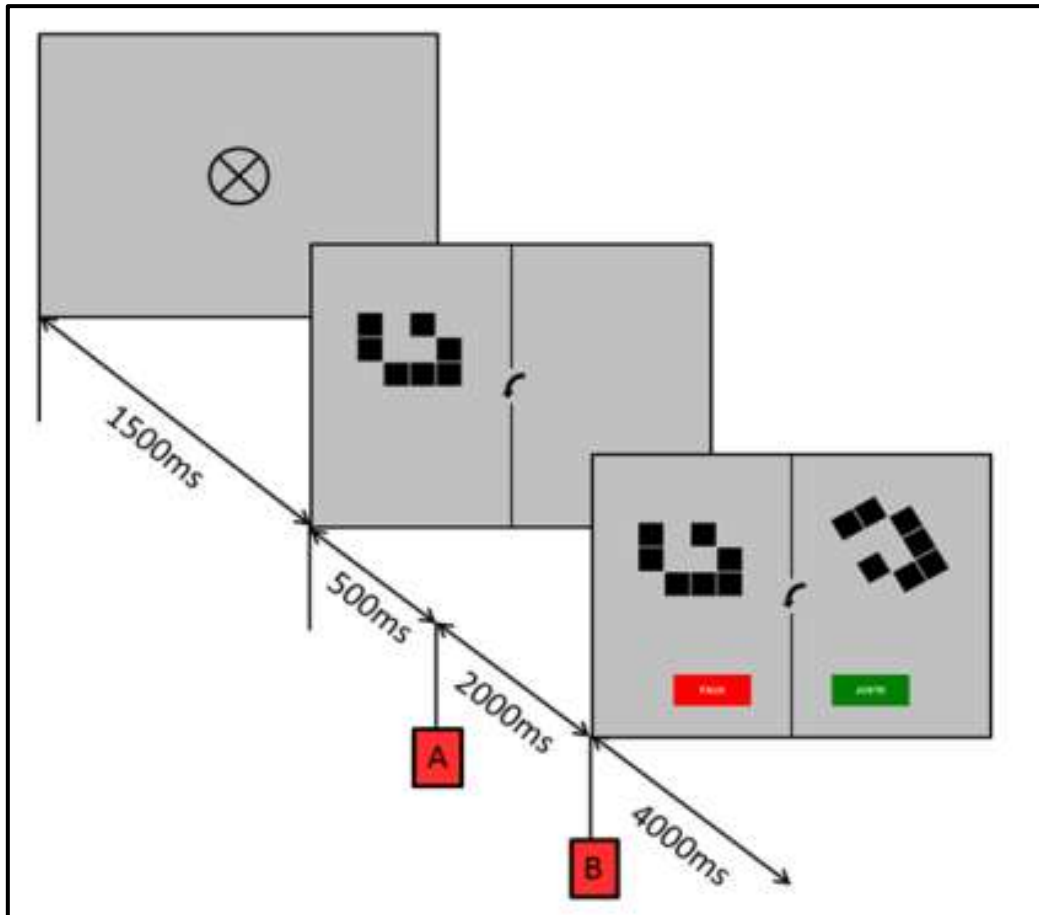


Figure 11. Graphical summary of the procedure in Experiment 2a. The letters *A* and *B* indicate the moment of presentation of irrelevant words. The correct answer to the displayed mental rotation example is "wrong".

On each trial of the mental rotation task, an irrelevant word was presented auditorily via headphones. Words were presented either during the delay period or at the same time as the target; the headphones remained silent the rest of the time. The onset of words presented during the delay period was 500ms after the beginning of the delay (point *A* in Figure 11) and their offset was approximately 500ms before the end of the delay. Words presented concurrently with the target were presented at the same time as the appearance of the target and offsetted approximately 1500ms later (point *B* in Figure 11).

**Stimuli for the mental rotation task.** Spatial shapes used in the mental rotation task were constituted of 6 to 12 black squares displayed against a grey background (see the example in Figure 11). The squares were slightly disjointed to facilitate perceptual processing of the shape components. The spatial shapes were created by randomly generating a large number of random shapes and selecting those that were neither too simple, nor too complex. Comparison shapes were created by rotating the shapes at one of five angles, from 30° to 150° in steps of

30°. Half the shapes were rotated to the left and half to the right. A mirror image of half the comparison shapes was created for use as incorrect comparison shapes.

**Irrelevant words stimuli.** All irrelevant stimuli were three-syllable words; this word length was chosen so that the auditory presentation lasted a sufficient time to allow for detection and cognitive processing by the participants. All words were common nouns with frequency comprised between 5 and 20 per million in French (as defined in the Lexique 3.80 database; New, Pallier, Ferrand, & Matos, 2001). There were no marked semantic or phonological similarities between the words; the words likely to generate attentional capture were excluded from the list. Half the words were presented as irrelevant stimuli during the mental rotation task; the other half were used as distractors during the surprise recognition test. The list of words is presented in Appendix B, with irrelevant words presented during the mental rotation task appearing in Table B1 and distractors appearing in Table B2. Words presented as irrelevant stimuli during the mental rotation task were digitally recorded with a microphone, so that participants heard the words spoken aloud by a female voice in a neutral tone.

### 3.1.2.3. Procedure.

Participants completed the experiment individually in a testing room equipped with a computer, a 19 inches LCD screen and headphones. All participants provided written informed consent prior to the experimental session. They completed the mental rotation task, a short questionnaire about their perception of the irrelevant stimuli during the task, a surprise recognition test for the irrelevant stimuli, and the CCS, in order. The whole process took approximately 45 minutes.

The experiment began with instructions for the mental rotation task. Irrelevant stimuli were mentioned in these instructions to ensure that all participants would have similar expectations concerning these stimuli; however, participants were not explicitly told to "ignore" or "inhibit" the stimuli because subjects with high working memory capacity might have been more efficient at purposefully ignoring the words. The precise instructions stated: « *During the experiment, words with no relation to the task will be presented in the headphones; this is a verbal control variable. Your objective is to focus on the mental rotation task.* »

After the instructions, participants received five practice trials for the mental rotation task. Irrelevant words were presented during these trials; these words were two-syllable verbs to ensure that they were sufficiently distinct from stimuli presented during the actual task. The participants then completed 45 trials of the mental rotation task. Half the trials presented a



correct comparison shape and the other half presented a mirror image; mental rotation had to be performed to the left in half the trials and to the right in the other half; the irrelevant word was presented during the delay period in half the trials and concurrently with the target in the other half. These rules applied to both the practice and the task trials. All trials were presented in the same pseudo-random order for all participants, so as to remove one source of variance that could have interacted with individual differences. Both accuracy and response times were collected.

If participants had become aware of the fact that irrelevant words were actually relevant to the protocol, or if they tried to memorize the words, their data could have been significantly biased. To control for this problem, participants completed a short questionnaire on their perception of the irrelevant words at the end of the mental rotation task. They answered two questions: « Did you try to remember the words during the task? » and « During the task, did you suspect that the words would turn out to be important? ». The participants then completed the surprise recognition test.

For the recognition test, words were presented successively at the center of the screen; for each word, the participant had to indicate whether it had been presented during the mental rotation task or not. The test included 40 distractor words and 40 of the words presented during the mental rotation task; to avoid a recency effect, the last five words presented during the mental rotation task were excluded from the list of stimuli to recognize. The stimuli were presented in the same pseudo-random order for all participants. Three dependent variables were collected in the recognition test: the hit rate for words presented during the delay period; the hit rate for words presented concurrently with the comparison shape; and the false alarm rate, or the amount of distractors incorrectly identified as stimuli presented during the mental rotation task.

After the recognition test, participants completed the CCS and received a short debriefing (including the explicit instruction not to tell other students about the content of the experimental session).

### *3.1.3. Results*

#### *3.1.3.1. Preliminary analyses.*

Working memory scores were normally distributed and close to the population average ( $M = -0.08$ ,  $SD = 0.74$ , skewness =  $-0.17$ , kurtosis =  $-0.66$ ). A series of analyses was carried out to check the correct functioning of the experimental paradigm. The first set of preliminary analyses concerned performance on the mental rotation task. Descriptive statistics

for the task are displayed in Table 1. Overall, participants correctly answered 69% of trials in the task; a one-sample  $t$ -test indicated that this performance was above chance level,  $t(75) = 14.46, p < .001$ . As reported in the mental rotation literature, the difficulty of the task varied as a function of the angle of the rotation that had to be performed (Shepard & Metzler, 1971): increasing the angle of rotation increased RTs,  $F(4, 300) = 6.49, MSE = 88804, p < .001, \eta^2_p = .08$ , and decreased accuracy,  $F(4, 300) = 17.00, MSE = 1.89, p < .001, \eta^2_p = .18$ . When the comparison shape was a mirror image rather than simply a rotated version of the first shape, responses were both slower,  $F(1, 75) = 45.92, MSE = 58695, p < .001, \eta^2_p = .38$ , and less accurate,  $F(1, 75) = 27.07, MSE = 0.015, p < .001, \eta^2_p = .27$ . Response times were slower for trials where the irrelevant word was presented concurrently with the comparison shape rather than during the delay period,  $F(1, 75) = 34.82, MSE = 74459, p < .001, \eta^2_p = .32$ . Importantly, however, the moment of presentation of the irrelevant stimulus did not affect accuracy rates,  $F < 1$ . Lastly, working memory capacity was negatively correlated with the number of errors in the mental rotation task,  $r = -.35$ ; this correlation was significant,  $F(1, 74) = 10.41, MSE = 26.15, p = .002, \eta^2_p = .12$ . However, working memory capacity was unrelated to response times,  $F(1, 74) = 0.88, MSE = 180912, p = .352, \eta^2_p = .01, r = .11$ .

The second set of preliminary analyses examined answers on the questionnaire concerning the participants' perception of the irrelevant stimuli in the mental rotation task. Overall, 31% of participants reported trying to remember the irrelevant words presented during the task; 41% of participants reported suspecting that the irrelevant words were in fact important. Logistic regressions indicated that working memory capacity did not correlate with the suspicion that words were important,  $\chi^2(1) = 0.06, p = .805$ ; however, participants with low working memory capacity were more likely to report trying to remember the words,  $\chi^2(1) = 4.48, p = .034$ .

The third set of preliminary analyses examined performance on the surprise recognition test. The internal consistency for the recognition test was evaluated with Cronbach's alpha; the reliability coefficient was satisfying ( $\alpha = .79$ ). On average, participants correctly identified 57% of irrelevant stimuli presented during the mental rotation task ( $SD = 15$ ), significantly above chance level,  $t(75) = 3.97, p < .001$ ; they correctly classified 81% of distractors as new stimuli ( $SD = 12$ ), also significantly above chance level  $t(75) = 23.19, p < .001$ . The item effect for irrelevant stimuli heard during the task was significant,  $F(39, 3000) = 10.55, MSE = 0.218, p < .001, \eta^2_p = .12$ , indicating that certain items were recognized more often than others; for example, the word *réacteur* (reactor) was

recognized by 22% of participants ( $SD = 0.42$ ), while the word *cocaine* (cocaine) was recognized by 97% of participants ( $SD = 0.16$ ). However, the item effect did not interact with working memory capacity,  $F(39, 2960) = 1.19$ ,  $MSE = 0.218$ ,  $p = .200$ ,  $\eta^2_p = .02$ .

Table 1

*Descriptive statistics for the mental rotation task as a function of trial type*

Trial type	Average error rate (SD)	Median RT (SD)
Rotation angle		
Angle 30°	.26 (.18)	2255 (469)
Angle 60°	.27 (.15)	2259 (545)
Angle 90°	.24 (.17)	2382 (490)
Angle 120°	.31 (.18)	2462 (506)
Angle 150°	.42 (.22)	2333 (496)
Nature of the comparison shape		
Correct shape	.25 (.14)	2378 (516)
Mirror shape	.35 (.15)	2644 (581)
Moment of presentation of the words		
During the delay	.30 (.13)	2380 (482)
With the target	.30 (.14)	2642 (621)

### 3.1.3.2. Main analysis.

We expected participants using reactive control to recognize more words presented during the delay than words presented concurrently with the target, and participants using proactive control to recognize an equal number of words for both moments of presentation. This hypothesis was tested with a 2 (moment of presentation) \* working memory capacity design, with the number of correctly recognized irrelevant words as a dependent variable; we expected to observe an interaction between working memory capacity and moment of presentation. Overall, the main effect of the moment of presentation was significant,  $F(1, 74) = 30.35$ ,  $MSE = 4.33$ ,  $p < .001$ ,  $\eta^2_p = .29$ ; participants correctly recognized more words presented during the delay ( $M = 12.33$ ,  $SD = 3.66$ ) than words presented concurrently

with the target ( $M = 10.47$ ,  $SD = 3.13$ ). However, the main effect of working memory capacity was not significant,  $F(1, 74) = 0.40$ ,  $MSE = 38.17$ ,  $p = .530$ ,  $\eta^2_p = .01$ : participants with high working memory capacity did not correctly recognize more words,  $r = -.07$ . Importantly, the two-way interaction between working memory capacity and moment of presentation was not significant either,  $F(1, 74) = 0.33$ ,  $MSE = 4.32$ ,  $p = .568$ ,  $\eta^2_p = .00$ , indicating that all participants recognized more words presented during the delay than words presented concurrently with the target: working memory capacity did not correlate with the difference in the number of recognized stimuli as a function of the moment of presentation,  $r = -.07$ , contrary to our hypothesis.

Of secondary interest, if participants with high working memory capacity had used the delay period to carry out mental rotation ahead of time, the detrimental effect of the angle of rotation on performance should have been decreased for these participants. In other words, working memory capacity could be expected to interact with the effect of the angle of rotation on response times, with a low working memory capacity being associated with a larger effect. However, this was not the case,  $F(4, 296) = 1.543$ ,  $MSE = 88166$ ,  $p = .190$ ,  $\eta^2_p = .02$ .

### 3.1.3.3. *Complementary analyses.*

We expected to observe a two-way interaction between working memory capacity and the moment of presentation of the irrelevant stimuli; the result of this main analysis was directly at odds with our predictions. However, several reasons could explain why the interaction was not significant; because this study used a new experimental paradigm, we had little a priori knowledge of the factors that could influence the results. In a series of exploratory analyses, we tried to account for some of these factors.

As indicated by the preliminary analyses, a substantial number of participants reported suspecting that the irrelevant words were important and/or trying to remember the irrelevant words. This could significantly bias the results; to control for this problem, the two-way interaction between working memory capacity and moment of presentation was tested on the sub-sample of participants who did not pay attention to the words and did not suspect the experimental manipulation ( $n = 42$ ). This new analysis yielded very similar results: the main effect of the moment of presentation was significant,  $F(1, 40) = 10.69$ ,  $MSE = 4.55$ ,  $p = .002$ ,  $\eta^2_p = .21$ , but the main effect of working memory capacity was not,  $F(1, 40) = 0.79$ ,  $MSE = 22.92$ ,  $p = .380$ ,  $\eta^2_p = .02$ ,  $r = .14$ , and the two-way interaction was not significant either,  $F(1, 40) = 0.23$ ,  $MSE = 4.55$ ,  $p = .637$ ,  $\eta^2_p = .01$ ,  $r = .08$ .

As we have seen, a significant item effect existed in our sample: certain words were almost always correctly recognized, while other words were almost never recognized by participants. Although this item effect did not interact with working memory capacity, it could blur the effects of interest by introducing residual variance in the analysis. To control for this possibility, an exploratory analysis was carried out with a mixed-model design (using the package *lme4* for R and a restricted maximum likelihood estimation procedure). Both subjects and items were treated as random variables, so as to account for item-related variance. This analysis provided a significantly better fit to the data than a simple model including only subjects as a random variable,  $\chi^2(1) = 265.98$ ,  $p < .001$ ; the results indicated that there was actually more between-items variance ( $\sigma = .026$ ) than between-subjects variance ( $\sigma = .018$ ) in recognition performance. However, working memory capacity still did not interact with the moment of presentation in this analysis,  $\chi^2(1) = 0.64$ ,  $p = .425$ . Overall, the results of this mixed model analysis were comparable to a simpler model including only subjects as a random variable; therefore it was not explored further.

Because the surprise recognition test included both target and distractor words, an effect of working memory capacity could be masked by differences in the response biases of participants. For example, it could be the case that participants with low working memory capacity make as many correct hits but more false alarms than participants with high working memory capacity. A first way to control this problem is to compute a sensitivity index or  $d'$ , as described by the signal detection theory (see Stanislaw & Todorov, 1999); this index takes into account both correct hits and false alarms. We calculated one  $d'$  for words presented during the delay and one  $d'$  for words presented concurrently with the target. With these new dependent variables, the main effect of the moment of presentation was again significant,  $F(1, 73) = 26.57$ ,  $MSE = 0.086$ ,  $p = .520$ ,  $\eta^2_p = .27$ ; the sensitivity index was higher for words presented during the delay ( $M = -0.21$ ,  $SD = 0.43$ ) than for words presented concurrently with the target ( $M = -0.46$ ,  $SD = 0.43$ ). However, the main effect of working memory capacity was still not significant,  $F(1, 73) = 0.11$ ,  $MSE = 0.29$ ,  $p = .743$ ,  $\eta^2_p = .00$ ,  $r = -.06$ , and working memory capacity still did not interact with the moment of presentation,  $F(1, 73) = 0.42$ ,  $MSE = 0.086$ ,  $p = .520$ ,  $\eta^2_p = .006$ ,  $r = -.11$ .

A second way to control for the problem of accuracy on the distractors is to keep the number of correctly identified irrelevant stimuli as a dependent variable, and to include the number of false alarms as a covariable in the analysis. Although less orthodox, this analysis was also performed for exploratory purposes. When accuracy on the distractors was included in the analysis as a covariable, the two-way interaction between working memory capacity

and moment of presentation became significant,  $F(1, 72) = 3.97$ ,  $MSE = 3.99$ ,  $p = .050$ ,  $\eta^2_p = .06$ , congruent with our hypothesis.

### 3.1.4. Discussion

We expected participants using proactive control to devote less attention to irrelevant words presented during the delay of the mental rotation task than to words presented concurrently with the target, whereas we expected participants using reactive control to devote an equal amount of attention to all irrelevant words; as a consequence, we hypothesized that the effect of the moment of presentation on the number of irrelevant words correctly recognized would interact with working memory capacity. The two-way interaction was neither significant in our main analysis, nor in a series of exploratory analyses accounting for various possible issues. The interaction became significant in one exploratory analysis including the number of false alarms as a covariable, congruent with our hypothesis; however, this should not be seen as strong evidence in favour of our hypothesis, both because the effect size was very small despite the effect reaching significance, and because the large number of exploratory analyses run in this experiment means the probability of a type I error was substantially increased. Therefore, the significant result in this exploratory analysis could simply reflect a spurious effect created by adding the covariable to the model. Thus, in the absence of an independent replication of the effect, we can conclude that the results showed weak support for our hypothesis.

There are several possible explanations for this inconclusive result. A first possibility is that our task was simply not an appropriate operationalization of cognitive control. Since we used an innovative experimental paradigm, this suspicion is certainly warranted; however, it is difficult to test without a convergent validity measure. Another possible explanation would be an experimental problem with the paradigm. The set of preliminary analyses indicated that the mental rotation task functioned correctly; in particular, we replicated the well-known effect of the angle of rotation on performance (Shepard & Metzler, 1971). In other words, the weakness of the results is unlikely to be due to a problem with the main task. Participants demonstrated an appreciable level of accuracy in the surprise recognition test – higher than chance, but far from a ceiling effect – suggesting that they memorized some, but not all irrelevant stimuli. Therefore, the problem is not attributable to a lack of sensitivity of our dependent variable either.

The questionnaire indicated that a larger number of participants than expected suspected the experimental manipulation, which may undermine the validity of our paradigm;

however, working memory capacity had no effect on suspicion and restricting the analysis to the participants who did not suspect the manipulation did not alter the results. Participants with low working memory capacity did report a higher tendency to memorize the irrelevant words, but since this was not accompanied by more suspicion, this result may simply reflect the difficulty of these participants to focus on the relevant stimuli in the task (Conway et al., 2001). Additionally, participants with low working memory capacity did not demonstrate a higher recognition performance. In short, the results show no indication that a difference in the perception of the irrelevant stimuli as a function of working memory capacity could have masked the predicted interaction.

One other possible reason why the results were inconclusive is the significant item effect observed in our data, since certain stimuli showed very high or very low recognition rates and there was more experimental variance at the between-items level than at the between-subjects level. During the debriefing, many participants also reported attentional capture from certain words during the mental rotation task; this attentional capture was often attributed to irregularities in the human pronunciation of the words, such as « weird inflections ». Although we tried to control for this problem in a mixed model analysis, a statistical control may prove insufficient in this case: since the number of irrelevant stimuli for each moment of presentation was limited at 20 words per condition, attentional capture by even a few words may be sufficient to mask an effect of working memory capacity.

Overall, the only significant effect of working memory capacity in the protocol was the higher accuracy on the mental rotation task of participants with high working memory capacity. This result might stem from the fact that participants with high working memory capacity implemented proactive control during the delay period of the task and could be seen as congruent with our hypothesis. This interpretation might be correct, but mental rotation is thought to depend on visual working memory for the temporary maintenance of a mental representation of spatial shapes (Hyun & Luck, 2007), and participants with high working memory capacity are typically more efficient in mental rotation tasks even in the absence of a delay period (Kaufman, 2007; Pardo-Vazquez & Fernandez-Rey, 2012). Thus, performance in the mental rotation task probably reflects the contribution of working memory and should not be seen as an index of cognitive control.

In summary, the results of this experiment showed weak support for our hypothesis, with the predicted two-way interaction emerging only in an exploratory analysis including an unplanned covariate. The weakness of this result warranted independent replication in Experiment 2b.

## **3.2. Experiment 2b**

### *3.2.1. Rationale*

The motivation for Experiment 2b arose from the necessity of replicating the significant result observed in an exploratory analysis in Experiment 2a. Experiment 2b constituted a simple replication of Experiment 2a; the main objective was to evidence the two-way interaction between working memory capacity and moment of presentation of the irrelevant words in an independent sample. In order to account for the shortcomings of Experiment 2a, a few changes were also introduced in the experimental paradigm. Firstly, participants completed the AX-CPT along with the rest of the protocol. Performance on the AX-CPT was used as a convergent validity measure to test whether our paradigm actually assessed cognitive control; the difference in the amount of correctly recognized irrelevant stimuli as a function of the moment of presentation was expected to correlate with performance in the AX-CPT. Secondly, the surprise recognition test was modified; instead of viewing a series of words and deciding for each word whether it had been presented during the mental rotation task or not, participants were asked to choose the word they had heard among two alternatives. Using this procedure, the recognition test yielded a single performance measure, effectively removing the need to control for the number of false alarms. Thus, no spurious effect could be created by using the number of false alarms as a covariable as in Experiment 2a. Thirdly, in an effort to reduce the item effect leading to attentional capture that we observed in Experiment 2a, the stimuli were registered by a synthesized rather than a human voice.

### *3.2.2. Method*

#### *3.2.2.1. Participants.*

A sample of 83 participants completed the experiment (17 males and 66 females; age ranging from 17 to 25,  $M = 19.88$ ,  $SD = 1.42$ ). All participants were undergraduate students from the University of Grenoble 2 participating for course credit. The inclusion criteria were identical to Experiment 2a. None of the participants had participated in Experiment 2a.

#### *3.2.2.2. Materials.*

The materials were identical to Experiment 2a with the following exceptions.

**Irrelevant words stimuli.** The words associated with very high ( $n = 4$ ) or very low ( $n = 3$ ) recognition rates in Experiment 2a were replaced with words generated with the same criteria.



The new stimuli are presented in Appendix B, Table B3. Rather than read by a human voice and digitally recorded, words were generated by a vocal synthesis program (*Claire* voice from the Acapela group, retrieved from <http://www.acapela-group.com>) so as to minimize the slight irregularities in pronunciation and prosody that caused attentional capture in Experiment 2a. The distractors were identical to Experiment 2a (see Appendix B, Table B2).

**AX-CPT.** We used a version of the AX-CPT closely based on previous works. The task was an AX-CPT 70, with 70% of AX trials and 10% of each AY, BX and BY trials. Each trial comprised a cue presented for 1000ms, a 1500ms delay, and a probe presented for 1000ms; the ITI was 1000ms. The delay period and the ITI were unfilled (i.e., participants only saw a blank screen). Participants had to respond to each stimulus appearing on the screen – including both cues and probes – by pressing a "target" button (in yellow) or a "non-target" button (in blue); the program registered an error if participants did not respond within 1000ms. Participants were instructed to press the yellow button if the stimulus on the screen was an X probe and the previous cue had been an A, and to press the blue button in all other cases. Participants received an audio feedback after each response (with a "ding" sound indicating a correct response, a "buzz" sound indicating an incorrect response, and a "knock" sound indicating a too slow response). They were instructed to respond as quickly and as accurately as possible.

Our version of the task included two noteworthy features. Firstly, cues were selected from a first set of letters (*E, G, P, R, S, and A*) and probes were selected from a different, non-overlapping set (*F, J, M, Q, U, and X*); the cues were always presented in blue and the probes were always presented in white (as in Henderson et al., 2012). These two controls were used to decrease the role of working memory capacity in the task by helping participants keep track of which stimulus was the cue and which one was the probe within a trial. The letters in each set were chosen to be as visually distinctive as possible from the letters A and X. Secondly, the delay period was shortened in comparison with most AX-CPT studies, which typically use 5000ms delays; shortening the delay to 1500ms allowed us to increase the number of trials. This should not significantly alter the results, as the AX-CPT can function with delays in the range of 1000ms (e.g. Barch et al., 2001; Braver et al., 2005). Importantly, working memory capacity has been observed to correlate with a version of the AX-CPT with a 1000ms delay period (Redick & Engle, 2011); additionally, the effect of working memory capacity in the task does not seem to be modulated by the duration of the delay (Redick & Engle, 2011).

Error rates and median response times were collected for all trial types. Median RTs were computed on correct trials only. The main dependent variable on the task was the

proactive behavioural index (PBI; see Braver et al., 2009); this index was computed for both error rates and median response times by calculating:

$$(\text{Trial}_{\text{AY}} - \text{Trial}_{\text{BX}}) / (\text{Trial}_{\text{AY}} + \text{Trial}_{\text{BX}})$$

The result is an index of the tendency to use proactive control in a participant; a positive value indicates that the participant is less efficient on AY trials than BX trials, a pattern associated with proactive control. Conversely, a negative value indicates reactive control. The PBI was computed separately for error rates and response times; these two values were then standardized and averaged to yield a single composite index. One additional index was calculated using the signal detection theory: the  $d'$ -context, which is hypothesized to provide a measure of the tendency to use contextual information from the cue to drive the answer on the probe (e.g. Barch et al., 2001; Chatham et al., 2009; Redick & Engle, 2011). The  $d'$ -context is computed by opposing hit rates on AX trials to false alarms on BX trials after log-linear correction. Performing this calculation in our data yielded a large number of outlying values; in order to normalize the distribution of scores, a 90% winsorisation was applied to the resulting  $d'$ -context. A log-linear correction was applied on the number of errors prior to calculation of the PBI and the  $d'$ -context to adjust for error rates equal to zero (see Braver et al., 2009); this correction used the following formula:

$$\text{Error rate} = (0,5 + (\text{Error rate} * \text{Number of trials}) ) / (1 + \text{Number of trials})$$

### 3.2.2.3. Procedure.

The procedure was identical to Experiment 2a with the following exceptions. Participants completed the experimental session in groups of 4 to 8 individuals in a university computer room. They completed the mental rotation task, the questionnaire about their perception of irrelevant words, the surprise recognition test, the AX-CPT and the CCS, in order. The whole procedure took approximately 60 minutes.

The mental rotation task was identical to Experiment 2a with one exception: the spatial shapes and the irrelevant stimuli were still presented in pseudo-random order to remove one possible source of residual variance, but this order was changed from Experiment 2a. The questionnaire about irrelevant words was identical to Experiment 2a. The surprise recognition test was modified from Experiment 2a. Instead of presenting all words successively, the test presented pairs of words including one distractor and one irrelevant stimulus. One word was presented on the left and the other on the right of the screen; each word was randomly assigned one of the two positions in each trial. Participants were asked to click on the word that they had heard during the mental rotation task.

In the AX-CPT, participants first completed a series of 10 practice trials with the same trial frequencies as the actual task; the practice session was repeated until participants responded correctly to at least 75% of stimuli. They then completed a series of 110 trials presented in pseudo-random order (with 77 AX trials and 11 of each AY, BX and BY trials). The order was defined so that there were no series of more than five consecutive AX trials or two consecutive trials of another type.

### 3.2.3. Results

#### 3.2.3.1. Preliminary analyses.

Working memory scores were normally distributed and close to the population average ( $M = 0.03$ ,  $SD = 0.73$ , skewness = -0.41, kurtosis = -0.13). A first set of preliminary analyses examining performance on the mental rotation task yielded results similar to Experiment 2a. The second set of preliminary analyses examined answers on the questionnaire concerning the participants' perception of the irrelevant stimuli in the mental rotation task. Overall, 19% of participants reported trying to remember the irrelevant words presented during the task; 41% of participants reported suspecting that the irrelevant words were in fact important. These figures are close to those observed in Experiment 2a. A logistic regression again indicated that working memory capacity did not correlate with the suspicion that words were important,  $\chi^2(1) = 0.77$ ,  $p = .381$ ; however, contrary to Experiment 2a, there was no relationship between working memory capacity and the tendency to try to remember the words,  $\chi^2(1) = 1.27$ ,  $p = .259$ .

The third set of preliminary analyses examined performance on the surprise recognition test. On average, participants correctly classified 77% of the stimuli ( $SD = 7.36$ ), significantly above chance level,  $t(75) = 33.40$ ,  $p < .001$ . The item effect was significant, as in Experiment 2a, but its effect size was about two times smaller,  $F(39, 3920) = 6.07$ ,  $MSE = 0.160$ ,  $p < .001$ ,  $\eta^2_p = .06$ . As in Experiment 2a, the item effect did not interact with working memory capacity,  $F(39, 3480) = 0.73$ ,  $MSE = 0.161$ ,  $p = .891$ ,  $\eta^2_p = .01$ .

The fourth set of preliminary analyses examined performance in the AX-CPT. Descriptive statistics for the task are presented in Table 2. As expected, a significant effect of trial type appeared in the task for both error rates,  $F(3, 234) = 29.68$ ,  $MSE = 0.004$ ,  $p < .001$ ,  $\eta^2_p = .28$ , and RTs,  $F(3, 243) = 90.93$ ,  $MSE = 2474$ ,  $p < .001$ ,  $\eta^2_p = .53$ ; participants were slower and less accurate on AY and BX trials. The reliability of the AX-CPT was also assessed with the split-half method by computing all performance indices separately for odd and even trials and correlating the two values. This method allowed us to estimate the

reliability of complex indices such as the PBIs and the  $d'$ -context, for which a Cronbach's alpha coefficient could not be computed. The corresponding reliability coefficients are presented in Table 3; most coefficients were below the minimum recommended threshold of .70, with slightly higher values for indices calculated on RTs.

Table 2

*Descriptive statistics for the AX-CPT*

Trial type	Average error rate (SD)	Median RT (SD)
AX	.022 (.023)	443 (50)
AY	.065 (.076)	549 (75)
BX	.097 (.102)	457 (94)
BY	.014 (.031)	436 (76)
PBI	0.087 (0.450)	0.098 (0.087)
PBI-comp	0.000 (0.717)	
$d'$ -context	2.76 (0.56)	

*Note.* PBI-comp = average of the two other PBIs after standardization. The average value of the composite PBI is necessarily 0 since it is calculated as the average of two standardized measures.

The fifth set of preliminary analyses examined the relationship between working memory capacity and performance in the AX-CPT. Contrary to our expectations, working memory capacity was correlated neither with the PBI calculated on errors, the PBI calculated on response times, the composite PBI, or the  $d'$ -context, all  $F_s < 1$ . When considering individual trial types, working memory capacity did not correlate with performance on BX or AY trials, either in terms of error rates or response times, all  $F_s < 1$ . A high working memory capacity was associated with marginally faster response times on AX trials,  $F(1, 78) = 3.34$ ,  $MSE = 2453$ ,  $p = .072$ ,  $\eta^2_p = .04$ ,  $r = -.20$ , and BY trials,  $F(1, 78) = 3.22$ ,  $MSE = 5715$ ,  $p = .076$ ,  $\eta^2_p = .04$ ,  $r = -.20$ , but it was not correlated with response times on either AY or BX trials,  $F_s < 1$ . When controlling for performance on BY trials, as in Richmond et al. (2013), all correlations between working memory capacity and performance appeared non-significant for AX, AY and BX trials and for both response times and error rates, all  $F_s < 1$ .

Table 3

*Reliability coefficients for the AX-CPT*

Trial type	Error rate	Median RT
AX	.33	.90
AY	.42	.70
BX	.63	.56
BY	.45	.77
PBI	.42	.48
PBI-comp		.53
$d'$ -context		.59

*Note.* PBI-comp = average of the two other PBIs after standardization.

3.2.3.1. *Main analyses.*

Firstly, we examined recognition performance as a function of the moment of presentation and working memory capacity; we expected the moment of presentation to interact with working memory capacity, as was already our hypothesis in Experiment 2a. Contrary to Experiment 2a, there was no main effect of the moment of presentation,  $F(1, 81) = 0.50$ ,  $MSE = 3.93$ ,  $p = .483$ ,  $\eta^2_p = .01$ : participants recognized as many words presented during the delay ( $M = 17.22$ ,  $SD = 2.01$ ) as words presented concurrently with the target ( $M = 17.42$ ,  $SD = 2.31$ ). As in Experiment 2a, there was no effect of working memory capacity on recognition performance,  $F(1, 81) = 0.12$ ,  $MSE = 5.54$ ,  $p = .729$ ,  $\eta^2_p = .00$ ,  $r = -.04$ . Critically, working memory capacity did not interact with the moment of presentation,  $F(1, 81) = 0.70$ ,  $MSE = 3.93$ ,  $p = .405$ ,  $\eta^2_p = .01$ : there was no correlation between working memory capacity and the difference in the number of recognized stimuli as a function of the moment of presentation,  $r = .09$ , contrary to our hypothesis. As in Experiment 2a, when restricting the analysis to the participants who did not report trying to remember the words or suspecting the experimental manipulation ( $n = 46$ ) the two-way interaction was still non-significant,  $F(1, 44) = 1.15$ ,  $MSE = 5.23$ ,  $p = .288$ ,  $\eta^2_p = .03$ .

Secondly, we expected the difference in recognition performance between words presented during the delay and words presented concurrently with the target to constitute a marker of the tendency to use proactive control; as a consequence, this difference score was hypothesized to correlate with the composite PBI in the AX-CPT. This was not the case,

$F(1, 80) = 0.30$ ,  $MSE = 7.698$ ,  $p = .582$ ,  $\eta^2_p = .00$ ,  $r = .06$ ; in other words, the difference score was not related to the difference between AY and BX trials. The difference score was not correlated either with the PBI calculated on response times, the PBI calculated on error rates, or the  $d'$ -context, all  $F_s < 1$ . The difference score was also unrelated to performance on all trial types in the AX-CPT, be it in terms of accuracy or RTs, all  $F_s < 1$ .

### 3.2.3.3. Complementary analyses.

The difference between the results of Experiment 2a and Experiment 2b could be attributed to a systematic sample bias in working memory. For example, it could be the case that participants in one of the samples had lower average working memory capacity, or that there was less variability in one of the samples; such a bias could selectively increase or decrease effects in one sample. This hypothesis was tested by comparing the distributions of working memory scores in the two experiments. On average, scores on the CCS were equivalent in Experiment 10a ( $M = -0.08$ ,  $SD = 0.74$ ) and in Experiment 10b, ( $M = 0.03$ ,  $SD = 0.73$ ),  $t(157) = -1.00$ ,  $p = .317$ . A Levene test indicated that the variability of scores in both samples was also equivalent,  $F(1, 157) = 0.15$ ,  $p = .698$ . In other words, there were no differences in the distribution of working memory scores between the two samples.

The absence of a two-way interaction between working memory capacity and the moment of presentation in Experiment 2b could be masked by an insufficient number of participants. Because Experiment 2a and Experiment 2b used almost identical procedures, we elected to combine the two datasets in an exploratory analysis so as to increase statistical power. This yielded a significantly larger sample ( $N = 159$ ). We again tested the hypothesis of a two-way interaction between working memory capacity and moment of presentation. The score model included recognition performance as a dependent variable, moment of presentation and working memory capacity as independent variables, and the sample as a controlled variable. The main effect of the moment of presentation was significant,  $F(1, 155) = 13.44$ ,  $MSE = 4.13$ ,  $p < .001$ ,  $\eta^2_p = .08$ , but the main effect of working memory capacity was not,  $F(1, 155) = 0.05$ ,  $MSE = 10.90$ ,  $p = .817$ ,  $\eta^2_p = .00$ ; neither was the two-way interaction between working memory capacity and the moment of presentation,  $F(1, 155) = 0.07$ ,  $MSE = 4.13$ ,  $p = .794$ ,  $\eta^2_p = .00$ , contradicting our hypothesis. Again, even when restricting the analysis to the participants who did not report trying to remember the words or suspecting the experimental manipulation ( $n = 88$ ) the two-way interaction was not statistically significant,  $F(1, 84) = 0.32$ ,  $MSE = 4.96$ ,  $p = .570$ ,  $\eta^2_p = .00$ .

### 3.2.4. Discussion

This replication of Experiment 2a yielded similar results: participants with low working memory capacity did not correctly recognize more words presented during the delay than words presented concurrently with the target of the mental rotation task, when compared to participants with high working memory capacity. Thus, working memory capacity was not related to our proactive control measure. These results support the idea that the significant result observed in an exploratory analysis in Experiment 2a was a false positive<sup>9</sup>.

Combining the samples of Experiment 2a and Experiment 2b and restricting the analysis to the participants who did not suspect the experimental manipulation yielded similar results, suggesting that this failure was not due to a small sample size or to the fact that participants attempted to memorize the words. The item effect was attenuated in Experiment 2b when using words generated through vocal synthesis, and participants reported little attentional capture by the words during the debriefing. In short, our failure to observe the expected interaction does not seem attributable to an easily controlled experimental problem.

Instead, the fact that recognition of the irrelevant words did not correlate with performance in the AX-CPT provides a simple explanation for the unexpected results. If the tendency to use proactive control had been reflected in the difference score for recognized words, then a high difference score should have been associated with higher performance on AY trials and lower performance in BX trials. Because no relationship appeared between recognition performance and the AX-CPT whatsoever, it is likely that our experimental paradigm did not constitute an adequate operationalization of proactive control.

There does not seem to be an easy explanation for why the task did not adequately measure proactive control. Perhaps the mental rotation task was too difficult, leading all participants to adopt a similar strategy of using the delay to carry out mental rotation in advance; this interpretation may be supported by the relatively high error rate in the mental rotation task (up to 42% of errors for the largest angle of rotation). From a theoretical standpoint, perhaps the conceptual analogy between implementing proactive control and using the delay in the mental rotation task to perform mental rotation was unjustified; although this analogy seemed theoretically sound, the fact that the DMC framework has

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<sup>9</sup> A third experiment labeled Experiment 2c, not detailed here, attempted to replicate the results of Experiment 2a with an identical procedure although in a smaller sample ( $N = 48$ ). This time, the interaction between working memory capacity and moment of presentation of the words was not significant, even when controlling for false alarms,  $F(1, 45) = 0.00$ ,  $MSE = 6.17$ ,  $p = .962$ ,  $\eta^2_p = .00$ .

mostly been tested with the AX-CPT means it is difficult to anticipate how proactive and reactive control will translate in different paradigms. In any case, the present results did not suggest an easy way to modify the experimental paradigm so as to obtain a more valid measure of proactive control. Having reached a dead end, we elected to discontinue using this paradigm.

Although not directly relevant to our hypotheses in this study, the fact that working memory capacity did not correlate with the proactive behavioural index in the AX-CPT is worrying; this finding is counter to our thesis and constitutes a failure to replicate previous results in the literature (Redick & Engle, 2011; Richmond et al., 2013; Redick, 2014). This failure was only partial, however. On one hand, we did not observe the expected advantage of participants with high working memory capacity on BX trials (Redick & Engle, 2011; Richmond et al., 2013; Redick, 2104); on the other hand, participants with high working memory capacity were more efficient on AX and BY trials and performed similarly to participants with low working memory capacity on AY trials, exactly as in published articles (Redick & Engle, 2011; Redick, 2014). In other words, our results were congruent with the literature for all trial types except BX trials, which represent only 10% of the task. There were no significant differences in procedures between our version of the AX-CPT and the versions used in previous works that could explain the discrepancy. However, the fact that participants with high working memory capacity only performed better on AX and BY trials in our data sheds some doubt on the conclusion that the relationship observed between working memory and the AX-CPT represents a true difference in cognitive control mechanisms; instead, our results are more congruent with the idea of a nonspecific advantage of participants with high working memory capacity, as suggested in the introduction (pp. 81-82). We set aside this question for the time being, but we will come back to the relationship between working memory capacity and the AX-CPT in Chapter 6 (p. 161).

#### **4. Conclusion**

The two studies presented in this chapter do not provide strong evidence of a relationship between working memory capacity and the tendency to use proactive control. The results of Study 1 were rather promising; they fit rather well with our thesis and could be seen as evidence that working memory capacity is selectively related to the tendency to use proactive control. However, two major problems limit the theoretical impact of these results: first, interpreting them in terms of proactive and reactive control partly relies on the null result observed in Experiment 1a, a null result that was not originally predicted; second, the



superiority of participants with high working memory capacity in Experiment 1b could be attributed to factors other than a higher tendency to use proactive control. As for Study 2, it can be safely concluded that no effect of working memory capacity on our proactive control measures emerged in either Experiment 2a or Experiment 2b. However, because this study used a new experimental paradigm, we cannot rule out the possibility that this null result was simply due to an inadequacy of the mental rotation task; the absence of a correlation between the proactive control measure in the mental rotation task and performance in the AX-CPT supports this interpretation.

In short, neither the partial success of Study 1 nor the failure of Study 2 were entirely conclusive. In the next chapter, we tried to use a different approach by putting aside the idea of operationalizing proactive control as the implementation of preparatory processes; proactive control was instead tested by measuring the influence of contextual information on cognitive processing.

# CHAPTER 5. PROACTIVE CONTROL AS SENSITIVITY TO CONTEXT

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## 1. Overview

This chapter had the same objectives as the previous one: we aimed to develop innovative behavioural measures of the tendency to implement proactive control, and to use these measures to evidence a relationship with working memory capacity. As in Chapter 4, our motivation to develop new paradigms stemmed both from the wish to strengthen the DMC framework with results based on innovative tasks, and from the necessity to bypass the measurement problems raised by classic tasks such as the AX-CPT. Contrary to Chapter 4, however, the two studies presented in this chapter did not use measures based on the preparatory processes associated with proactive control.

As we have seen in the introduction (p. 67), implementing preparatory processes requires some sort of predictive contextual information: in order to implement proactive control and prepare cognitive processing in advance, one needs to be able to anticipate the processing that will be required when the critical event occurs. In the AX-CPT, for example, this predictive contextual information is provided by the identity of the cue: if the cue is a *B*, one can safely prepare a non-target response, and if the cue is an *A*, the high proportion of AX trials means that one can prepare a target response. Thus, proactive control is dependent on the existence of valid contextual information. This notion is intimately tied with the more general definition of proactive control as a top-down, or goal-driven, form of cognitive control: using endogenous representations to guide cognitive processing in a task requires contextual information – such as a precise task goal – to begin with. In contrast, the stimulus-driven nature of reactive control means that contextual information plays a less important role for this mechanism since this information is only selectively retrieved when needed.

This differential reliance on contextual information as a function of cognitive control mechanisms means that the use of contextual information may constitute an index of proactive control: the behavioural responses of participants who use proactive control should depend more on the context than on the features of the target stimulus, and the reverse should be true for reactive control. Accordingly, the two studies presented in this chapter operationalized proactive control as the degree of sensitivity to contextual information.

## 2. Study 3 – Disappearing animals

### 2.1. Rationale

We have seen that proactive control consists in guiding processing in a task on the basis of contextual information. Contextual information may take different forms and may be defined at different conceptual levels as a function of the situation, but the most basic form of contextual information that regulates cognitive processing in a laboratory task is simply the task goal. A subject being confronted with a stimulus in a task – a picture for example – could process this stimulus in a variety of ways and perform a myriad of different actions: he could name the object depicted in the picture, try to memorize its appearance, or rate its aesthetic appeal on a Likert scale, to name just a few. Only the task instructions lead the participant to perform one of these actions rather than another.

The impact of task instructions on the way a subject processes a stimulus is obvious in many cases because they directly influence the actions he performs in response to this stimulus. However, the influence of instructions may be more subtle in certain cases. In a very influential work, Yarbus (1967; see also Tatler, Wade, Kwan, Findlay, & Velichkovsky, 2010) observed that task instructions had an effect on the way a subject explores a visual stimulus. This conclusion was evidenced by recording the eye movements of participants visually exploring the *unexpected visitor* picture (see Figure 12); gaze patterns were significantly altered by the goal that the participant was trying to achieve. For example, the subjects focused their gaze on the faces of characters when trying to infer their age, whereas their eye fixations were evenly distributed across the picture when trying to remember the positions of people and objects in the room (see Figure 12). Yarbus' results were replicated and extended in more recent studies with different materials and more sophisticated statistical analyses (Tatler et al., 2010; Borji & Itti, 2014). Overall, these results demonstrate that the nature of the task goals can affect relatively low-level processes such as visual perception.

Since proactive control consists in the top-down regulation of behaviour and since the task goal is actively maintained by participants throughout the task, the goal precedes the stimulus; in other words, participants actively try to pursue the goal before the stimulus is even presented. As a consequence, task goals may be expected to bear a strong influence on the basic visual processing of a stimulus for participants who use proactive control; to put this differently, the eye movements of participants using proactive control should be mostly driven by the task goals, similar to Yarbus' (1967) observations. On the other hand, participants who use reactive control can be expected to rely on stimulus-driven processing and to only reactivate the task goal when needed; as a consequence, the eye movements of

these participants should depend on the characteristics of the stimulus more than on the task instructions. For example, a visually salient, but task-irrelevant feature in a stimulus should receive more eye fixations from a participant using reactive control than from a participant using proactive control.

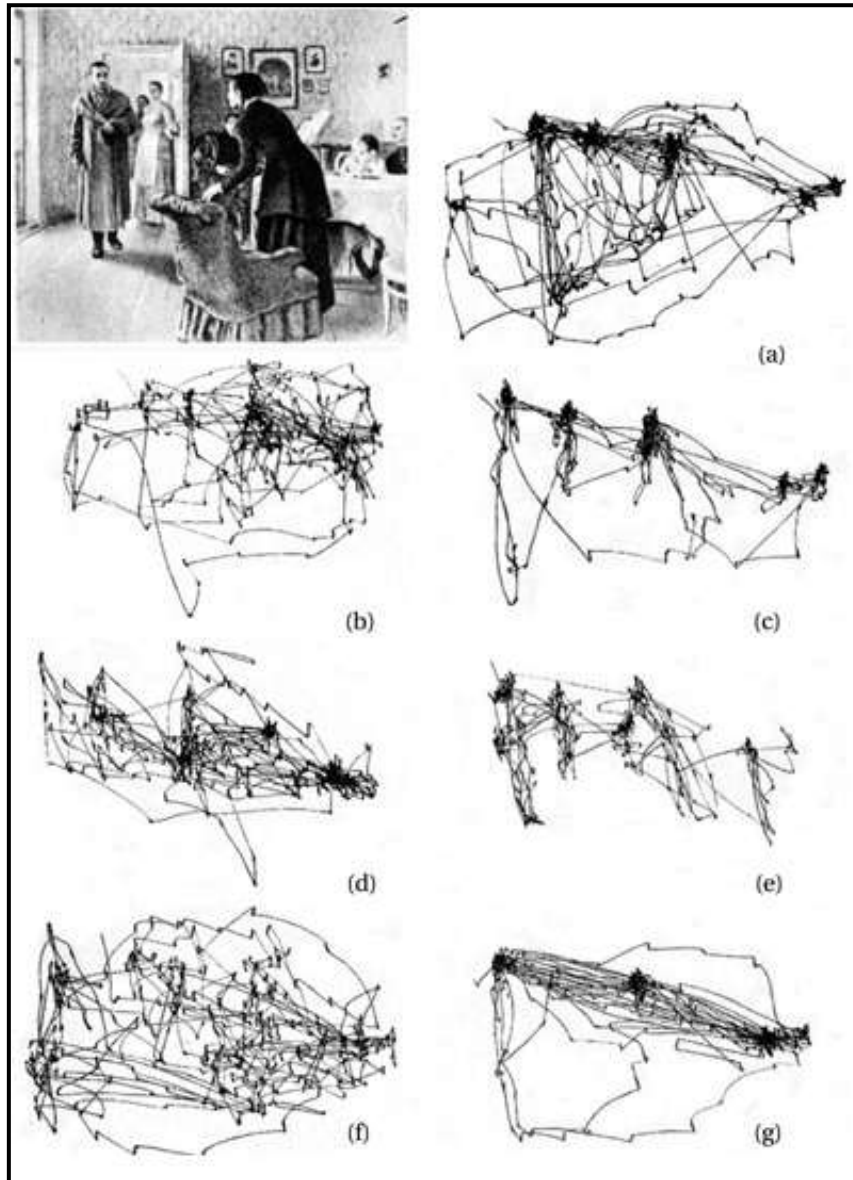


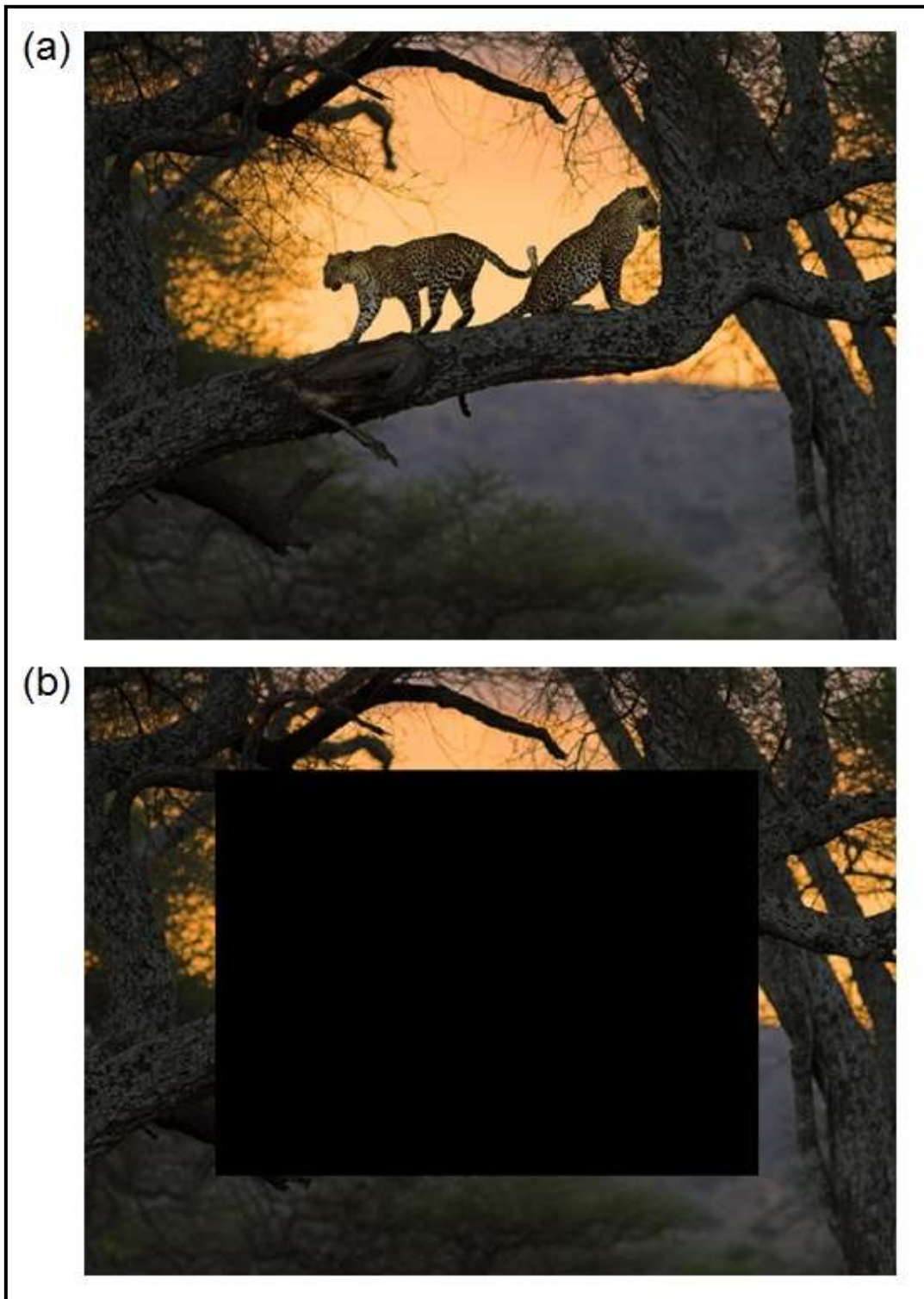
Figure 12. Eye movements of one subject visually exploring the *Unexpected Visitor* picture (top left) with the following instructions: (a) Free examination. (b) Estimate the material circumstances of the family in the picture. (c) Give the ages of the people. (d) Surmise what the family had been doing before the arrival of the "unexpected visitor". (e) Remember the clothes worn by the people. (f) Remember the position of the people and objects in the room. (g) Estimate how long the unexpected visitor had been away from the family. Each record lasted three minutes. From "Yarbus, eye movements, and vision" by B. W. Tatler, N. J. Wade, H. Kwan, J. M. Findlay and B. M. Velichkovsky, 2010, *I-Perception*, 1(1), p. 14. Copyright 2010 by the authors.

This prediction is reminiscent of the results observed with the antisaccade task (Kane et al., 2001; Unsworth et al., 2004; McVay & Kane, 2012a; Unsworth, Redick, et al., 2012): recall that participants with high working memory capacity were more efficient at looking away from a flashing cue (see pp. 47-48), which fits well with the idea that these participants used proactive control and that their eye movements tended to be more goal-driven. Along the same lines, a recent study found that working memory capacity predicted the outcome of visual search in a display, but only when the detection of the target required goal-driven processing, not when the target was a salient feature of the display (Shipstead, Harrison, & Engle, 2012).

In this study, we used this rationale to test the hypothesis that participants with high working memory capacity are more prone to using proactive control. We predicted that participants with high working memory capacity would tend to visually explore only the features of a stimulus that were relevant to the current task, and that they would consequently demonstrate lower ability to remember the irrelevant features of the stimulus. In the first phase of the experiment, we confronted participants with visual stimuli representing animals depicted against a natural background (see Figure 13a). The participants received simple instructions – to identify the animals as fast as possible. We expected participants with high working memory capacity to use proactive control and to focus their gaze on the animals, as per the task goal; on the contrary, we expected participants with low working memory capacity to use reactive control and to make more erratic eye movements, driven by the salient features of the pictures rather than by the task goal. In a second phase of the experimental session, the animals were removed from the pictures, leaving only the backgrounds (see Figure 13b). Participants were asked to complete a surprise recognition test: they had to recognize the pictures presented in the first phase among distractors, using the backgrounds as their only source of information. Since participants with high working memory capacity were expected to have focused their gaze on the animals during the first phase, they were hypothesized to perform worse in the second phase of the experiment and recognize less stimuli. Conversely, participants with low working memory capacity were expected to have looked at various parts of the pictures during the first phase and to perform better in the second phase.

In this experiment, the DMC framework offers an especially powerful test of the hypothesis that working memory is related to cognitive control: if participants with high working memory capacity do perform worse than their counterparts, it will be extremely

difficult to interpret this finding in terms of their higher general cognitive efficiency, better memory abilities or higher processing speed.



*Figure 13.* Example of an animal photograph used in Study 3. (a) The picture appearing in the animals identification task. (b) The same picture appearing in the surprise recognition test, with the animals masked. Source of the photograph unknown, copyright by the original author.

## **2.2. Method**

### **2.2.1. Participants**

A sample of 74 participants completed the experiment (11 males and 63 females; age ranging from 18 to 26,  $M = 21.12$ ,  $SD = 1.43$ ). All participants were undergraduate students from the University of Grenoble 2 or the University of Savoy participating for course credit. Participants were included if they met the following criteria: native French speaker, no history of neurological disorders and without psychoactive medication.

### **2.2.2. Materials**

**Working memory task.** Working memory capacity was measured with the CCS (see Appendix A). The dependent variable on the task was the composite working memory score.

**Animals identification task.** Pictures representing animals were presented serially on a computer screen for 2750ms; they were separated by a 2000ms ITI. The animals were always presented at the center of the pictures (see Figure 13a). Participants were instructed to say aloud the name and the direction faced by the animal (i.e., "right", "left" or "neutral") in each picture as quickly as they could.<sup>10</sup> Response times were recorded for each picture by a microphone fixed on the desk in front of the computer screen and attached to a voice key (E-prime SRBOX device; Schneider, Eschman, & Zuccolotto, 2002).

**Surprise recognition test.** The pictures presented in the animals identification task were modified so that the middle two-thirds of each picture were replaced by a black rectangle, effectively masking the animals (see Figure 13b). These pictures were then intermixed with an equal number of distractors and presented sequentially in a surprise recognition test. Participants were instructed to indicate, for each picture, whether it had been presented in the animals identification task. Performance indices on this task were calculated using the signal detection theory (Stanislaw & Todorov, 1999): we calculated a sensitivity index or  $d'$ , corresponding to the participant's ability to discriminate between targets and distractors, and a

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<sup>10</sup> These parameters were chosen after pilot testing on five subjects. The results of the pilot testing suggested that a presentation time of at least 2000ms was necessary to allow for above-chance performance in the surprise recognition test. However, the results also indicated that participants were able to name the animals in only a few hundreds of milliseconds. As a consequence, the instructions regarding the direction faced by the animals were added to the task so as to introduce a second processing requirement besides naming the animals. The objective was to force participants to consider the animal for a longer duration, instead of freely looking at the rest of the picture.

bias index or  $C$ , corresponding to the participants' tendency to classify any picture as having been presented during the animals identification task regardless of it being a target or a distractor.

**Animal pictures stimuli.** Two sets of 31 pictures of animals were used as stimuli for the tasks. One set of pictures was presented in the animals identification task and the other set was used for distractors in the surprise recognition test; the two sets were counterbalanced across participants. Both sets included the same animals (in other words, every animal appearing in one set also appeared in the other set); this prevented participants from using contextual clues to guide their answers during the surprise recognition task (for example, they could not answer "yes" when confronted to an underwater landscape in the surprise recognition test because they remembered seeing a dolphin, since both sets included a dolphin). Participants were informed of this detail prior to the recognition test.

All animal pictures were selected from various photographic databases using the same criteria. The pictures had to be colour photographs with at least 1024x768 resolution; they had to represent one or several animals of the same species. All selected photographs depicted different animals belonging to taxa as diverse as possible (for example, the pictures included a starfish, a snail, an eagle, an ape, a penguin, a shark and an elephant); the animals had to be subjectively easy to identify. The animals had to occupy as much surface as possible in the middle two-thirds of the picture; however, the remaining surface of the picture (one-sixth on each side) had to contain only the background. The backgrounds of the pictures were chosen to be as diverse and as characteristic as possible so as to facilitate recognition (for example, the pictures included a field of yellow flowers and a misty mountain at dusk); however, they did not include salient or unique features such as manmade objects that could have guaranteed later recognition.

### *2.2.3. Procedure*

Participants completed the experiment individually in a testing room equipped with a computer, a 19 inches LCD screen, a microphone fixed on the desk, and headphones for phonic isolation. All participants provided written informed consent prior to the experimental session. Study 3 and Study 4 were completed during the same testing session; participants completed the animals identification task and the surprise recognition task for Study 3, the procedure for Study 4, and the working memory task, in order. The whole process took approximately 60 minutes.



The experimental session began with calibration of the microphone; the sensitivity of the device was set up individually for each participant so that they did not need to keep in mind the necessity of raising their voice. Participants completed 31 trials of the animals identification task with one set of pictures as stimuli; they then completed 62 trials of the surprise recognition test with the other set serving as distractors. As in Study 2, the pictures were presented in the same pseudo-random order for all participants in both the animals identification task and the surprise recognition test, so as to eliminate one possible source of between-subjects variance.

After the surprise recognition test, participants completed the task for Study 4, the CCS, and then received a short debriefing (including the explicit instruction not to tell other students about the content of the experimental session).

## **2.3. Results**

### **2.3.1. Preliminary analyses**

Working memory scores were normally distributed and close to the population average ( $M = -0.01$ ,  $SD = 0.69$ , skewness =  $-0.22$ , kurtosis =  $-0.88$ ). On average, participants named the animals in the pictures in 1113ms ( $SD = 184$ ); identification times were equivalent for the two pictures sets,  $F(1, 72) = 0.47$ ,  $MSE = 34180$ ,  $p = .497$ ,  $\eta^2_p = .01$ . A high working memory capacity was not predictive of faster identification times,  $F(1, 72) = 0.32$ ,  $MSE = 34248$ ,  $p = .578$ ,  $\eta^2_p = .00$ ,  $r = .07$ . Although the verbal responses on the identification task were not recorded, participants made virtually no mistake throughout the task; only two pictures (a marmot and a raccoon) proved difficult to identify and elicited numerous errors.

As for the recognition phase, participants correctly identified 66% of stimuli on average ( $SD = 6.93$ ); this was significantly above chance level,  $t(73) = 20.08$ ,  $p < .001$ . The average correct recognition rate for stimuli seen during the animals identification task was 54% ( $SD = 11.06$ ), significantly above chance level,  $t(73) = 3.19$ ,  $p = .002$ ; the average correct rejection rate for distractors was 78% ( $SD = 11.80$ ), also significantly above chance level,  $t(73) = 20.59$ ,  $p < .001$ . None of these proportions differed as a function of the pictures set, all  $F_s < 1$ . An approximately normal distribution was observed for the two indices of performance in the task, the  $d'$  ( $M = 0.80$ ,  $SD = 0.39$ , skewness =  $0.73$ , kurtosis =  $0.67$ ) and the  $C$  ( $M = 0.45$ ,  $SD = 0.46$ , skewness =  $-0.35$ , kurtosis =  $2.07$ ).

### 2.3.2. Main analysis

Our main hypothesis was that a high working memory capacity would be associated with lower recognition performance. This hypothesis was tested in a score model controlling for the pictures set viewed in the animals identification task. No correlation appeared between working memory capacity and  $d'$  values,  $F(1, 68) = 0.23$ ,  $MSE = 0.135$ ,  $p = .633$ ,  $\eta^2_p = .00$ ,  $r = .06$ . This result is represented in Figure 14.

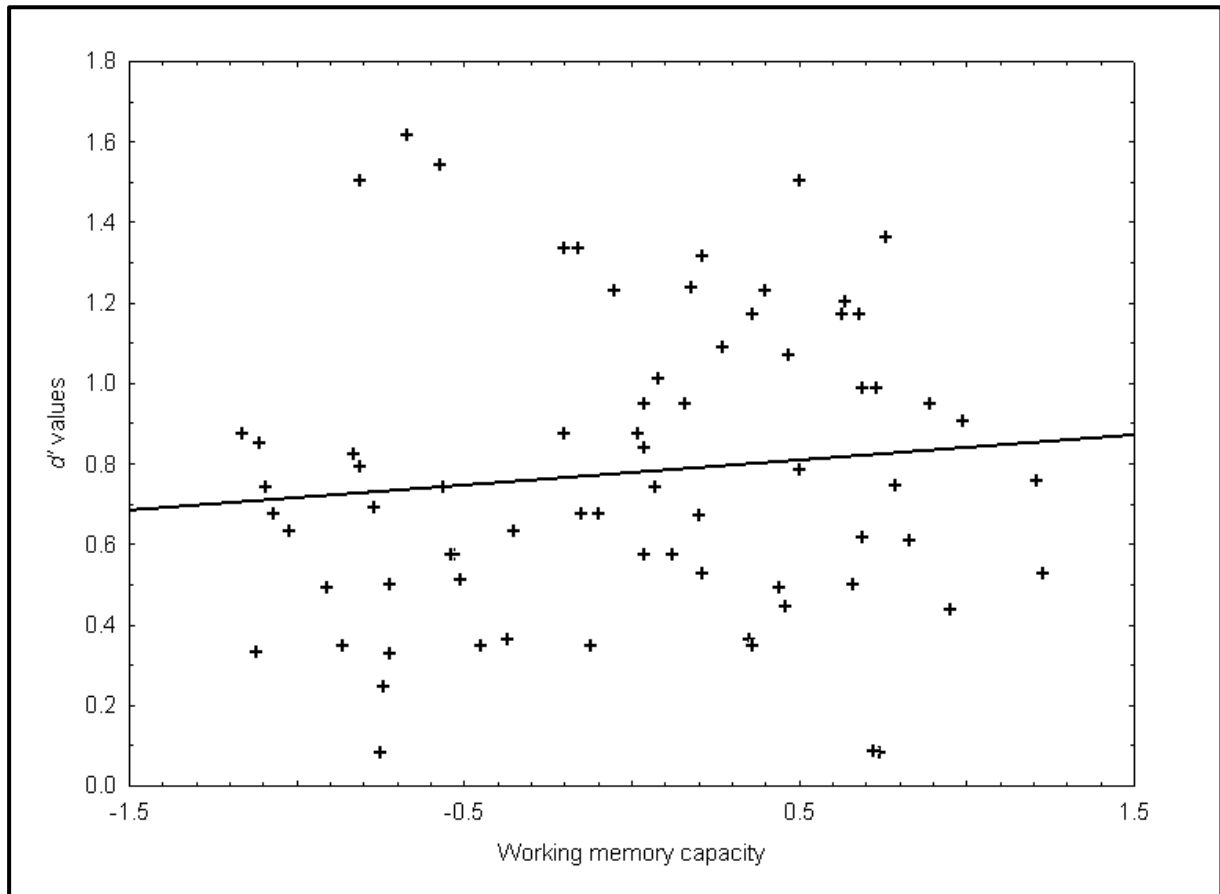


Figure 14. Correlation between working memory capacity and  $d'$  values in the surprise recognition task.

### 2.3.3. Complementary analyses

Differences in identification times could be expected to mask an effect of working memory capacity on recognition performance by giving more time to certain participants to process and memorize the pictures. However, the correlation between working memory capacity and  $d'$  values was still non-significant when adding identification times as a covariable in the score model,  $F(1, 64) = 0.24$ ,  $MSE = 0.142$ ,  $p = .624$ ,  $\eta^2_p = .00$ ,  $r = .07$ . Although not directly relevant to our hypothesis, the relationship between working memory

capacity and response bias was also tested to ensure that a difference in sensitivity was not masked by a difference in response bias. The correlation between working memory capacity and response bias was not significant,  $F(1, 67) = 0.30$ ,  $MSE = 0.200$ ,  $p = .584$ ,  $\eta^2_p = .00$ ,  $r = .07$ .

## **2.4. Discussion**

In this study, we tested the hypothesis that participants with high working memory capacity would use proactive control to process only the relevant parts of visual stimuli and that they would consequently demonstrate a lower ability to recognize the stimuli based on their irrelevant features. Contrary to this hypothesis, working memory capacity had no effect on recognition performance. Thus, the behaviour of participants with high working memory capacity did not seem to be more guided by contextual information.

As in Study 2, the fact that we used an innovative experimental paradigm means that this null result is not necessarily indicative of the absence of a link between working memory capacity and proactive control. Instead, it is very possible that this failure was due to a problem with the paradigm, and that the ability to recognize the backgrounds of the pictures in the second phase of the experiment did not adequately assess proactive control. Several reasons could explain why this may be the case.

Since participants identified the animals in about 1100ms on average while the pictures were presented for 2750ms, it could be argued that all participants had a lot of time to freely explore the pictures, leading both participants using reactive control and participants using proactive control to process the irrelevant features of the stimuli and eliciting comparable memory performance. However, three arguments suggest that this interpretation is incorrect. First, the microphone directly triggered when participants started speaking, but saying the whole answer aloud required several hundreds of milliseconds. Second, the behaviour of participants during the experiment was not congruent with the idea that they freely explored the pictures: they typically named the animal as fast as possible and used the remainder of the presentation time to correct their answer or discuss the exact breed of the animals. Third, the correct recognition rate of participants in the second phase was barely above chance level for pictures presented during the first phase, implying that they did not overall remember the pictures very well and that they mainly looked at the animals in the first phase. Therefore we do not believe this possibility to be likely.

A first plausible possibility is that task goals do not have a strong enough influence on eye movements to elicit an effect on memory performance. Several authors, using procedures

analogous to those of Yarbus (1967), have reported that the effect of instructions on eye movements is typically small (Greene, Liu, & Wolfe, 2012; Borji & Itti, 2014). If participants with high working memory capacity do have a higher tendency to use proactive control, but the difference with participants with low working memory capacity is not very marked, and if the effect of using proactive or reactive control on eye movements is also small, then it is not too surprising that no effect on memory performance emerges in this type of paradigm.

A second possibility is that proactive and reactive control did not actually lead to different gaze patterns in the task. Our hypothesis was that participants using reactive control would tend to look at the salient features of the stimuli rather than follow the task goal. However, since the animals were centrally presented and occupied the two-thirds of the pictures and since the backgrounds were devoid of unique features, it could be argued that the animals were actually the most salient features of the stimuli. In this sense, it is possible that participants with high working memory capacity did make more goal-driven eye movements, but that both goal-driven and stimulus-driven strategies led participants to process the same portion of the pictures. If all participants mainly looked at the animals during the first phase of the experiment, then no differences in recognition performance would be expected in the second phase.

A third possibility is that the results were blurred by the overall better memory performance of participants with high working memory capacity. Indeed, it is possible that participants with high working memory capacity used more proactive control and looked more at the animals and less at the background, but that they still remembered what little they saw better than participants with low working memory capacity. In other words, it is possible that all participants demonstrated comparable recognition performance, but that this performance stemmed from qualitatively different processes, with participants with low working memory capacity looking at the whole picture but demonstrating poor memory performance and participants with high working memory capacity looking mainly at the animals but demonstrating better memory performance.

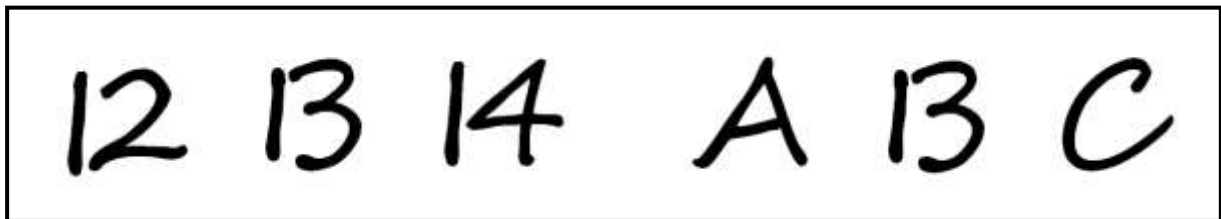
In any case, the data did not provide a direct explanation for the failure of this experiment. The fact that animals were the most salient feature in the pictures could have been corrected in a follow-up experiment, but the other problems could hardly have been fixed. Thus, in the absence of an easily feasible solution, we elected to discontinue using this experimental paradigm – similar to Study 2.

### 3. Study 4 – Ambiguous figures

#### 3.1. Rationale

Ambiguous figures are a form of optical illusion in which the same features of an image can be interpreted in different ways. This results in the same pictorial elements of an image forming different figures (see G. M. Long & Toppino, 2004, for a review on perceptual processes in play with ambiguous figures). One classic example of ambiguous picture is Rubin's vase, in which the observer can perceive either a vase or two faces.

The effect of context on the perception of ambiguous picture is well-known. In a seminal study, Bruner and Minturn (1955) observed that presenting the same symbol in two different contexts influences the way it is perceived, as illustrated in Figure 15. The same effect is observed when an ambiguous picture appears after a series of non-ambiguous pictures presented successively. For example, Bugelski and Alampay (1961) used an ambiguous picture that could be perceived either as a rat or as the face of a man. They observed that presenting the ambiguous picture after a series of non-ambiguous animal pictures (such as a cat, a dog and a fish) led most participants to perceive the rat, whereas presenting the ambiguous picture after a series of face pictures (such as a baby, an old woman and a young girl) led most participants to perceive the man's face.



*Figure 15.* Illustration of the effect of context on the perception of an ambiguous figure. The same symbol is read as either "13" or "B" depending on the surrounding stimuli. After "Perceptual identification and perceptual organization" by J. S. Bruner and A. Minturn, 1955, *Journal of General Psychology*, 53.

It could be argued that the effect of context is due to perceptual similarities between one of the two figures in the ambiguous picture and the preceding non-ambiguous stimuli. In the Bugelsky and Alampay study (1961) for example, one could think that all the pictures of faces share certain perceptual traits, and that viewing a series of faces primes participants to focus on these traits in the ambiguous pictures, which biases their perception. However, there is strong evidence that the biasing effect of surrounding information is actually due to the creation of a true semantic context by participants, rather than a simple perceptual priming

effect. For example, one study used the rat/man ambiguous picture and had participants listen to a taped message discussing the life conditions of rats (Liu, 1976). These participants were biased towards perceiving the rat in the ambiguous figure, despite the man being the most prevalent perception in control subjects. Thus, it seems that participants use abstract contextual information to guide their perception of the ambiguous picture.

The effect of context on perception is generally labeled as a "top-down effect". Although well-described, it is not the only determinant of perception in ambiguous figures: bottom-up mechanisms also play a role (see G. M. Long & Toppino, 2004, for a review). For example, varying certain features of the stimulus, such as luminance or completeness of the figure, influences which figure is perceived (G. M. Long & Toppino, 2004). Both the top-down and bottom-up mechanisms operate in parallel and affect perception of the ambiguous figures (Intaitė, Noreika, Šoliūnas, & Falter, 2013). As can be seen, determinants of perception in ambiguous figures bear a strong conceptual similarity with the DMC framework: context-driven and stimulus-driven mechanisms coexist, reminiscent of proactive and reactive control. A logical corollary is that the perception of participants using proactive control should be influenced by the context of presentation at a higher degree than the perception of participants using reactive control. On the other hand, the perception of participants using reactive control should be more strongly influenced by features of the stimuli.

In this experiment, we tried to take advantage of the effect of context on the perception of ambiguous figures to obtain a measure of proactive control. The rationale was the same as in Bugelski and Alampay (1961): ambiguous pictures were presented without warning after a series of non-ambiguous pictures designed to create a context. The non-ambiguous pictures belonged to one of two main categories corresponding to the two figures represented in the ambiguous image. These two categories had different frequencies so that the context favoured one of the figures over the other. The participants' task was to categorize the stimuli; their first response to the ambiguous picture was recorded and classified as either congruent with the context or not. Participants with high working memory capacity were hypothesized to use proactive control, to guide their perception with contextual information, and to perceive the figure most congruent with the context in the ambiguous picture. On the other hand, participants with low working memory capacity were hypothesized to use reactive control, to be more influenced by features of the stimuli, and to perceive the ambiguous figure less as a function of the context.

The main point of this paradigm is that there is no correct answer to the ambiguous picture: both figures are actually contained in the picture and both possible perceptions are equally valid. In this context, the DMC framework does predict a difference in response patterns as a function of working memory capacity, but no difference in efficiency. As in Study 2 and Study 3, this prediction is especially interesting in that results congruent with our hypotheses may not be interpreted in terms of a higher performance for participants with high working memory capacity.

### **3.2. Pre-test experiment**

A pilot experiment was set up so as to select the ambiguous pictures for the main task. This pilot experiment was required for three reasons. First, it was necessary to select ambiguous pictures in which participants could reliably perceive two different figures; a picture where one of the two figures was so salient that all participants gave the same answer would have been of no use to the experiment. Second, we needed to ensure that there were no baseline differences between the answers of participants as a function of working memory capacity; in other words, we needed pictures in which participants with low working memory capacity would tend to see the same figure as participants with high working memory capacity in the absence of a biasing context. Third, we needed to determine which of the two possible answers in a picture was the most prevalent; the objective was to use contextual information to bias participants towards the other, less frequent answer, so as to increase the sensitivity of the paradigm in the main experiment. This necessity was motivated by the observation that the context effect can reinforce the perception of the least salient figure, but has little effect on the perception of the most salient figure (e.g. Bugelski & Alampay, 1961; Goolkasian, 1987). In most ambiguous pictures, one of the figures emerges from a global view of the image while the other is tied to local details (see Figure 16 for examples). We expected answers relative to the global figure to be more prevalent, due to the well-known global precedence effect (Navon, 1977).

All stimuli were selected with the same constraints: they had to be ambiguous pictures of subjectively high visual quality with at least 1024x768 resolution; each picture had to include two easily identifiable figures; and the two figures had to be reversals of one another – in other words, the two figures had to be constructed from the same image components and to be distinguished only by the interpretation of these components. This set of constraints proved surprisingly difficult to follow: in most available ambiguous pictures, one of the two figures appeared obvious while the other was much harder to perceive. Five ambiguous

pictures were selected for use in the pre-test. The pictures were resized so that they occupied the full height of the computer screen used for pilot testing.

The pilot experiment was carried out in the same testing session as Experiment 2a, after the debriefing for the main experiment. Since Experiment 2a measured working memory with the CCS, the participants' answers on the pre-test experiment could be matched with their working memory capacity. Each participant received the following instructions: « Tell me, as fast as possible, the first thing that you see in these pictures. » The ambiguous pictures were then presented sequentially on a computer screen; the participants' first answer for each picture was manually recorded by the experimenter. These answers were classified as relative to either the global or the local figure.

A sample of 53 participants completed the pilot study. Three of them were excluded from data analysis because they could not reliably identify one figure in the ambiguous pictures; thus, the final sample comprised 50 participants. For each ambiguous picture, we computed the percentage of participants who first perceived the global figure. For one of the five ambiguous pictures, the participants did not demonstrate a strong bias towards one of the two possible answers ( $M = 58\%$ ,  $SD = 50$ ); they had significant difficulties detecting the global figure in another ( $M = 20\%$ ,  $SD = 40$ ). The three remaining pictures are presented in Figure 16. For all three pictures, the participants demonstrated the expected bias towards perceiving the global figure (for *Family of birds*,  $M = 74\%$ ,  $SD = 44$ ; for *Berggeist*,  $M = 84\%$ ,  $SD = 37$ ; for *Mouth of the flower*,  $M = 78\%$ ,  $SD = 42$ ). Logistic regressions indicated that the probability of perceiving the global figure first did not vary as a function of working memory capacity (for *Family of birds*,  $\chi^2(1) = 1.26$ ,  $p = .26$ ; for *Berggeist*,  $\chi^2(1) = 2.45$ ,  $p = .12$ ; for *Mouth of the flower*,  $\chi^2(1) = 1.90$ ,  $p = .17$ ). These three pictures were retained for use in the main task.

### **3.3. Method**

#### **3.2.1. Participants**

A sample of 64 participants completed the experiment (9 males and 55 females; age ranging from 18 to 26,  $M = 20.50$ ,  $SD = 1.43$ ). All participants were undergraduate students from the University of Grenoble 2 or the University of Savoy participating for course credit. Participants were included if they met the following criteria: native French speaker, no history of neurological disorders and without psychoactive medication.



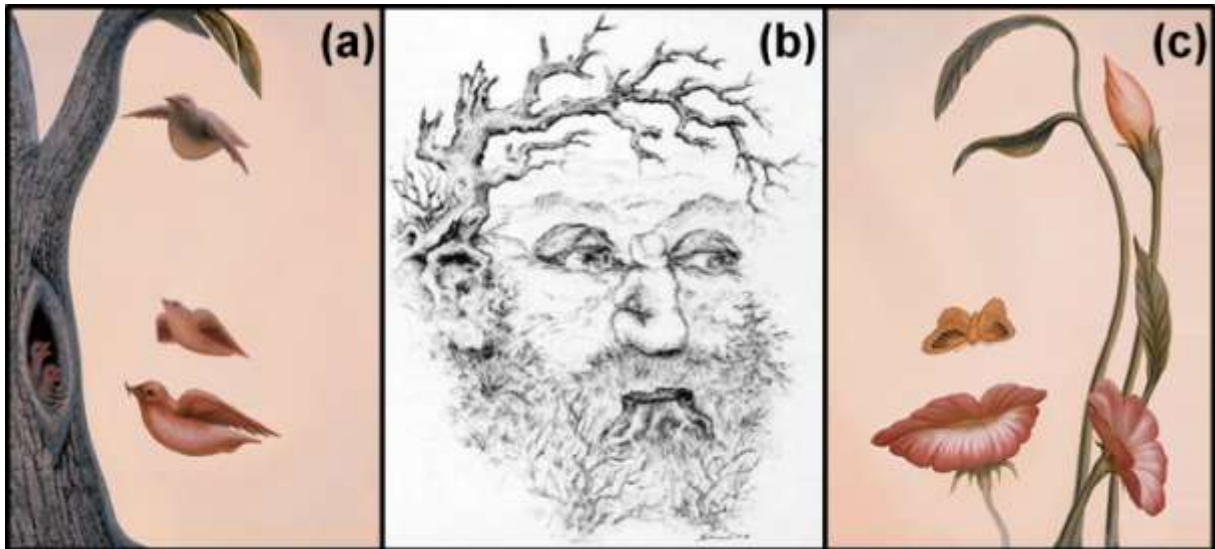


Figure 16. Ambiguous pictures retained for use in Study 4. (a) *Family of birds*, by O. Ocampo; (b) *Berggeist* [Spirit of the mountain], by S. Del Prete; (c) *Mouth of the flower*, by O. Ocampo. Copyright 2014 by the authors.

### 3.2.2. Materials

**Working memory task.** Working memory capacity was measured with the CCS (see Appendix A). The dependent variable on the task was the composite working memory score.

**Pictures classification task.** The main task confronted participants with series of pictures appearing in quick succession. Each series comprised 60 non-ambiguous pictures followed by one ambiguous picture. The task included three series of pictures – one for each ambiguous image retained in the pre-test experiment. In other words, participants saw a total of 183 pictures divided into three series of 61 pictures. The order of the series was counterbalanced across participants. Within each series, all non-ambiguous pictures belonged to one of three categories: one category corresponding to the local figure in the ambiguous picture (for example, birds for *Family of birds*), one category corresponding to the global figure (faces for *Family of birds*) and a third category independent of the ambiguous picture (images of space in all three series). The names of the three categories were specified to the participant at the beginning of each series; all names were two-syllable words (for example, the three categories were named "oiseau", "visage" and "espace" [bird, face and space] for *Family of birds*).

Importantly, the non-ambiguous stimuli in a series had unbalanced frequencies: stimuli from the category matching the local figure in the ambiguous picture were twice as frequent as stimuli from the category matching the global figure. In other words, the series for *Family of birds* contained twice as many birds as faces. More specifically, there were 15 stimuli of the global category, 30 stimuli of the local category, and 15 neutral stimuli in each

series. The non-ambiguous stimuli in a series were presented in the same pseudo-random order for all participants; we ensured that there were no successions of more than three pictures belonging to the same category. The last two stimuli of a series before the ambiguous picture appeared were always neutral images of space to avoid a priming effect on the ambiguous picture itself. The antepenultimate stimulus was always a face.

The pictures appeared at the center of the screen in quick succession. Participants were instructed to classify each picture in one of the three categories by saying its name out loud (for example, "oiseau" [bird]), as fast as possible. The instructions emphasized speed over accuracy so as to avoid any hesitations; participants were also instructed that they had to classify each picture into one category and that they were not allowed to answer "I don't know" or "both". A microphone attached to a voice key was placed on the desk in front of the participants (E-prime SRBOX device; Schneider et al., 2002); each picture disappeared from the screen as soon as the microphone detected an answer, and the next picture appeared after a 1000ms ISI. The ambiguous pictures appeared normally at the end of their respective series without a warning or any distinguishing feature; participants were not informed beforehand that certain pictures would be ambiguous. Participants' responses on the ambiguous pictures were manually coded by the experimenter and their response times were recorded by the microphone; no data was collected for the non-ambiguous pictures forming the rest of the series. At the end of the task, a context score was calculated as the number of ambiguous pictures classified in the category congruent with the context by the participant (in other words, the number of times when the participant's first percept in the ambiguous picture was the local figure); this score varied between zero and three.

**Non-ambiguous stimuli for the classification task.** Non-ambiguous pictures were selected from various image databases. All pictures had to occupy the full height of the screen with 1024x768 resolution; they had to represent one object falling into one of the relevant categories. In order to create contextual information based on the semantic content rather than the perceptual aspect of the images, we ensured that the pictures were perceptually varied. All categories of images included 50% of photographs and 50% of drawings; the proportions of coloured and black-and-white pictures were as balanced as possible. The other features of the pictures were varied as a function of the category. For example, half the pictures of faces represented men and the other half represented women; half the pictures of birds represented one bird and the other half represented multiple birds or even a flock, and the birds were selected among as many different species as possible. All pictures of space represented

complex celestial objects such as nebulae and galaxies so as to maintain the same level of perceptual complexity as other categories.

### 3.2.3. Procedure

Participants completed the experiment individually in a testing room equipped with a computer, a 19 inches LCD screen, a microphone fixed on the desk, and headphones for phonic isolation. All participants provided written informed consent prior to the experimental session. Study 3 and Study 4 were completed during the same testing session; participants completed the whole procedure for Study 3, then the pictures classification task for Study 4 and the working memory task, in order. Participants were explicitly instructed that the procedure for Study 4 bore no relationship to Study 3 and that there would be no surprise recognition test for stimuli presented during Study 4. The whole procedure took approximately 60 minutes. Participants received a short debriefing at the end of the session, including the instruction not to tell other students about the content of the experiment.

## 3.4. Results

### 3.4.1. Preliminary analyses

Working memory scores were normally distributed and close to the population average ( $M = 0.01$ ,  $SD = 0.70$ , skewness =  $-0.26$ , kurtosis =  $-0.84$ ). Classification times were trimmed for the preliminary analyses, with response times more than 2.5 standard deviations from the average removed from the sample; this concerned less than 5% of observations for each ambiguous picture. On average, participants classified the ambiguous pictures in 722ms ( $SD = 328$ ). Classification times differed marginally as a function of the ambiguous picture,  $F(2, 114) = 3.01$ ,  $MSE = 64630$ ,  $p = .053$ ,  $\eta^2_p = .05$ ; they were slightly slower for *Mouth of the flower* ( $M = 754$ ,  $SD = 346$ ) than for *Family of birds* ( $M = 654$ ,  $SD = 260$ ) and *Berggeist* ( $M = 652$ ,  $SD = 265$ ). Classification times were not affected by the order in which the series were presented, all  $F_s < 1$ .

The percentage of participants perceiving the global figure was calculated for each ambiguous picture for comparison with the pre-test data. Overall, the global figure was perceived by 47% of participants ( $SD = 50$ ) in *Family of birds*, by 88% of participants ( $SD = 33$ ) in *Berggeist*, and by 54% of participants ( $SD = 50$ ) in *Mouth of the flower*. One sample  $t$ -tests indicated that these proportions were significantly lower than in the pre-test experiment for *Family of birds*,  $t(63) = 4.31$ ,  $p < .001$ , and *Mouth of the flower*,  $t(63) = 5.21$ ,  $p < .001$ , suggesting that the context manipulation was successful in reinforcing perception of

the local figure in these two pictures. However, this was not the case for *Berggeist*,  $t(63) = -0.84$ ,  $p = .404$ . The latter picture was therefore removed from all subsequent analyses.

The percentage of participants perceiving the global figure was not affected by the order in which the series were presented for *Family of birds*,  $F(1, 62) = 0.11$ ,  $MSE = 2566.1$ ,  $p = .744$ ,  $\eta^2_p = .00$ ; however, participants were marginally more likely to perceive the global figure in *Mouth of the flower* when it was presented last,  $F(1, 62) = 3.77$ ,  $MSE = 2411.4$ ,  $p = .057$ ,  $\eta^2_p = .06$ .

### 3.4.2. Main analysis

Our main hypothesis was that a high working memory capacity would be associated with a higher context score, or a higher tendency to perceive the ambiguous picture in a way congruent with the context. This hypothesis was tested with a polytomous logistic regression, with a score model including the order of presentation of the series as a controlled variable. Working memory capacity was not associated with the context score,  $\chi^2(1) = 1.35$ ,  $p = .245$ , contrary to our hypothesis.

### 3.4.3. Complementary analyses

It could be the case that participants using proactive control were more likely to use contextual information to guide their perception, but that participants using reactive control selectively reactivated contextual information in a bottom-up manner when confronted with the ambiguous picture. In that case, both groups of participants should differ in terms of response times. In practice, a high working memory capacity was not associated with faster response times, incongruent with this hypothesis,  $F(1, 62) = 0.72$ ,  $MSE = 192864$ ,  $p = .398$ ,  $\eta^2_p = .01$ .

As we have seen in the preliminary analyses, the order of presentation of the series had an effect on perception of the global figure, at least for *Mouth of the flower*. This finding may be explained by the fact that the presence of an ambiguous picture at the end of a series was no longer a surprise for participants after the first time, or by the fact that faces became the most prevalent stimulus over the course of the task because they appeared in all three series. To control for both these problems, the relationship between working memory capacity and the context score was tested again, this time only taking into account the participant's answer on the first presented ambiguous picture. A logistic regression indicated that the relationship between working memory capacity and the context score was again non-significant,  $\chi^2(1) = 0.02$ ,  $p = .88$ .

### **3.5. Discussion**

In this study, we tried to test the hypothesis that participants differ in their perception of ambiguous pictures as a function of their working memory capacity. We hypothesized that participants with high working memory capacity would tend to use proactive control and that their perception of ambiguous pictures would be guided by contextual information, whereas participants with low working memory capacity would tend to use reactive control and answer as a function of salient features of the stimuli. Our hypotheses were not supported by the data; working memory capacity was not related to the effect of context on perception.

The preliminary analyses indicated that our contextual manipulation did affect the participants' perception, as evidenced by the fact that they were more likely to answer in a way congruent with the context in the main experiment than in the pre-test. Thus, it seems that perception of the ambiguous pictures did index the influence of context on perception. The null result was presumably not due to a lack of statistical power either, since participants with high working memory capacity had a descriptively lower context score than participants with low working memory capacity. In short, it seems to be the case that working memory capacity was genuinely unrelated to the effect of context on perception.

It could be the case that both participants using reactive control and participants using proactive control used contextual information to bias their perception of the ambiguous picture: the DMC framework does not suggest that only proactive control makes use of contextual information; instead, it suggests that proactive control is much more reliant on contextual information but that reactive control also requires some context. Indeed, the framework predicts that participants using reactive control reactivate contextual information in a bottom-up manner whenever they detect significant conflict. Thus, it may be the case that the ambiguous pictures elicited significant conflict in participants, prompting those using reactive control to resort to contextual information to resolve this ambiguity. However, there are two problems with this interpretation: the fact that classification times on the ambiguous pictures were descriptively fast, suggesting that participants processed them as they would have for non-ambiguous pictures, and the fact that response times were unrelated to working memory capacity.

There does not seem to be an easy explanation for the failure of this study. As for Study 2 and Study 3, it may be attributed to problems with the experimental paradigm rather than the falsity of our thesis. At any rate, however, we can safely conclude that participants with high working memory capacity did not demonstrate a higher sensitivity to contextual information in this study. Unfortunately, there seemed to be no easy way to modify the task:

we could have increased the number of series, but the interaction with the order of presentation meant that only answers on the first trial were truly reliable; we could have tried to use the context to bias participants towards perceiving the local figure rather than the global figure, but results in the literature suggest that the context has no effect on perception of the most salient figure (Bugelski & Alampay, 1961; Goolkasian, 1987); there were no others easily available ambiguous pictures that matched the constraints of the experiment. Facing yet another dead end, we discontinued using this paradigm, just as in Study 2 and Study 3.

#### **4. Conclusion**

The two studies presented in this chapter did not allow us to evidence a relationship between working memory capacity and the tendency to use proactive control. The fact that both studies used novel experimental paradigms, combined with the complete lack of significant results, makes interpretation difficult. Just as Study 1 in the previous chapter, this failure could be due to the fact that our thesis is wrong, or to the fact that our innovative experimental paradigms were not adequate operationalizations of cognitive control at all. In the next chapter, we elected to abandon our attempt to develop new behavioural measures of the tendency to use proactive control; instead, we choose to put our thesis to the test with variants of classic cognitive control tasks.

# CHAPTER 6. PROACTIVE CONTROL MEASURED IN CLASSIC TASKS

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## 1. Overview

In Chapter 4 and Chapter 5, we tried to develop new behavioural measures of the tendency to use proactive control in the perspective of demonstrating a relationship between these measures and working memory capacity. This attempt met with little success; most of our new measures were completely unrelated with working memory capacity. The fact that these measures were based on new experimental paradigms made it difficult to interpret the absence of the predicted correlation with working memory capacity: it is equally possible that working memory capacity is not actually related to proactive control or that none of the paradigms that we have developed was a valid measure of cognitive control. In the present chapter, we elected to use classic cognitive control tasks to index the tendency to use proactive control.

The two studies presented in this chapter relied on tasks that have been frequently used to assess cognitive control; of course, this includes the AX-CPT, but also the Stroop task and the cued task-switching paradigm. Certain versions of the tasks were modified to place more emphasis on the measure of proactive control rather than cognitive control in general, but all retained the core features that made them successful cognitive control tasks. Contrary to Chapter 4 and Chapter 5, the studies presented here did not explicitly rely on a specific aspect of proactive control – such as the use of contextual information or preparatory activity – to test its relationship with working memory capacity; instead, we simply expected working memory capacity to be positively correlated with measures depending on the successful use of proactive control. Thus, this chapter provided a simpler test of our thesis; importantly, any failure to observe a relationship between working memory capacity and cognitive control tasks could not be attributed to the use of novel paradigms.<sup>11</sup>

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<sup>11</sup> All the studies presented in this chapter were realized at or in collaboration with the Cognitive Control and Psychopathology lab at Washington University in Saint Louis. We thank Todd Braver, Julie Bugg, Marie Krug and Kevin Oksanen for their help with task scripts and data collection.

## **2. Study 5 – Inducing control shifts in the AX-CPT**

### **2.1. Experiment 5a**

#### **2.1.1. Rationale**

The AX-CPT is the paradigmatic task for the DMC framework and constitutes an obvious choice to test the relationship between proactive control and working memory capacity. As we have seen in the introduction (pp. 80-87), several studies have attempted to correlate working memory capacity with performance in the AX-CPT, with debatable results: out of four studies, one did not report a relationship (Braver et al., 2005), two reported that participants with high working memory capacity performed better in all trial types despite being hindered on AY trials (Redick, 2009; Redick & Engle, 2011), and a single unpublished study reported the predicted pattern of lower performance on AY trials and higher performance on BX trials for participants with high working memory capacity (Richmond et al., 2013). We can add to this list the results of Experiment 2b, where we observed no correlation whatsoever between working memory capacity and performance on any of the trial types of the AX-CPT (p. 134).

These mixed results could be due to the absence of a true relationship between working memory capacity and proactive control, but they may also stem from the flaws of the correlational method: under certain conditions, actual differences in mechanisms of information processing may not be reflected in performance. For example, it may be the case that participants with high working memory capacity are more unsettled than their counterparts on AY trials, as predicted by our thesis, but that this difficulty is counterbalanced by their generally higher cognitive efficiency, resulting in a performance equivalent or even superior to that of participants with low working memory capacity. In other words, a true difference in the use of cognitive control mechanisms could be masked by differences in some of the confounds of cognitive control, such as processing speed or short-term memory, acting in the opposite direction. It may also be the case that the relationship between working memory and cognitive control mechanisms is too tenuous to be reliably detected in small samples. The only study to evidence the predicted negative correlation between working memory capacity and performance in AY trials reported a quite small effect size, with an average  $R^2 = .031$  (Richmond et al., 2013); a power analysis suggests that more than 200 subjects would be needed to obtain a desirable .80 statistical power.

If these two ideas are correct, then our thesis will prove difficult to validate by correlating working memory capacity with performance in the AX-CPT. Interestingly, this



problem may be partly resolved through the use of experimental manipulations: manipulating rather than measuring cognitive control may elicit effect sizes much higher than normal individual differences. Experimental manipulations have the added advantage that they make it easier to disentangle the relationships between the constructs because it is generally easier to understand the effect of a manipulation than to understand the source of a correlation (a looming problem for research in working memory). Several methods have been successfully used in past studies to manipulate cognitive control in the AX-CPT by encouraging participants to preferentially use reactive or proactive control; these methods include training participants to use proactive control (Paxton et al., 2006; Braver et al., 2009; Edwards et al., 2010), introducing interferent stimuli in a trial to decrease the use of proactive control (Braver, Barch, & Cohen, 1999; Study 5 and Study 7), and introducing unpredictable no-go trials in the task (see Braver et al., 2009).

Of course, simply manipulating cognitive control is not sufficient to test our thesis: in order to understand the relationship between individual differences in working memory capacity and cognitive control, the experimental manipulation has to be combined with a measure of individual differences. Assessing the effect of experimental manipulations on individual differences corresponds to a combined correlational-experimental approach as advocated by Cronbach (1957), which constitutes a powerful tool to understand the interrelations between different variables.

In this experiment, we tried to take advantage of a combined correlational-experimental approach to test the relationship between working memory capacity and the tendency to use proactive control in the AX-CPT. Instead of simply correlating working memory capacity with performance in the task as in previous studies, we modified the AX-CPT to create an experimental condition where proactive control constituted a less advantageous strategy than in the standard version of the task. This modification was implemented by adding no-go trials to the task; all participants completed the standard version of the AX-CPT as well as the version with no-go trials. Besides AX trials, where participants had to make a target response, and AY, BX and BY trials, where participants had to make a non-target response, no-go trials were added where participants had to refrain from responding altogether. No-go trials were indicated by the probe being a digit rather than a letter; thus, participants had no way to anticipate the need to withhold their response before the probe appeared. Participants using the delay between cue and probe to prepare their answer were exposed to making more errors, because B-cues were no longer unambiguously associated with a non-target response and A-cues became less predictive of the need to make

a target response; as a consequence, no-go trials were hypothesized to make proactive control less relevant and to limit the tendency of all participants to use this strategy (see Braver et al., 2009). The differences in performance on the AX-CPT as a function of working memory capacity reported in previous studies (Redick & Engle, 2011; Richmond et al., 2013; Redick, 2014) were attributed to the higher tendency of participants with high working memory capacity to use proactive control; therefore, making all participants use reactive control should reduce the differences between participants as a function of their working memory capacity. As a consequence, we expected participants with high working memory capacity to demonstrate a higher tendency to use proactive control – manifest as a higher performance on BX trials but a lower performance on AY trials – in the standard, but not in the modified version of the AX-CPT.

### 2.1.2. Method

#### 2.1.2.1. Participants.

A sample of 95 participants completed the experiment (21 males and 74 females; age ranging from 17 to 25,  $M = 20.18$ ,  $SD = 1.80$ ). All participants were undergraduate students at the University of Savoy participating for course credit. Participants were included if they met the following criteria: native French speaker, right-handed, no history of neurological disorders and without psychoactive medication.

#### 2.1.2.2. Materials.

**Working memory task.** Working memory capacity was measured with the modified version of the CCS replacing the reading span by the alpha span (see Appendix A). The dependent variable on the task was the composite working memory score.

**Standard AX-CPT.** Participants completed a variant of the classic AX-CPT, the AX-CPT 40 (Richmond et al., 2013)<sup>12</sup>. This task includes 40% of AX trials, 10% of AY trials, 10% of BX trials and 40% of BY trials; in other words, the frequencies of the critical AY and BX trials are equivalent to the standard AX-CPT, but the frequency of AX trials is lowered and equated

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<sup>12</sup> The AX-CPT 40 used by Richmond and colleagues (2013) should not be confused with the AX-CPT 40 used by Redick (2009, 2014), which includes 40% of AX trials, 40% of AY trials, 10% of BX trials and 10% of BY trials. The AX-CPT 40 used by Redick was designed to make proactive control irrelevant on AX trials by equating the conditional frequency of target and non-target responses following an A cue, an objective which differs completely from the AX-CPT 40 used by Richmond and colleagues.

to the frequency of BY trials. This change relative to the standard AX-CPT has the desirable effect of equating the overall frequency of A cues and B cues, while leaving the conditional probability of target responses relatively unaffected (80% of A cues are followed by an X, as opposed to 87.5% in the original AX-CPT).

The materials for the task were largely similar to the version of the AX-CPT used in Experiment 2b. Each trial comprised a cue presented for 500ms, a 3500ms delay, and a probe presented for 500ms; the ITI was 1000ms. The delay period and the ITI were unfilled (i.e., participants only saw a blank screen). Cues were always presented in blue and selected among a first set of letters (*E, G, P, R, S, and A*); probes were always presented in white and selected among a non-overlapping set of letters (*F, J, M, Q, U, and X*). Participants had to respond to each stimulus appearing on the screen – including both cues and probes – by pressing a "target" button (in yellow) or a "non-target" button (in blue); the program registered an error if they did not respond within 1000ms. Participants were instructed to press the yellow button if the stimulus on the screen was an X probe and the previous cue had been an A, and to press the blue button in all other cases. Participants received an audio feedback after each response (with a "ding" sound indicating a correct response, a "buzz" sound indicating an incorrect response, and a "knock" sound indicating a too slow response). They were instructed to respond as quickly and as accurately as possible.

The same dependent variables as in Experiment 2b were collected in the task. Error rates and median response times were recorded for all trial types; median RTs were computed on correct trials only. The main dependent variable was the proactive behavioural index (or the difference between AY and BX trials divided by the sum of the two; see Experiment 2b or Braver et al., 2009), calculated separately for error rates and for response times. A composite proactive behavioural index was also computed by standardizing and averaging the indices for error rates and response times.<sup>13</sup> Lastly, the  $d'$ -context values were computed with the same procedure as in Experiment 2b.

**No-go AX-CPT.** The no-go condition of the AX-CPT was identical to the standard condition with the following change. In certain trials, labeled as "no-go trials", the probe took the form of a digit (*1, 2, 3, 7, 8, or 9*) rather than a letter. No-go trials could start with any letter in the set of cues; thus, certain no-go trials began with an A cue and certain no-go trials began with

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<sup>13</sup> Standardizing the two individual proactive behavioural indices before averaging was carried out by subtracting the mean and dividing by the standard deviation calculated across both conditions of the task, so as to allow for comparison of the combined proactive behavioural index between the two experimental conditions.

other cues. Participants were instructed to withhold their response altogether when the probe was a digit. Thus, participants had to react in one of three ways in each trial: pressing the yellow button to indicate a target response if the cue was an A and the probe was an X, pressing the blue button to indicate a non-target response if the cue and the probe were any other letters, or not pressing any key if the probe was a digit rather than a letter. As a consequence, a new type of error appeared in the task: pressing any button in response to a digit probe; an additional type of feedback (a "dee-dum" sound) was implemented to signal this error. Adding no-go trials to the task did not change the relative frequencies of the other trial types (in other words, there remained four times more AX and BY trials than AY and BX trials in the task), but it did change their absolute frequencies. The new frequencies were as follows: AX = 32%, AY = 8%, BX = 8%, BY = 32%, no-go with an A cue = 10%, no-go with a B cue = 10%.

### *2.1.2.3. Procedure.*

Participants completed the experimental session in groups of 4 to 8 individuals in a university computer room equipped with computers, 19 inches LCD screens and headphones for phonic isolation. All participants provided written informed consent prior to the experimental session. They completed the modified CCS and the AX-CPT, in order. The whole process took approximately 50 minutes. Participants completed one block of trials for the standard AX-CPT and one block for the no-go AX-CPT; the order of the two blocks was counterbalanced across participants. Participants completed 100 trials in the standard AX-CPT (40 AX, 10 AY, 10 BX and 40 BY trials) and 125 trials in the no-go AX-CPT (40 AX, 10 AY, 10 BX, 40 BY, and 25 no-go trials including 12 trials with an A cue and 13 trials with another cue); thus, the number of trials per trial type was identical for the two conditions of the AX-CPT. Trials were presented in the same pseudo-random order for all participants; the order was defined so that there were no series of more than five consecutive AX trials or two consecutive trials of another type. Each task block was preceded by a practice session including 12 trials, with trial frequencies similar to the following task block; the practice session was repeated until participants reached 70% of correct answers.

### *2.1.3. Results*

#### *2.1.3.1. Preliminary analyses.*

Working memory scores were normally distributed and close to the population average ( $M = 0.06$   $SD = 0.76$ , skewness = -0.19, kurtosis = -0.78). Descriptive statistics for

the AX-CPT are presented in Table 4 (for performance on each trial type) and Table 5 (for complex indices of the tendency to use proactive control) as a function of task condition.

Table 4

*Descriptive statistics for the AX-CPT as a function of trial type and task condition*

Dependent variable	Trial type	Standard AX-CPT	No-go AX-CPT
Average error rate	AX	.048 (.066)	.063 (.075)
	AY	.102 (.118)	.078 (.091)
	BX	.068 (.105)	.213 (.177)
	BY	.009 (.017)	.013 (.022)
	NGA	/	.161 (.140)
	NGB	/	.269 (.175)
Median RT	AX	385 (45)	433 (52)
	AY	454 (53)	529 (57)
	BX	381 (87)	491 (81)
	BY	351 (60)	440 (50)

*Note.* Average values with standard deviations in parentheses. NGA = no-go trials starting with an A-cue; NGB = no-go trials starting with any other cue. Median response times were not calculated for no-go trials because making any response on these trials reflected an error; additionally, errors in no-go trials were not frequent enough to provide a reliable estimate of response times.

A first preliminary analysis compared the reliability of the standard and no-go conditions of the AX-CPT. Internal consistency was assessed with the split-half method by computing all performance indices separately for odd and even trials and correlating the two values. The results of this analysis are presented in Table 6. Overall, internal consistency was comparable across the two experimental conditions, with slightly higher values for the no-go AX-CPT.

Table 5

*Descriptive statistics for complex indices of performance in the AX-CPT as a function of task condition*

Trial type	Standard AX-CPT	No-go AX-CPT
PBI-errors	0.096 (0.450)	-0.290 (0.423)
PBI-RTs	0.096 (0.087)	0.040 (0.079)
PBI-composite	0.363 (0.751)	-0.363 (0.667)
$d'$ -context	3.08 (0.70)	2.39 (0.84)

*Note.* Average values with standard deviations in parentheses. PBI-errors = PBI calculated on errors; PBI-RT = PBI calculated on median response times; PBI-composite = average of the two other PBIs after standardization.

The second preliminary analysis tested the effect of adding no-go trials to the AX-CPT on the use of proactive control. Participants in the no-go condition were expected to use less proactive control, resulting in lower performance on BX trials but higher performance in AY trials. For error rates, the two-way interaction between task block and trial type was significant,  $F(3, 282) = 38.78$ ,  $MSE = 0.00687$ ,  $p < .001$ ,  $\eta^2_p = .29$ , indicating that the pattern of performance as a function of trial type differed in the standard and in the no-go condition of the AX-CPT. This interaction is represented in Figure 17. Follow-up  $t$ -tests indicated that participants made more errors on BX trials in the no-go condition,  $t(94) = -8.15$ ,  $p < .001$ , but marginally less errors on AY trials,  $t(94) = 1.67$ ,  $p = .098$ , consistent with a reduced tendency to use proactive control in this condition.

For response times, the two-way interaction between task block and trial type was also significant,  $F(3, 282) = 27.02$ ,  $MSE = 1210$ ,  $p < .001$ ,  $\eta^2_p = .22$ ; this interaction is represented in Figure 18. Decomposing this interaction revealed that participants were on average 73ms slower on AY trials than on BX trials ( $SD = 70$ ) in the standard condition, whereas they were only 37ms slower on AY trials ( $SD = 78$ ) in the no-go condition; this difference was significant,  $t(94) = 3.98$ ,  $p < .001$ . In other words, participants were slower on AY trials than on BX trials in the standard condition, consistent with a tendency to use proactive control, but this difference was reduced in the no-go condition, consistent with a reduced tendency to use proactive control. This two-way interaction was associated with a prominent main effect of task condition on response times,  $F(1, 94) = 409.53$ ,  $MSE = 3013$ ,  $p < .001$ ,  $\eta^2_p = .81$ : on average, participants were slower on all trial types in the no-go condition.

Table 6

*Internal consistency for each dependent variable as a function of task condition*

Dependent variable	Trial type	Standard AX-CPT	No-go AX-CPT
Average error rate	AX	.63	.75
	AY	.14	.20
	BX	.27	.56
	BY	.14	.16
	NGA	/	.36
	NGB	/	.23
Median RT	AX	.81	.88
	AY	.71	.65
	BX	.50	.51
	BY	.89	.89
PBI-errors		.21	.24
PBI-RTs		.35	.51
PBI-composite		.37	.51
$d'$ -context		.40	.57

*Note.* NGA = no-go trials starting with an A-cue; NGB = no-go trials starting with any other cue; PBI-errors = PBI calculated on errors; PBI-RT = PBI calculated on median response times; PBI-composite = average of the two other PBIs after standardization. No reliability coefficient was computed for response times on no-go trials because making any response on these trials reflected an error and because there were not enough data points to provide a reliable estimate of the correlation.

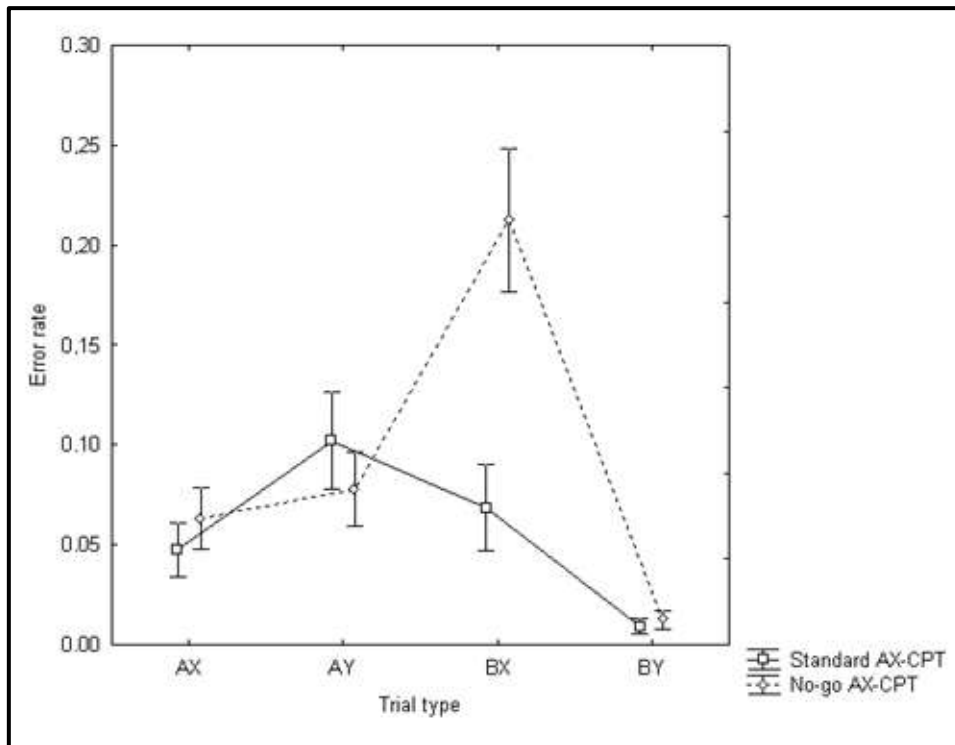


Figure 17. Average error rates in the AX-CPT as a function of trial type and task condition. Error bars represent standard errors of the mean.

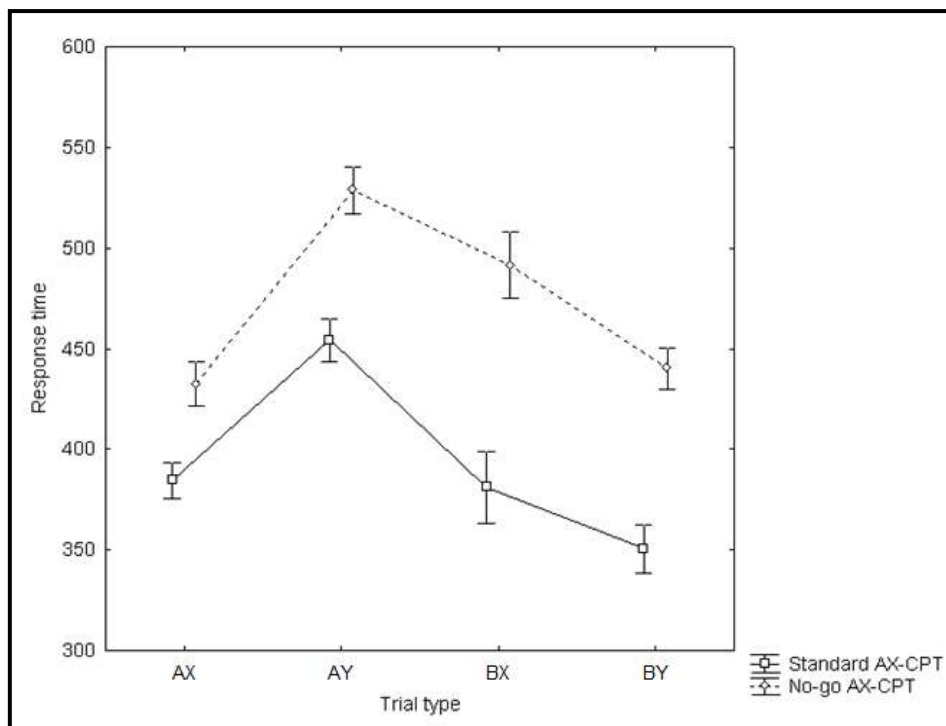


Figure 18. Average response times in the AX-CPT as a function of trial type and task condition. Error bars represent standard errors of the mean.



The effect of task condition was also examined for the complex measures of the tendency to use proactive control, namely the proactive behavioural indices and the  $d'$ -context. The PBIs were lower in the no-go condition than in the standard condition, indicating a lower tendency to use proactive control in the no-go condition; this was true for the PBI calculated on error rates,  $F(1, 94) = 48.13$ ,  $MSE = 0.148$ ,  $p < .001$ ,  $\eta^2_p = .34$ , the PBI calculated on response times,  $F(1, 94) = 28.53$ ,  $MSE = 0.00520$ ,  $p < .001$ ,  $\eta^2_p = .23$ , and the combination of the two,  $F(1, 94) = 75.06$ ,  $MSE = 0.334$ ,  $p < .001$ ,  $\eta^2_p = .44$ . The  $d'$ -context was also lower in the no-go condition than in the standard condition,  $F(1, 94) = 62.82$ ,  $MSE = 0.364$ ,  $p < .001$ ,  $\eta^2_p = .40$ ; this indicates a lesser efficiency to use contextual information from the cue to drive responses to the probe in the no-go condition, presumably reflecting a decrease in the use of proactive control. In summary, the introduction of no-go trials in the AX-CPT appeared to successfully reduce the tendency of participants to use proactive control.

### 2.1.3.2. *Main analyses.*

Our main hypothesis was that a high working memory capacity would be associated with a higher tendency to use proactive control in the standard AX-CPT, but that this association would be reduced in the no-go AX-CPT. This hypothesis was tested with a 2 (task condition) x WMC design, with the order of the two task blocks (standard AX-CPT performed first or no-go AX-CPT performed first) as a controlled variable. We expected to observe a two-way interaction between working memory capacity and experimental condition; this hypothesis was tested separately for each performance index.

All simple effects, corresponding to bivariate correlations between working memory and performance indices in each experimental condition, are presented in Table 7. Contrary to our hypotheses, the two-way interaction between working memory capacity and experimental condition was not statistically significant for either the composite PBI,  $F(1, 93) = 0.96$ ,  $MSE = 0.334$ ,  $p = .330$ ,  $\eta^2_p = .01$ , or the PBI calculated on errors only,  $F(1, 93) = 0.66$ ,  $MSE = 0.148$ ,  $p = .420$ ,  $\eta^2_p = .01$ . The two-way interaction was significant for the PBI calculated on RTs only,  $F(1, 93) = 4.85$ ,  $MSE = 0.0050$ ,  $p = .030$ ,  $\eta^2_p = .05$ : the correlation between working memory capacity and the PBI calculated on RTs was descriptively positive in the standard AX-CPT and descriptively negative in the no-go AX-CPT (see Table 7). However, interpretation of this effect was made difficult by the fact that the bivariate correlations did not approach statistical significance in either experimental condition, and by the fact that the correlations between working memory capacity and the tendency to use

proactive control were in opposite directions for errors and response times in the no-go condition (see Table 7). Lastly, the two-way interaction was significant at the trend level for the  $d'$ -context,  $F(1, 93) = 3.47$ ,  $MSE = 0.276$ ,  $p = .066$ ,  $\eta^2_p = .04$ : the correlation between working memory capacity and  $d'$ -context was close to zero in the standard condition but significant and positive in the no-go condition (see Table 7), suggesting that if anything, participants with high working memory capacity were more efficient at using contextual information to regulate their answer in the no-go AX-CPT, contrary to our hypotheses.

Table 7

*Bivariate correlations between working memory and performance indices as a function of task condition*

Performance index	Standard AX-CPT	No-go AX-CPT
PBI-errors	.05	.16
PBI-RTs	.12	-.16
PBI-composite	.11	.00
$d'$ -context	.10	.27**

*Note.* PBI-errors = PBI calculated on errors; PBI-RT = PBI calculated on median response times; PBI-composite = average of the two other PBIs after standardization.  $^{\circ} p < .10$ ,  $* p < .05$ ,  $** p < .01$ ,  $*** p < .001$ .

### 2.1.3.3. Complementary analyses.

In order to better understand the relationship between working memory capacity and performance in the AX-CPT, we examined the correlation between working memory capacity and performance on each trial type as a function of the task block. This data is presented in Table 8. Overall, working memory capacity was associated with faster response times on all trial types; it was however unrelated to error rates except for a slight tendency of participants with high working memory capacity to make less errors on AX and BY trials in the no-go condition. When controlling for performance on BY trials (as in Richmond et al., 2013), working memory capacity was unrelated to performance on all trial types in both conditions, both in terms of error rates and in terms of RTs, all  $ps > .10$ .

Table 8

*Bivariate correlations between working memory and performance indices as a function of trial type and task condition*

Dependent variable	Trial type	Standard AX-CPT	No-go AX-CPT
Average error rate	AX	.03	-.23*
	AY	-.05	.04
	BX	-.16	-.14
	BY	-.03	-.24*
	NGA	/	-.03
	NGB	/	-.11
Median RT	AX	-.20*	-.26**
	AY	-.24*	-.29**
	BX	-.19°	-.03
	BY	-.27**	-.24*

*Note.* NGA = no-go trials starting with an A-cue; NGB = no-go trials starting with any other cue. The correlations between working memory capacity and response times on no-go trials were not computed because there were not enough data points to provide a reliable estimate. °  $p < .10$ , \*  $p < .05$ , \*\*  $p < .01$ , \*\*\*  $p < .001$ .

#### 2.1.4. Discussion

In this experiment, we hypothesized that a high working memory capacity would be related to a higher tendency to use proactive control in the AX-CPT, that adding no-go trials to the AX-CPT would induce a shift away from proactive control in all participants, and that the relationship between working memory capacity and the tendency to use proactive control would be reduced in the no-go condition as a result.

The first hypothesis was not supported by the data: a high working memory capacity was not associated with a higher tendency to use proactive control in the standard AX-CPT. This finding is worrying and contradicts previous results in the literature. Could the bivariate relationships between working memory capacity and performance on the different trial types tell us something informative to explain this problem? A high working memory capacity was associated with generally faster response times on all trial types, inconsistent with the hypothesis that participants with high working memory capacity tend to use more proactive

control, but consistent with a general advantage for these participants in the task. Contrary to previous work (Redick & Engle, 2011; Richmond et al., 2013; Redick, 2014), participants with high working memory capacity performed better on AY trials; this finding is especially inconsistent with our thesis. There were no marked differences between the tasks used in the previous studies and the current version of the AX-CPT that could explain this difference; Richmond and colleagues in particular used a version of the AX-CPT 40 similar to ours. Although our findings run counter to previous results in the literature, it is worth noting that they are entirely in agreement with the results of Experiment 2b: working memory capacity was unrelated to the tendency to use proactive control in the standard condition of the AX-CPT and was only associated with generally faster response times.

One possible explanation for the discrepancy between our results and the literature lies in sample differences: while our experiments were carried out in France, all prior studies on the relationship between working memory and the AX-CPT have tested American samples. Thus, it is possible that there exists a systematic difference between the samples; for example, it could be the case that American students have on average a higher tendency to use proactive control than French students. This idea could make sense: for example, the criteria for entering university may be more permissive in France, resulting in a wider range of abilities in participants. The idea of a systematic difference between samples was tested by comparing the values observed in this experiment for the various dependent variables with the values observed in two American samples using a similar version of the AX-CPT. The results of this analysis are presented in Appendix C. Overall, there were no systematic differences between the samples that could explain the discrepancy in the results; the various performance indices were comparable across the samples, as were reliability indices.

The very low values of the reliability estimates observed in this experiment could be seen as another possible culprit: if the AX-CPT was not reliable enough to obtain a valid measure of proactive control, this could explain the non-significant relationship between working memory and indices of the tendency to use proactive control. However, there are two problems with this interpretation. First, the low internal consistency of the AX-CPT is in large part attributable to the very small number of AY and BX trials, which only allowed for a very restricted range of scores and necessarily limited the value of internal consistency indices; for example, the average error rate on BX trials in the standard condition was .07 with a .11 *SD*, which means most participants made between zero and two errors on these trials. Importantly, this problem stems from the structure of the AX-CPT, which means published studies certainly used versions of the AX-CPT with similar internal consistency; in support of this

interpretation, most reliability indices were not statistically lower in our sample than in an American sample using a comparable version of the task (see Appendix C). It should also be noted that using the split-half method to compute the indices certainly resulted in underestimating reliability coefficients given the small number of trials; assessing reliability with a test-retest method might have yielded very different values. Second, the highly significant effect of our experimental manipulation on performance also suggests that the task retained significant construct validity despite the low values of internal consistency indices. In short, no obvious reason explains the inconsistency between our findings and the literature.

The data supported the effectiveness of the no-go manipulation; the pattern of results in the no-go condition was entirely consistent with a lesser tendency to use proactive control. Participants in the no-go condition demonstrated higher performance in AY trials but lower performance in BX trials; the effect of task condition was highly significant on all complex performance indices, the PBIs and the  $d'$ -context, suggesting that the manipulation was successful in reducing the tendency of all participants to use proactive control. This result is not in itself uninteresting; to our knowledge, this experiment was the first to systematically test the effect of introducing no-go trials in the AX-CPT in a large sample.

On the other hand, the results did not support the hypothesis that no-go trials would decrease the tendency of participants with high working memory capacity to use proactive control. The relationship between working memory capacity and composite PBI was not affected by no-go trials; the relationships with the PBI calculated on errors and the PBI calculated on RTs were slightly affected but in opposite directions. Thus, adding no-go trials to the AX-CPT did not seem to decrease the relationship between working memory capacity and the tendency to use proactive control.

The fact that the no-go trials did not produce the expected result cannot be attributed to a problem with the experimental manipulation, since we observed the expected effect of no-go trials on the various performance indices. Actually, the fact that the experimental manipulation was highly successful supports the construct validity of our version of the AX-CPT, which rules out most possible explanations for the fact that the data were incongruent with our hypotheses. The fact that working memory capacity was not associated with a higher tendency to use proactive control in the standard AX-CPT does not explain the problem, either; as explained above, the experimental manipulation could have elicited bigger effect sizes than individual differences and could have made a relationship between working memory capacity and proactive control apparent. For example, if working memory capacity was not correlated with lower performance on AY trials in the standard condition because of

the overall better performance of participants with high working memory capacity, as suggested above (p. 162), the experimental manipulation could have revealed the relationship by making participants with high working memory capacity perform *better* on AY trials.

Perhaps the most surprising aspect of the results was the significant two-way interaction between working memory capacity and experimental condition for the  $d'$ -context; this interaction ran counter to our predictions, since a high working memory capacity was associated with a more efficient use of contextual information in the no-go condition. The finding that the experimental manipulation affected the relationship between working memory capacity and the  $d'$ -context, but not the PBIs, is due to the fact that the  $d'$ -context contrasts error rates on AX and BX trials whereas the PBIs contrast AY and BX trials. The relationship between working memory capacity and error rates on BX trials was equivalent across task conditions; in fact, the positive correlation between working memory capacity and the  $d'$ -context in the no-go condition was driven by the positive correlation between working memory capacity and accuracy on AX trials in this condition (see Table 8). In other words, the two-way interaction between working memory capacity and experimental condition for the  $d'$ -context was due to the fact that participants with high working memory capacity performed better on AX trials in the no-go, but not in the standard AX-CPT.

There are several ways to explain this result. One possibility is that it does not bear any theoretical relevance. It could be a false positive, a non-absurd possibility given the large number of performance indices and the large set of statistical comparisons performed without correction in this study. It could also be the case that this correlation simply reflects the greater general efficiency of participants with high working memory capacity, as suggested by the fact that the correlation with AX trials disappeared when controlling for performance on BY trials. However, a second interpretation is also possible, based on two key points: one, the no-go condition seemed to shift all participants towards a reactive control strategy – in other words, towards waiting for the probe to appear before retrieving the cue information; and two, it has been argued that AX errors for participants using reactive control may reflect incorrect retrieval of the cue when the probe is presented (e.g. Redick, 2014). On these grounds, one could argue that all participants in the no-go condition used reactive control and relied on selective retrieval of the cue information, but that participants with high working memory capacity were better at retrieving the cue in memory (not incongruent with Unsworth & Engle, 2007a). In other words, the higher performance of participants with high working memory capacity in the no-go condition could be due to their efficiency at retrieving information in memory, rather than to their use of a different cognitive control mechanism.

A third possible interpretation is that the correlation between working memory and performance on AX trials reflected the fact that participants with high working memory capacity were actually more likely to use proactive control than their counterparts in the no-go AX-CPT; in that case, the two-way interaction between experimental condition and working memory capacity would indicate that all participants were equally likely to use proactive control in the standard AX-CPT, but that the no-go trials shifted participants with low working memory capacity away from proactive control. Although not predicted by our hypotheses, this interpretation could make sense: it could be the case that proactive control is the preferred strategy of all young, non-pathological adult participants in the AX-CPT, but that those with low working memory capacity default to a reactive control strategy when the situation is less favourable to proactive control whereas participants with high working memory capacity continue to use proactive control even when the situation makes it more difficult. According to this interpretation, our experimental manipulation would have been successful in revealing a relationship between working memory capacity and the tendency to use proactive control, although in an unpredicted way.

The data were not sufficient in this experiment to disentangle these different possibilities. However, the third possibility is certainly the most interesting in the perspective of our thesis: it suggests that there is actually a relationship between working memory capacity and the tendency to use proactive control, but that this relationship only emerges in situations where using proactive control is discouraged by the features of the task. This possibility also suggests that the no-go AX-CPT could serve as a baseline condition to test the relationship between working memory capacity and the tendency to use proactive control; this idea is all the more seducing that the no-go AX-CPT demonstrated slightly higher reliability indices than the standard version. This idea served as the basis for Experiment 5b.

## **2.2. Experiment 5b**

### **2.2.1. Rationale**

In Experiment 5a, we observed that working memory capacity was not related to the tendency to use proactive control in a standard version of the AX-CPT; however, the significant correlation with the  $d'$ -context in the no-go condition suggested that the relationship might be stronger in a version of the AX-CPT including no-go trials. Several reasons motivated the replication of this result in a different sample, including the fact that it was not predicted and the fact that it was observed amid many statistical tests performed without correction.

The first objective of Experiment 5b was to reproduce the findings of Experiment 5a by confronting participants with a no-go AX-CPT; we expected to observe the same correlation between working memory and the  $d'$ -context. The second objective was to extend the findings of Experiment 5a with a second attempt to manipulate cognitive control mechanisms in participants. If our interpretation of the results of Experiment 5a was correct, then all participants used a proactive control strategy by default in the standard version of the AX-CPT, and introducing no-go trials shifted participants with low working memory capacity towards using reactive control. In that view, Experiment 5a did not actually test our hypothesis that inducing all participants to use reactive control would reduce the relationship between working memory capacity and performance in the AX-CPT. In order to test this hypothesis, the solution would be to use the no-go AX-CPT as a baseline, and to use another manipulation to shift all participants towards even more reactive control. One possibility would be to add monetary penalties for errors on no-go trials; this would strongly incentivize participants to avoid any errors on these trials and, in turn, to always wait for the appearance of the probe instead of preparing a response. In this situation, participants with high working memory capacity should turn to reactive control and the differences in performance as a function of working memory capacity should decrease.

Another possible extension of the results would be to shift participants with low working memory capacity towards proactive control. Inducing participants to use proactive control has been successfully done in the literature through strategy training; as described in the introduction (pp. 71-73), several studies have used strategy training to shift participants towards using proactive control (Paxton et al., 2006; Braver et al., 2009; Edwards et al., 2010). This manipulation was mainly tested with older adults, but there is no reason that participants with low working memory capacity could not be induced to use more proactive control through strategy training; if our thesis is correct, then having the participants go through strategy training should lead them all to use proactive control and reduce the differences in performance as a function of working memory capacity. One study tested this hypothesis and reported that working memory capacity had no effect on performance after strategy training, confirming our hypothesis (Richmond et al., 2013); however, the authors did not try to evidence a correlation between working memory capacity and performance before the training and they confounded the strategy training with a change in the features of the task, which casts doubt upon their findings.

In summary, the objective of Experiment 5b was to replicate and extend the main finding of Experiment 5a – namely, the significant correlation between working memory



capacity and the  $d'$ -context in the no-go condition. We used the no-go AX-CPT as a baseline condition; we expected participants with high working memory capacity to use more proactive control in this condition, as reflected by the  $d'$ -context. Participants also completed a no-go AX-CPT with monetary penalties for errors on no-go trials; we expected participants with high working memory capacity to switch to reactive control in this condition and the correlation between working memory capacity and the  $d'$ -context to decrease relative to the baseline condition. Lastly, participants completed a no-go AX-CPT after proactive strategy training; we expected participants with low working memory capacity to switch to proactive control in this condition and the correlation between working memory capacity and the  $d'$ -context to decrease relative to the baseline condition.

### 2.2.2. Method

#### 2.2.2.1. Participants.

A sample of 35 participants completed the experiment (12 males and 23 females; mean age = 20.90 years). All participants were undergraduate students from Washington University in Saint Louis participating for payment (\$10.00 an hour). All participants were native English speakers.

#### 2.2.2.2. Materials.

**Working memory tasks.** Working memory capacity was measured with the classic versions of the reading span, symmetry span and operation span (Unsworth et al., 2005). The partial credit load method was used to score performance in each task (Conway et al., 2005). Scores in each subtest were standardized and then averaged, yielding a single composite working memory score. Due to the small sample size, no participants were excluded on the basis of their accuracy on the processing tasks (contrary to Unsworth et al., 2005).

**Baseline AX-CPT.** The baseline AX-CPT was mostly identical to the no-go AX-CPT presented in Experiment 5a, with the following changes. The delay period was increased from 3500ms to 4500ms and the ITI was increased from 1000ms to 1500ms. The sets of stimuli used for cues and probes were overlapping and larger than in Experiment 5a ( $C, D, E, F, G, H, M, N, P, T, U, A$  and  $X$ ); the set of digits for the probes on no-go trials comprised all digits from 1 to 9. The frequency of no-go trials was equated to the frequency of AY and BX trials, contrary to Experiment 5a; this did not change the relative frequencies of the other trial types. The absolute frequencies of each trial type in Experiment 5b were as follows: AX = 33.3%,

AY = 8.3%, BX = 8.3%, BY = 33.3%, no-go with an A cue = 8.3%, no-go with a B cue = 8.3%. The same dependent variables as in Experiment 5a were collected.

**Penalty AX-CPT.** The penalty AX-CPT was identical to the baseline condition with one exception. Before they started performing the task, participants were instructed that they would earn \$5.00 at the end of the task on top of their base payment of \$10.00 an hour, but that they would lose \$0.30 off this amount every time they made an error by incorrectly making a response on a no-go trial.

**Strategy training AX-CPT.** The strategy training AX-CPT was identical to the baseline condition except that participants completed a strategy training session prior to performing the actual task. The strategy training was closely based on Paxton and colleagues (2006) and comprised three phases; the detailed instructions for the training are presented in Appendix D. In the first phase, participants were advised that the best strategy to successfully perform the task was to use the cue to predict their response to the probe and to prepare this response during the delay period. In the second phase, the experimenter completed a series of 14 practice trials by pressing the response buttons; at the same time, participants had to say out loud "yellow" (indicating a target response) during the delay period if the cue was an A and "blue" (indicating a non-target response) if the cue was not an A. In the third phase, participants completed a series of 24 practice trials by pressing the response buttons themselves; they still had to say "yellow" or "blue" out loud during the delay period.

In order to ensure that the strategy training had an actual influence on the strategy used in the task, participants were also required to complete a short questionnaire at the end of the session. The questionnaire comprised five questions; participants had to respond to each question by indicating their answer on a 9-point scale ranging from "not at all" to "completely". The following questions were asked in random order:

1. *Did you try to follow the strategy instructions during the task?*
2. *Do you think the strategy training influenced the way you performed the task?*
3. *Did you have trouble following the strategy instructions during the task?*
4. *Do you think the strategy training influenced your speed or accuracy in the task?*
5. *Were you already using the advance preparation strategy in the two previous sessions of the task?*

### 2.2.2.3. Procedure.

Participants completed the experiment individually in a testing room equipped with a computer, a 23 inches LCD screen and headphones. All participants provided written informed consent prior to the experiment. The tasks in the protocol were always completed in the same order to avoid introducing a supplementary source of variance that could interact with individual differences; the task order was chosen to limit interference between the conditions: the baseline AX-CPT was completed first and the penalty AX-CPT was completed second to prevent participants from focusing too much on no-go trials in the baseline AX-CPT, and the strategy training AX-CPT was completed last to prevent participants from generalizing the proactive strategy to the other conditions.

The protocol was divided in two testing sessions separated by one week so as to limit cognitive fatigue and boredom for the participants. The different versions of the AX-CPT were interleaved with Stroop tasks used in a different study not reported here. In the first session, participants completed a Stroop task, the baseline AX-CPT, the reading span, symmetry span and operation span, in order; the whole procedure took approximately 100 minutes. In the second session, participants completed a Stroop task, the penalty AX-CPT, another Stroop task, and the strategy training AX-CPT, in order; the whole procedure took approximately 90 minutes.

Participants completed four blocks of 48 trials for each version of the AX-CPT, for a total of 192 trials per condition. This total included 24 AX trials, 8 AY trials, 8 BX trials, 24 BY trials, 8 no-go trials with an A cue, and 8 no-go trials with a B cue. The baseline and penalty AX-CPT were preceded by 12 practice trials, which were repeated until the participant responded correctly on at least 70% of stimuli. The participants took short breaks between each task block. Trials were presented in random order with the constraint that there could be no more than two consecutive AY trials, BX trials, no-go trials with an A cue, or no-go trials with a B cue.

### *2.2.3. Results*

#### *2.2.3.1. Method of analysis.*

The method of analysis was similar to other studies with one exception. Due to the small sample size, several variables had non-normal distributions with many outlying values; to account for this problem, a 90% winsorisation was applied to all variables.

#### *2.2.3.2. Preliminary analyses.*

Working memory scores were normally distributed ( $M = 0.14$ ,  $SD = 0.67$ , skewness =  $-0.83$ , kurtosis =  $0.22$ ). Descriptive statistics for the AX-CPT are presented in Table 9 (for performance on each trial type) and Table 10 (for complex indices of the tendency to use proactive control).

Table 9

*Descriptive statistics for the AX-CPT as a function of trial type and task condition*

Dependent variable	Trial type	Baseline AX-CPT	Penalty AX-CPT	Strategy training AX-CPT
Average error rate	AX	.080 (.075)	.088 (.114)	.112 (.140)
	AY	.082 (.092)	.132 (.146)	.282 (.239)
	BX	.200 (.152)	.170 (.177)	.152 (.165)
	BY	.020 (.040)	.021 (.062)	.042 (.079)
	NGA	.100 (.100)	.018 (.036)	.254 (.226)
	NGB	.179 (.133)	.053 (.068)	.377 (.251)
Median RT	AX	423 (56)	463 (95)	395 (82)
	AY	518 (43)	540 (66)	520 (83)
	BX	523 (101)	554 (110)	445 (118)
	BY	450 (54)	465 (68)	400 (73)

*Note.* Average values with standard deviations in parentheses. NGA = no-go trials starting with an A-cue; NGB = no-go trials starting with any other cue. Median response times were not calculated for no-go trials because making any response on these trials reflected an error; additionally, errors in no-go trials were not frequent enough to provide a reliable estimate of response times.

A first preliminary analysis compared the reliability of the standard, penalty and strategy training conditions of the AX-CPT. Internal consistency was assessed with the split-half method by computing all performance indices separately for odd and even trials and correlating the two values. The results of this analysis are presented in Table 11; overall, internal consistency was comparable across the three experimental conditions.

Table 10

*Descriptive statistics for complex indices of performance in the AX-CPT as a function of task condition*

Trial type	Baseline AX-CPT	Penalty AX-CPT	Strategy training
			AX-CPT
PBI-errors	-0.244 (0.369)	-0.059 (0.449)	0.182 (0.472)
PBI-RTs	0.003 (0.082)	0.007 (0.076)	0.087 (0.082)
PBI-composite	-0.359 (0.686)	-0.213 (0.794)	0.572 (0.850)
$d'$ -context	2.23 (0.67)	2.37 (0.98)	2.35 (0.93)

*Note.* Average values with standard deviations in parentheses. PBI-errors = PBI calculated on errors; PBI-RT = PBI calculated on median response times; PBI-composite = average of the two other PBIs after standardization.

The second preliminary analysis sought to ensure that the penalty condition had the desired effect of increasing reactive control in participants. Participants in the penalty condition were expected to demonstrate higher AY performance, lower BX performance, and lower values of the PBIs and the  $d'$ -context. For error rates, the two-way interaction between task and trial type was significant,  $F(3, 102) = 4.01$ ,  $MSE = 0.00476$ ,  $p = .009$ ,  $\eta^2_p = .11$ , indicating that the pattern of performance as a function of trial type differed in the baseline and the penalty AX-CPT. This interaction is represented in Figure 19. Follow-up  $t$ -tests indicated that participants made more errors on AY trials in the penalty condition,  $t(34) = -2.17$ ,  $p = .037$ , and a similar number of errors on BX trials,  $t(34) = 1.13$ ,  $p = .267$ , inconsistent with an increased tendency to use reactive control in this condition. For RTs, the two-way interaction between task and trial type was not significant,  $F(3, 102) = 2.10$ ,  $MSE = 1009$ ,  $p = .104$ ,  $\eta^2_p = .06$ ; this result is represented in Figure 20. The main effect of task was however highly significant,  $F(1, 34) = 14.39$ ,  $MSE = 3499$ ,  $p < .001$ ,  $\eta^2_p = .30$ , indicating a general slowing in the penalty condition.

The effect of task condition was significant for the PBI calculated on errors,  $F(1, 34) = 6.20$ ,  $MSE = 0.0966$ ,  $p = .018$ ,  $\eta^2_p = .15$ , suggesting that participants were significantly more likely to use proactive control in the penalty condition. However, there was no effect of task condition on the composite PBI,  $F(1, 34) = 1.46$ ,  $MSE = 0.257$ ,  $p = .236$ ,  $\eta^2_p = .04$ , the PBI calculated on RTs,  $F(1, 34) = 0.62$ ,  $MSE = 0.00263$ ,  $p = .436$ ,  $\eta^2_p = .02$ , or the  $d'$ -context,  $F(1, 34) = 1.20$ ,  $MSE = 0.288$ ,  $p = .282$ ,  $\eta^2_p = .03$ . In summary, the penalty AX-CPT did not seem to achieve its goal of shifting participants towards reactive control.

Table 11

*Internal consistency for each dependent variable as a function of task condition*

Dependent variable	Trial type	Baseline AX-CPT	Penalty AX-CPT	Strategy training
				AX-CPT
Average error rate	AX	.78	.88	.94
	AY	.54	.47	.72
	BX	.64	.66	.57
	BY	.59	.94	.84
	NGA	.46	N. C.	.76
	NGB	.31	.15	.68
Median RT	AX	.92	.97	.96
	AY	.70	.64	.64
	BX	.55	.82	.73
	BY	.86	.95	.96
PBI-errors		.39	.19	.54
PBI-RTs		.43	.51	.56
PBI-composite		.39	.50	.33
<i>d'</i> -context		.55	.68	.71

*Note.* NGA = no-go trials starting with an A-cue; NGB = no-go trials starting with any other cue; PBI-errors = PBI calculated on errors; PBI-RT = PBI calculated on median response times; PBI-composite = average of the two other PBIs after standardization. No reliability coefficient was computed for response times on no-go trials because making any response on these trials reflected an error and because there were not enough data points to provide a reliable estimate of the correlation. The reliability coefficient was not computable for no-go trials with an A cue in the reactive condition because no participant made any error on even-numbered trials.

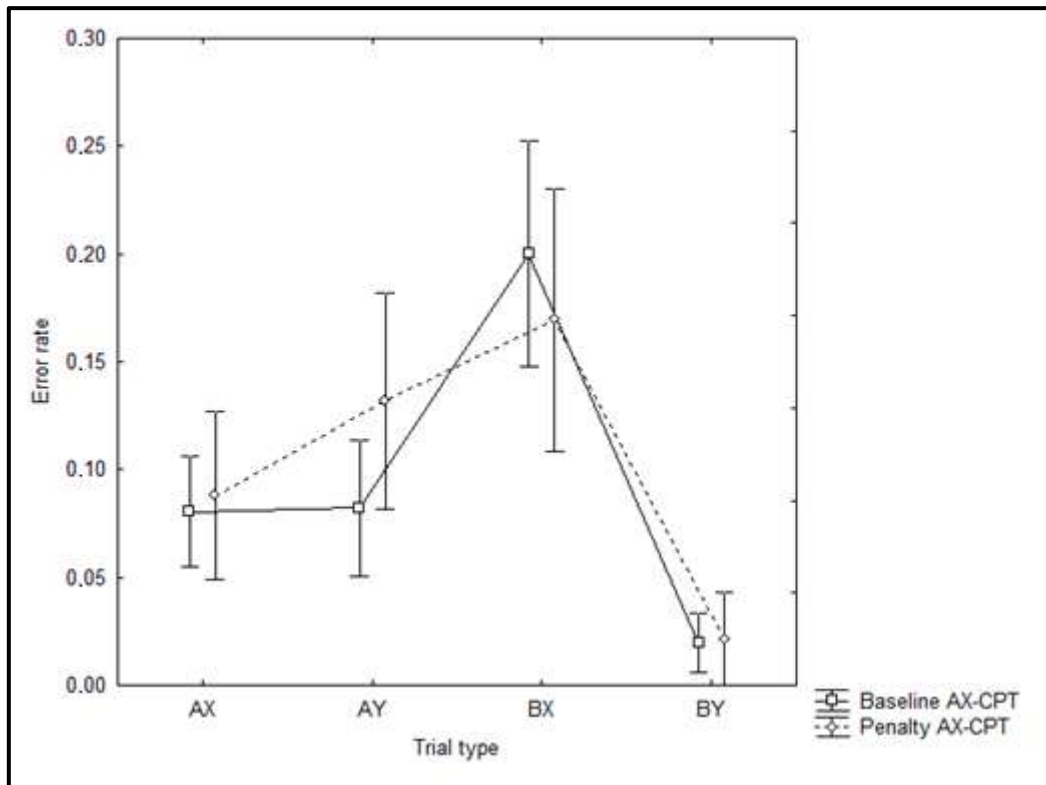


Figure 19. Average error rates in the AX-CPT as a function of trial type and task condition. Error bars represent standard errors of the mean.

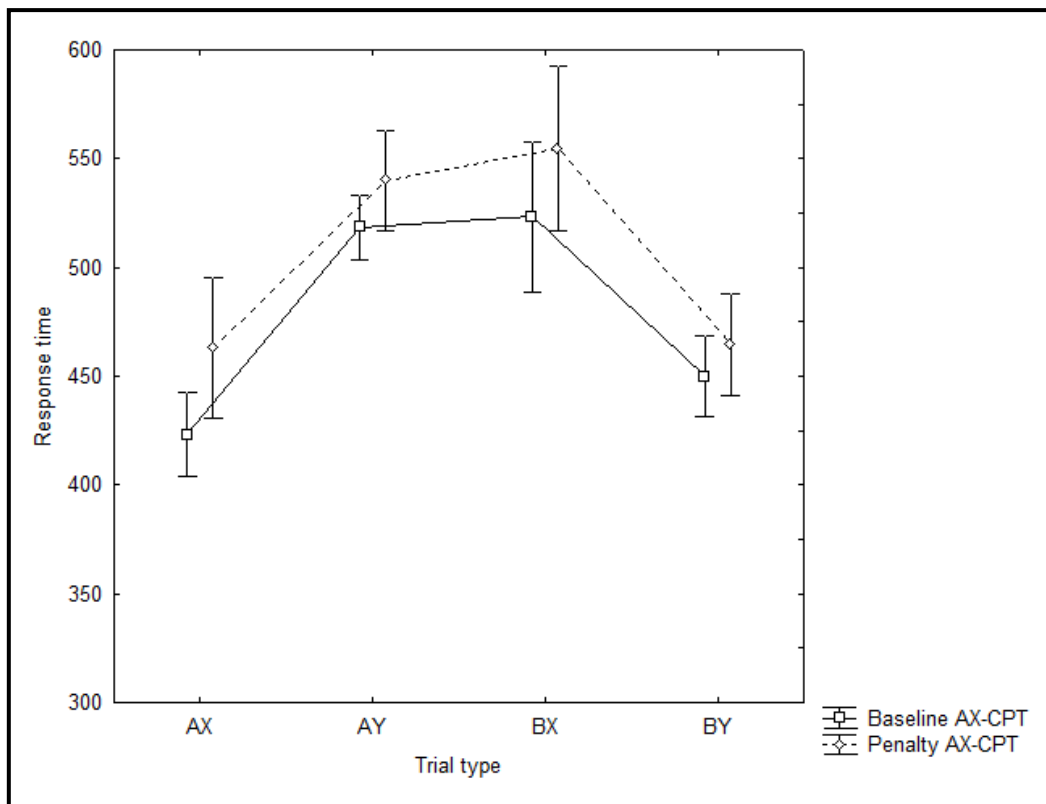


Figure 20. Average response times in the AX-CPT as a function of trial type and task condition. Error bars represent standard errors of the mean.

The third preliminary analysis tested whether the strategy training condition had the desired effect of shifting participants towards proactive control. Participants in the strategy training condition were expected to demonstrate lower AY performance, higher BX performance, and higher values of the PBIs and the  $d'$ -context. For error rates, the two-way interaction between task and trial type was significant,  $F(3, 102) = 17.14$ ,  $MSE = 0.0113$ ,  $p < .001$ ,  $\eta^2_p = .34$ , indicating that the pattern of performance as a function of trial type differed in the baseline and the strategy training AX-CPT. This interaction is represented in Figure 21. Follow-up  $t$ -tests indicated that participants made more errors on AY trials in the strategy training condition,  $t(34) = -5.41$ ,  $p < .001$ , and a similar number of errors on BX trials,  $t(34) = 1.30$ ,  $p = .203$ , consistent with an increased tendency to use proactive control in this condition. For RTs, the two-way interaction between task and trial type was also significant,  $F(3, 102) = 14.99$ ,  $MSE = 1339$ ,  $p < .001$ ,  $\eta^2_p = .31$ ; this result is represented in Figure 22. Follow-up  $t$ -tests indicated that participants had similar response times on AY trials in both conditions,  $t(34) = -0.13$ ,  $p = .898$ , but that they were faster on BX trials in the strategy training condition,  $t(34) = 4.90$ ,  $p < .001$ , also consistent with an increased tendency to use proactive control in this condition. In other words, the strategy training condition both decreased performance on AY trials (by increasing error rates) and increased performance on BX trials (by lowering response times). The effect of task condition was significant for the composite PBI,  $F(1, 34) = 50.43$ ,  $MSE = 0.300$ ,  $p < .001$ ,  $\eta^2_p = .60$ , for the PBI calculated on RTs,  $F(1, 34) = 31.93$ ,  $MSE = 0.00395$ ,  $p < .001$ ,  $\eta^2_p = .48$ , and for the PBI calculated on errors,  $F(1, 34) = 25.19$ ,  $MSE = 0.126$ ,  $p < .001$ ,  $\eta^2_p = .43$ , indicating that participants were significantly more likely to use proactive control in the strategy training condition, although there was no effect of task condition on the  $d'$ -context,  $F(1, 34) = 0.50$ ,  $MSE = 0.434$ ,  $p = .482$ ,  $\eta^2_p = .01$ . In summary, the strategy training AX-CPT was successful in shifting participants towards proactive control.



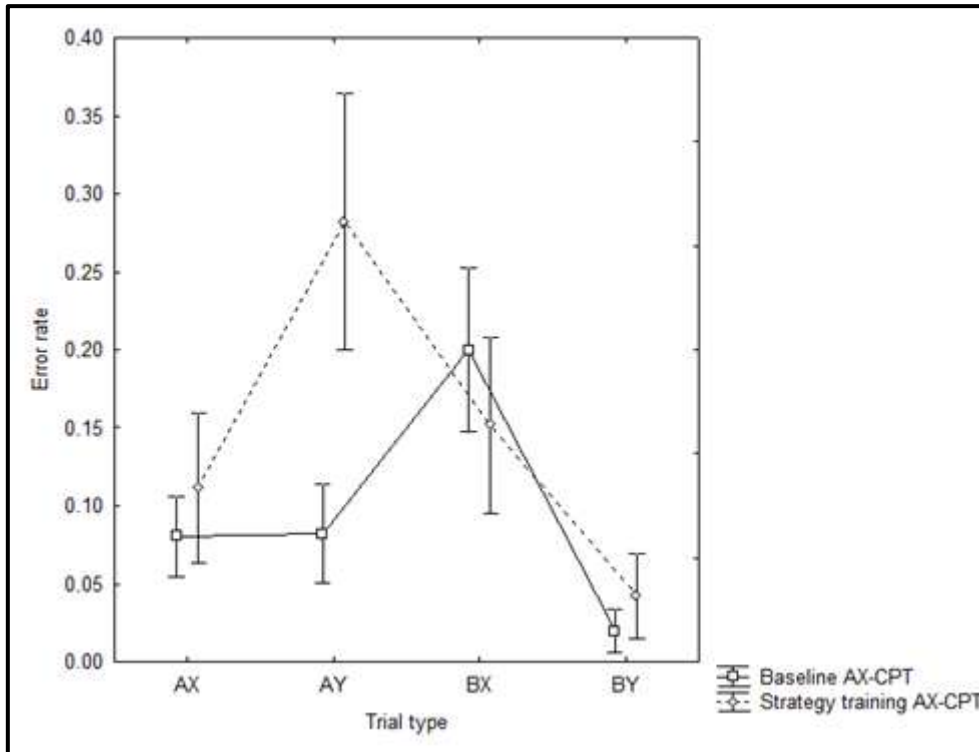


Figure 21. Average error rates in the AX-CPT as a function of trial type and task condition. Error bars represent standard errors of the mean.

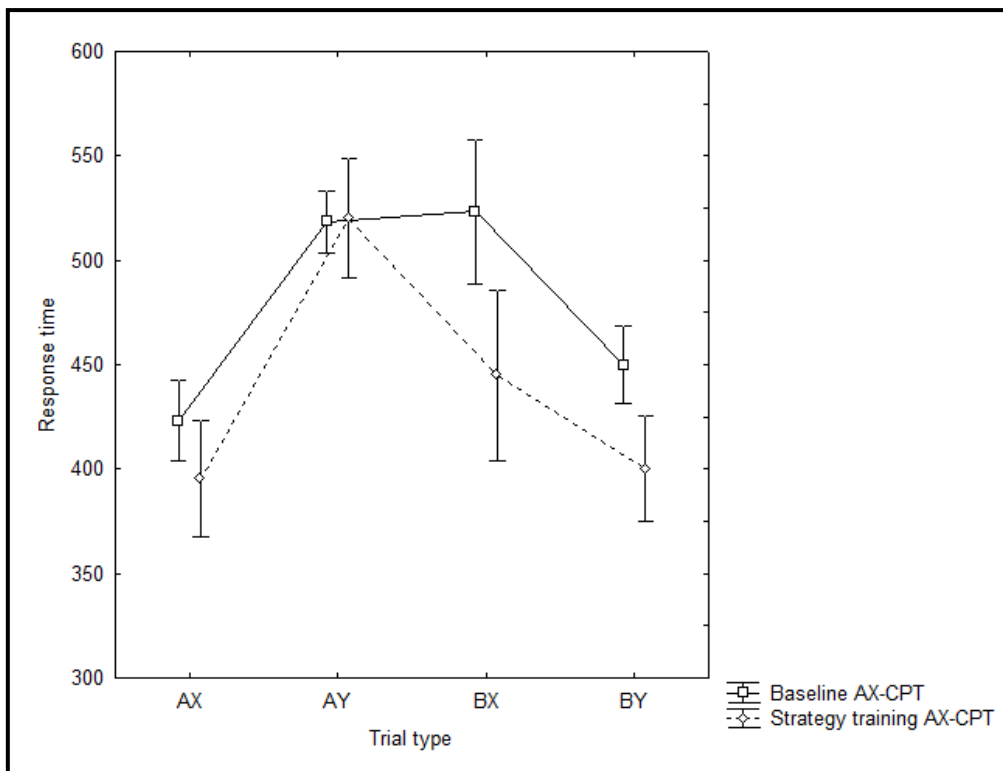


Figure 22. Average response times in the AX-CPT as a function of trial type and task condition. Error bars represent standard errors of the mean.

The fourth preliminary analysis studied responses on the strategy training questionnaire and their relationships with working memory capacity. An exploratory factor analysis (using an independent component analysis followed by normalized varimax rotation; the number of retained factors was determined using Cattell's scree test) revealed that the various items in the questionnaire could not be regrouped in fewer factors, except for questions 2 and 4 which formed a single factor; responses on these two questions were averaged for subsequent analyses. Overall, the participants tried to follow the strategy instructions ( $M = 5.91$ ,  $SD = 1.34$ , range = 1 – 7 out of a possible 9) and did not have any trouble following the instructions ( $M = 2.69$ ,  $SD = 1.64$ , range = 1 – 6 out of a possible 9); they reported that they were already preparing their response in advance in the baseline and penalty AX-CPT ( $M = 5.22$ ,  $SD = 1.92$ , range = 1 – 9 out of a possible 9), but that the strategy instructions did influence the way they performed the task ( $M = 4.99$ ,  $SD = 1.56$ , range = 1 – 8 out of a possible 9). Importantly, none of the questions correlated with working memory capacity, all  $F_s < 1$ , suggesting that participants were not differentially affected by the strategy training as a function of their working memory capacity.

### 2.2.3.3. *Main analyses.*

Our first hypothesis was that working memory capacity would be positively correlated with the  $d'$ -context in the baseline AX-CPT, indicating that participants with high working memory capacity were more likely to use proactive control and replicating the results of Experiment 5b. This was not the case,  $F(1, 34) = 0.00$ ,  $MSE = 0.559$ ,  $p = .971$ ,  $\eta_p^2 = .00$ ,  $r = -.01$ , in direct contradiction with Experiment 5b. Neither was working memory capacity associated with the composite PBI,  $F(1, 34) = 0.13$ ,  $MSE = 0.482$ ,  $p = .723$ ,  $\eta_p^2 = .00$ ,  $r = -.06$ , the PBI calculated on errors,  $F(1, 34) = 0.31$ ,  $MSE = 0.00691$ ,  $p = .579$ ,  $\eta_p^2 = .01$ ,  $r = -.10$ , or the PBI calculated on RTs,  $F(1, 34) = 0.00$ ,  $MSE = 0.559$ ,  $p = .971$ ,  $\eta_p^2 = .00$ ,  $r = -.01$ . Thus, working memory capacity was not associated with a higher tendency to use proactive control in the baseline AX-CPT.

Our second hypothesis was that the relationship between working memory capacity and the tendency to use proactive control would differ between the baseline AX-CPT and the penalty AX-CPT, with the difference between participants as a function of their working memory capacity being reduced in the penalty AX-CPT. Although this hypothesis was invalidated by the preliminary analysis indicating that the penalty AX-CPT did not succeed in shifting participants towards reactive control, the analysis was carried out all the same for exploratory purposes. The two-way interaction between working memory capacity and task

condition was not significant for either the  $d'$ -context or any of the PBIs, all  $F_s < 1$ , indicating that the relationships between working memory capacity and performance indices were similar in the baseline and the penalty AX-CPT. Congruent with this conclusion, working memory capacity did not correlate with either the  $d'$ -context or any of the PBIs in the penalty AX-CPT, all  $F_s < 1$ , similar to the baseline AX-CPT.

Our third hypothesis was that the relationship between working memory capacity and the tendency to use proactive control would differ between the baseline AX-CPT and the strategy training AX-CPT, with the difference between participants as a function of their working memory capacity being reduced in the strategy training AX-CPT. The two-way interaction between working memory capacity and task condition was not significant for either the  $d'$ -context or any of the PBIs, all  $F_s < 1$ , indicating that the relationships between working memory capacity and performance indices were similar in the baseline and the penalty AX-CPT. Working memory capacity did not correlate with either the  $d'$ -context, the PBI calculated on errors or the composite PBI in the strategy training AX-CPT, all  $F_s < 1$  except for the PBI calculated on RTs,  $F(1, 32) = 2.71$ ,  $MSE = 0.00581$ ,  $p = .110$ ,  $\eta^2_p = .08$ ,  $r = -.28$ .

#### 2.2.3.4. *Exploratory analyses.*

As in Experiment 5a, we examined the correlation between working memory capacity and performance on each trial type as a function of the task block to better understand the relations between working memory capacity and performance. This data is presented in Table 12. Working memory capacity was not significantly related to performance on any trial type, either in terms of error rates or RTs, all  $p_s > .10$ ; controlling for performance on BY trials did not change this conclusion.

#### 2.2.4. *Discussion*

In this experiment, we expected to evidence a correlation between working memory capacity and the tendency to use proactive control in a baseline version of the AX-CPT 40 including no-go trials, thus replicating the results of Experiment 5a; we also expected this correlation to be reduced in a penalty AX-CPT designed to shift participants towards reactive control and in a strategy training AX-CPT designed to shift participants towards proactive control. The results did not confirm these hypotheses: working memory capacity was completely unrelated to the tendency to use proactive control in the baseline AX-CPT as well as in the two others conditions.

Table 12

*Bivariate correlations between working memory and performance indices as a function of trial type and task condition*

Dependent variable	Trial type	Baseline AX-CPT	Penalty AX-CPT	Strategy training
				AX-CPT
Average error rate	AX	.04	.14	.10
	AY	.03	-.00	.00
	BX	.01	-.04	-.06
	BY	.11	-.18	-.03
	NGA	.13	.26	-.25
	NGB	.07	.09	-.20
Median RT	AX	-.09	.06	.15
	AY	.11	.12	-.17
	BX	.13	.00	.09
	BY	-.03	.10	.08

*Note.* NGA = no-go trials starting with an A-cue; NGB = no-go trials starting with any other cue. The correlations between working memory capacity and response times on no-go trials were not computed because there were not enough data points to provide a reliable estimate. None of the correlations were significant.

The strategy training AX-CPT appeared entirely successful in biasing participants towards proactive control. As expected, all performance indices suggested that participants were more likely to use proactive control after being trained to do so; this finding constitutes a replication of previous studies (Paxton et al., 2006; Braver et al., 2009; Edwards et al., 2010). One caveat in interpreting the results of the strategy training is that participants always completed this condition last, which means the effect of the strategy training was confounded with task order. This is an important problem because a previous study has suggested that the tendency of participants to use proactive control increases with practice on the AX-CPT, independently of any strategy training (Paxton et al., 2006). Although the participants' answers on the strategy questionnaire suggest that the training did affect the way they performed the task, it would be interesting for future studies to distinguish the effect of strategy training from the practice effect.

By contrast, the monetary penalties in the penalty AX-CPT appeared unsuccessful in biasing participants towards using reactive control. In terms of response times, it seems that the main effect of the penalty manipulation was to induce a general slowing in responses on all trial types, rather than a selective slowing on BX trials as expected; thus, it would seem that participants did not significantly change their strategy on the task, but that they simply took more time to check the nature of the probe in all trials. As for error rates, the results suggested that participants were more likely to use proactive control in the penalty AX-CPT, also contrary to our hypothesis. The DMC framework predicts that proactive control is more likely to be used in tasks in which participants strive to maximize rewards, due in part to the dependency of proactive control on the dopaminergic system also involved in motivation and reinforcement learning (Braver et al., 2007), which might explain the greater involvement of proactive control in the penalty AX-CPT. However, a simpler interpretation is that the monetary stakes in the penalty AX-CPT increased task engagement and in turn the probability that participants would use the more costly proactive control strategy. An even simpler interpretation relies on the fact that the penalty condition was always completed after the baseline condition; as mentioned above, the use of proactive control tends to increase with practice in the AX-CPT, which suggests the higher tendency of participants to use proactive control in the penalty condition may be due to the practice effect rather than the penalty manipulation itself.

All relationships between working memory capacity and indices of the tendency to use proactive control were non-significant in the various conditions of the AX-CPT. None of the versions of the AX-CPT used in this experiment has previously appeared in the literature, which precludes direct comparisons; however, a correlation between working memory capacity and performance should definitely have appeared in the baseline AX-CPT, since it was very similar to common versions of the task – save for the no-go trials, which did not prevent a correlation with working memory capacity from emerging in Experiment 5a. Thus, the results of Experiment 5b should be considered a non-replication of the relationship between working memory and the AX-CPT.

At 35 participants, the sample size of this study was quite small, which may explain part of our failure to replicate the relationship; for example, the fact that working memory capacity was not negatively related to RTs in Experiment 5b, contrary to Experiment 2b and Experiment 5a, may simply be due to the lack of statistical power. However, the problem of power is insufficient to fully explain the lack of replication: the main result of Experiment 5a that we expected to replicate, namely the relationship between working memory capacity and

the  $d'$ -context in the baseline condition, was associated with an  $F$  equal to zero and a  $p$  greater than .95. This result suggests that the correlation between working memory capacity and the  $d'$ -context in the no-go AX-CPT in Experiment 5a may have been due to chance; although Experiment 5a had about twice as much statistical power, recall that the relationship between working memory capacity and the  $d'$ -context had been unpredicted and observed amid a large set of statistical tests performed without correction.

In summary, Study 5 did not manage to evidence a relationship between working memory capacity and the tendency to use proactive control in the AX-CPT. Although our attempt to manipulate the use of cognitive control mechanisms in the task was successful for both the no-go AX-CPT and the strategy training, suggesting that our versions of the task had significant construct validity, these manipulations did not lead to reproducible modulation of the relationship between working memory capacity and performance. Instead, a high working memory capacity was only associated with non-specific differences in performance such as generally faster response times in Experiment 5a.

### **3. Study 6 – A global measure of proactive control**

#### **3.1. Rationale**

Studies 2 to 5 did not manage to convincingly evidence a relationship between working memory capacity and behavioural measures of the tendency to use proactive control, contrary to our thesis. Did these studies share a design flaw that could explain their failure? One common feature of all studies presented in Chapters 4 to 6 was the use of a single cognitive control task to assess proactive control and test its relationship with working memory capacity. This design leaves open the possibility that a single task is not sufficient to obtain a valid measure of the tendency to use proactive control. This idea is plausible: given that cognitive control deals with the regulation of other abilities, its measure is intimately tied with the specific task being used; as a consequence, performance in a cognitive control task should reflect joint contributions of cognitive control and various other abilities, such as the efficiency of task-specific processes (see pp. 62-63 for a discussion of this point). As a consequence, the absence of a correlation between working memory capacity and performance in the cognitive control tasks used in previous studies may be explained by the confounding of cognitive control with irrelevant task-specific processes. The low reliability estimates found for cognitive control tasks in previous studies may also contribute to worsening the validity of these tasks. Importantly, this problem could be solved by the use of multiple cognitive control tasks to obtain a domain-general measure of the tendency to use

proactive control: if using very different tasks to measure cognitive control, the variance common to all tasks can be expected to reflect the underlying cognitive control ability rather than task-specific processes. This logic is equivalent to the motivation for measuring working memory capacity with the CCS, which combines multiple complex span tasks based on different materials. A strong argument in favour of this idea is that individual cognitive control tasks are often observed to be weakly correlated with other constructs, whereas latent variables estimated on the basis of the same tasks are typically more successful (for examples of this phenomenon, see e.g. Unsworth et al., 2010; Unsworth & Spillers, 2010).

Study 6 was based on the straightforward idea of using multiple tasks to assess cognitive control mechanisms; participants completed a set of three classic cognitive control tasks hypothesized to be influenced by the use of proactive control. These three cognitive control tasks were chosen for their prevalence in the literature. The first task was simply a classic version of the AX-CPT 70, similar to Experiment 2b. The second task was a modified version of the Stroop task where most stimuli were congruent; as detailed in the introduction (p. 48), this version of the task is hypothesized to hold a prominent relation with goal maintenance and in turn with proactive control. More specifically, participants performing a mostly congruent version of the Stroop task are hypothesized to use a global cognitive control mechanism operating throughout the task to actively maintain the task goal of naming the colour rather than reading the word; this global cognitive control mechanism conceptually maps onto proactive control (Bugg, 2012). Participants who effectively use proactive control may be expected to actively maintain the task goal and perform adequately in the task, whereas participants who do not use proactive control may be expected to make more errors. Importantly, a significant number of studies have evidenced a relationship between working memory capacity and performance in the mostly congruent version of the Stroop task (D. L. Long & Prat, 2002; Kane & Engle, 2003; Unsworth & Spillers, 2010; Hutchison, 2011; Morey et al., 2012; Unsworth, Redick, et al., 2012; Meier & Kane, 2012).

The third task was a cued task-switching paradigm (see Rogers & Monsell, 1995; Monsell, 2003). Task-switching, or alternating between two different tasks in quick succession, tends to induce a significant cost in performance, a finding which is often interpreted in terms of interference between the two tasks. Resolving this interference is thought to require cognitive control; the ability to perform task-switching (sometimes termed *shifting*) is frequently classified as an executive function (e.g. Miyake et al., 2000). Cued task-switching refers to a specific task-switching paradigm where each trial requires participants to perform one of two tasks, with the specific task to perform changing randomly from trial to

trial; a cue presented shortly before the beginning of each trial indicates which task should be performed. Past studies have shown that the impact of task-switching on performance is significantly reduced when the subjects are given enough time to prepare before the task-switching occurs (Monsell, Sumner, & Waters, 2003). In other words, the cost of switching between two different tasks tends to decrease when the subject is able to prepare in advance, an observation which may be phrased in terms of proactive control (Monsell, Sumner, & Waters, 2003): proactive control seems to allow participants to reduce the amount of interference due to task-switching.

Given that the AX-CPT, the mostly congruent Stroop and the cued task-switching are all hypothesized to benefit from the use of proactive control, a high performance in these tasks could reflect a high tendency to use proactive control. Participants completed all three cognitive control tasks; we collected indices of the tendency to use proactive control in each task and used them to calculate a domain-general measure of cognitive control. The hypotheses were straightforward: we expected participants using proactive control to perform better in the cognitive control tasks, yielding a higher score on the global cognitive control measure, and we expected the global cognitive control variable to correlate with working memory capacity.

## **3.2. Method**

### **3.2.1. Participants**

A sample of 52 participants completed the experiment (7 males and 45 females; age ranging from 16 to 27,  $M = 19.68$ ,  $SD = 1.87$ ). All participants were undergraduate students from the University of Savoy participating for payment (€10.00 an hour). Participants were included if they met the following criteria: native French speaker, no history of neurological disorders and without psychoactive medication.

### **3.2.2. Materials**

**Working memory task.** Working memory capacity was measured with the CCS (see Appendix A). The main dependent variable was the composite working memory score; we also collected the working memory score in each subtest – in other words, the total number of stimuli correctly recalled across all trials of the subtest after standardization (see Appendix A).

**AX-CPT.** We used a version of the AX-CPT 70 identical to Experiment 2b (see pp. 131-132), with a single exception: in an effort to increase the difficulty of the task, the delay between



the cue and the probe was increased from 1500ms to 3500ms, and the cue and probe were presented for 500ms instead of 1000ms. Median response times and error rates were collected for each trial type; as in Experiment 2b and Study 5, PBIs were computed to index the tendency to use proactive control. In order to balance the number of proactive control indices collected in each of the three cognitive control tasks, only the PBI calculated on errors and the PBI calculated on response times were computed in this study.

**Stroop task.** The Stroop task was modeled after the work of Kane and Engle (2003). Words printed in a certain colour successively appeared on the screen; participants were instructed to name the colour of the ink as quickly and as accurately as possible. Their response times were collected with a microphone attached to a voice key (E-prime SRBOX device; Schneider et al., 2002). An experimenter was present throughout the testing session and manually coded the participants's answers on a keyboard; error rates were collected on all trials. The experimenter coded a scratch trial when the participant provided an unclear answer, or when the voice-key was not tripped by the onset of the participant's answer. Stimuli were lowercase words displayed at the center of the screen against a grey background. Each word remained visible until the voice key detected an answer; trials were separated by a 1000ms ITI. The stimuli could be one of six words (*red, yellow, blue, green, black, white, purple* and *pink*) printed in one of the six corresponding colours. 75% of stimuli were congruent (the colour matched the word) and the remaining 25% were incongruent.

Error rates and median response times were collected throughout the task for incongruent and congruent trials. Median RTs were computed on correct trials only; all trials with RTs lower than 200ms or higher than 3000ms were dropped from the analysis. These measures were used to calculate two indices of the magnitude of Stroop interference (one for error rates and one for RTs); these two Stroop cost indices were computed as:

$$(\text{Trial}_{\text{incongruent}} - \text{Trial}_{\text{congruent}}) / (\text{Trial}_{\text{incongruent}} + \text{Trial}_{\text{congruent}}).$$

A high value of the Stroop cost indices reflected a large amount of interference on incongruent trials when compared to congruent trials. Because proactive control was hypothesized to provide a benefit in resolving interference in the task, a small value of the Stroop cost indices was hypothesized to reflect a high tendency to use proactive control.

**Number-letter task.** The number-letter task was adapted from the work of Rogers and Monsell (1995). In each trial, participants saw one digit and one letter presented at the center of the screen. The stimuli appeared with the letter to the left of the digit in half the trials and the other way around in the other half, counterbalanced across trials. The digits could be even

(2, 4, 6 or 8) or odd (3, 5, 7 or 9); the letters could be vowels (*A, E, I or U*) or consonants (*K, N, R or T*). The digit 0 was excluded from the set of stimuli to avoid confusion with the letter *O* and the vowel *Y* was excluded because pilot testing suggested that certain participants could not tell whether this letter was a vowel or a consonant.

The two stimuli appeared at the center of the screen for 1500ms. Participants had to perform one of two tasks before the expiration of this delay: either decide whether the letter was a vowel or a consonant, or decide whether the digit was even or odd. The nature of the task to perform was indicated by an audio cue presented 3000ms before the stimuli appeared on the screen; this delay was chosen to allow sufficient time for participants to implement proactive control. The audio cue was simply the sound of a synthetic voice saying either "letter" or "digit". Participants were to respond by pressing one of two buttons (blue for "odd" and "consonant" responses, and yellow for "even" and "vowel" responses). They received audio feedback after their response (identical to the AX-CPT, with three sounds indicating a correct answer, an incorrect answer or a too slow answer); the next trial followed after a 1000ms ITI. Participants first completed two single-task blocks of trials – in other words, two blocks where the same task had to be performed on all trials (letters-only first and digits-only second). They then completed a mixed block of trials where the task varied from trial to trial in pseudo-random order.

Error rates and median response times were collected for all trials; these values were then used to compute the dependent variables of interest. Three dependent variables are typically used in the number-letter task. The first dependent variable, the switching cost, corresponds to the cost of switching from one task to another on two consecutive trials; it is computed as:

$$(\text{Trial}_{\text{switch}} - \text{Trial}_{\text{noswitch}}) / (\text{Trial}_{\text{switch}} + \text{Trial}_{\text{noswitch}})$$

A large value of the switching cost index reflects a large decrease in performance when having to switch tasks between from one trial to the next. Since participants were allowed a long delay to prepare for the task prior to each trial and since the switching cost has been shown to be sensitive to proactive control (Monsell et al., 2003), a small value of the switching cost was hypothesized to reflect a high tendency to use proactive control.

The second dependent variable, the mixing cost, corresponds to the cost of completing a block of trials including task-switching constraints; it is computed as:

$$(\text{Block}_{\text{mixed}} - [\text{Block}_{\text{letters}} + \text{Block}_{\text{digits}}] / 2) / (\text{Block}_{\text{mixed}} + [\text{Block}_{\text{letters}} + \text{Block}_{\text{digits}}] / 2)$$

A large value of the mixing cost index reflects a large decrease in performance from the two single-task blocks to the mixed block. To our knowledge, this variable has not been studied in

relation with proactive control; however, a large mixing cost can be assumed to reflect a difficulty in dealing with the task-switching requirements, which could result from a low tendency to use proactive control.

The third dependent variable usually collected in the task-switching paradigm is the task-rule incongruency cost; this dependent variable refers to the cost of performing a task when the two stimuli elicit two different responses – for example, when the letter is a consonant associated with the blue button and the digit is a vowel associated with the yellow button. This cost is computed as the difference in response times between trials where the two stimuli elicit the same answer and the trials where the two stimuli elicit different answers. The interference due to task-rule incongruency has been shown to persist even with a long preparation delay, prompting authors to conclude that this incongruency is resolved through a reactive control mechanism (Monsell et al., 2003); because we were interested in the tendency to use proactive control, this dependent variable was not computed.

### 3.2.3. Procedure

Participants completed the experiment individually in a testing room equipped with a computer, a 19 inches LCD screen, a microphone fixed on the desk, and headphones for phonic isolation. All participants provided written informed consent prior to the experimental session. The protocol was divided in two testing sessions separated by one week so as to limit cognitive fatigue and boredom for the participants. In the first session, participants completed a Sternberg task not presented here, the number-letter task, and the AX-CPT, in order; the whole process took approximately 60 minutes. In the second session, participants completed the Stroop task followed by the CCS, which also took approximately 60 minutes.

The first experimental session began with a Sternberg task irrelevant to the present study, which lasted approximately 20 minutes. Participants then completed the number-letter task; they completed 40 trials in the letters-only task block, 40 trials in the digits-only task block, and 80 trials in the mixed task block. The two single-task blocks were preceded by four practice trials and the mixed task block was preceded by eight practice trials. All trials were presented in pseudo-random order; we ensured that the same task (letter or digit) never had to be performed on four consecutive trials or more, and that the same stimulus (for example, the same letter) never appeared on two consecutive trials. Several variables were counterbalanced across all trials: half the digits were even; half the letters were consonants; the two stimuli in a trial were associated with different responses (for example, an odd digit with a vowel) in half the trials; and half the trials in the mixed block required task-switching. After the number-

letter task, participants completed the AX-CPT, with the same procedure as in Experiment 2b: it included 10 practice trials followed by 110 trials presented in pseudo-random order (with 77 AX trials and 11 of each AY, BX and BY trials).

The second experimental session began with calibration of the microphone; sensitivity of the device was set up individually for each participant so that they did not need to keep in mind the necessity of raising their voice. Participants then completed 288 trials of the Stroop task; these trials were divided into three blocks, and participants took a break between each block. The proportion congruency was 75% within each task block. The trials were presented in the same pseudo-random order for all participants; this order was defined so that there were never two consecutive incongruent trials, and so that the stimuli in two consecutive trials were never the same word or the same colour. The task was preceded by 24 practice trials with 75% proportion congruency; practice trials were repeated until the participant understood the task. At the end of the Stroop task, participants completed the CCS and received a short debriefing.

### **3.3. Results**

#### *3.3.1. Method of analysis*

The method of analysis was similar to other studies with one exception. Due to the small sample size, several variables had non-normal distributions with many outlying values; to account for this problem, a 90% winsorisation was applied to all variables.

#### *3.3.2. Preliminary analyses*

Composite working memory scores were normally distributed and close to the population average ( $M = -0.005$ ,  $SD = 0.69$ , skewness = -0.22, kurtosis = -0.88). For reference, the scores on the subtests of the CCS were also normally distributed and close to the population values (for the reading span,  $M = 0.00$ ,  $SD = 0.97$ , skewness = -0.33, kurtosis = -0.72; for the symmetry span,  $M = 0.04$ ,  $SD = 1.14$ , skewness = -0.34, kurtosis = -1.16; for the operation span,  $M = 0.12$ ,  $SD = 1.10$ , skewness = -0.73, kurtosis = -0.71). Descriptive statistics for the AX-CPT are presented in Table 13.

A first preliminary analysis examined the construct validity of the number-letter task. Overall, RTs were slower in the mixed block ( $M = 724\text{ms}$ ,  $SD = 120$ ) than in the single-task blocks ( $M = 644\text{ms}$ ,  $SD = 72$ ); this difference was significant,  $t(51) = 6.44$ ,  $p < .001$ . Response times were also slower on trials with task-switching ( $M = 738\text{ms}$ ,  $SD = 128$ ) than on trials without task-switching ( $M = 705\text{ms}$ ,  $SD = 125$ ); the difference was significant,

$t(51) = 3.95, p < .001$ . The same effects appeared for error rates: error rates were higher in the mixed block ( $M = .088, SD = .070$ ) than in the single-task blocks ( $M = .041, SD = .028$ ); this difference was significant,  $t(51) = 5.44, p < .001$ ; error rates were descriptively higher on trials with task-switching ( $M = .096, SD = .079$ ) than on trials without task-switching ( $M = .082, SD = .078$ ), although the difference was not significant,  $t(51) = 1.39, p = .171$ .

In other words, participants did demonstrate a cost in performance when task-switching was required.

Table 13

*Descriptive statistics for the AX-CPT*

Trial type	Average error rate (SD)	Median RT (SD)
AX	.046 (.033)	387 (95)
AY	.160 (.145)	489 (94)
BX	.147 (.150)	350 (120)
BY	.044 (.062)	350 (118)
PBI	0.073 (0.460)	0.179 (0.106)

*Note.* Average values with standard deviations in parentheses.

A second preliminary analysis examined the construct validity of the Stroop task. Overall, RTs were slower on incongruent trials ( $M = 818\text{ms}, SD = 116$ ) than on congruent trials ( $M = 639\text{ms}, SD = 71$ ); the difference was significant,  $t(51) = 16.14, p < .001$ . Error rates were also higher in incongruent trials ( $M = .085, SD = .057$ ) than on congruent trials ( $M = .002, SD = .003$ ); the difference was significant,  $t(51) = 10.37, p < .001$ . In other words, the expected Stroop effect appeared in the task. On average, 7.1% of all trials per participant were coded as scratch ( $SD = 4.8$ ).

The final preliminary analysis examined the reliability of the cognitive control tasks. Internal consistency was assessed with the split-half method by computing all performance indices separately for odd and even trials and correlating the two values. The corresponding reliability coefficients are presented in Table 14. Overall, most reliability indices were low and below the minimum recommended threshold of .70; this was especially the case for the complex indices of the tendency to use proactive control – the PBIs, the switching and mixing cost, and the Stroop cost.

Table 14

*Reliability coefficients for the cognitive control tasks*

Task	Dependent variable	Error rate	Median RT
	Single-task blocks	.21	.93
	Mixed block	.71	.89
Number-letter	Mixing cost	.51	.75
	No-switch trials	.56	.77
	Switch trials	.66	.77
	Switching cost	.34	-.07
	Incongruent trials	.55	.86
Stroop	Congruent trials	.83	.86
	Stroop cost	.41	.57
	AX trials	.60	.98
	AY trials	.40	.89
AX-CPT	BX trials	.50	.84
	BY trials	.09	.84
	PBI	.28	.59

*Note.* Single-task blocks = average value for the letters-only and the digits-only blocks.

The matrix of bivariate correlations between all measures of interest is presented in Table 15. Overall, the various indices collected within the same task were correlated, except for the number-letter task where the performance indices did not correlate. However, the correlations between indices collected in different tasks were weak and largely non-significant. No meaningful pattern of correlations was apparent in the matrix.

Table 15

*Matrix of bivariate correlations between the measures of interest*

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1. WMC	–											
2. RSpan	<b>.69</b>	–										
3. SSpan	<b>.64</b>	<b>.36</b>	–									
4. OSpan	<b>.70</b>	<b>.59</b>	<b>.33</b>	–								
5. PBI-errors	.09	.01	-.01	.17	–							
6. PBI-RTs	.03	-.15	-.01	.23	<b>.41</b>	–						
7. StroopErr	-.17	-.05	-.10	-.07	.19	.10	–					
8. StroopRT	-.10	<b>-.33</b>	-.10	-.25	.19	.22	<b>.29</b>	–				
9. MixingErr	<b>-.32</b>	-.24	-.17	-.18	.04	-.15	.07	-.01	–			
10. MixingRT	.11	-.02	.09	-.12	-.27	.03	-.05	-.03	.03	–		
11. SwitchErr	-.11	-.03	-.20	-.08	-.17	-.17	-.15	-.06	.07	.16	–	
12. SwitchRT	.07	.05	-.27	.04	-.06	-.05	-.01	.04	.05	-.07	-.12	–

*Note.* Significant correlations in bold. WMC = composite working memory score on the CCS; RSpan = score on the reading span subtest of the CCS; SSpan = score on the symmetry span subtest of the CCS; OSpan = score on the operation span subtest of the CCS; PBI-errors = PBI calculated on errors; PBI-RTs = PBI calculated on RTs; PBI-comp = average of the two other PBIs after standardization; StroopErr = Stroop cost calculated on errors; StroopRT = Stroop cost calculated on RTs; MixingErr = mixing cost calculated on errors; MixingRT = mixing cost calculated on RTs; SwitchErr = switching cost calculated on errors; SwitchRT = switching cost calculated on RTs.

### 3.3.3. Main analysis

Our main hypothesis in this study was that calculating a global measure of the tendency to use proactive control by taking into account performance in multiple cognitive control tasks would demonstrate a higher correlation with working memory capacity than individual indices. Although a latent variable analysis would be the most appropriate technique to test this hypothesis, the low sample size in this study did not allow for this approach. Instead, we chose the less fine-grained method of standardizing and then averaging the scores on the various indices representing proactive control to form a global cognitive

control score; this global score comprised the two PBIs, the two Stroop costs, and the average of the two switching costs and the two mixing costs<sup>14</sup>. This global cognitive control score approximately followed a normal distribution ( $M = 0.00$ ,  $SD = .38$ , skewness = .34, kurtosis = .05).

We expected the global cognitive control score to correlate with working memory capacity. This was indeed the case,  $F(1, 50) = 5.38$ ,  $MSE = 0.168$ ,  $p = .024$ ,  $\eta^2_p = .10$ ,  $r = .31$ . This correlation is depicted in Figure 23; overall, participants with high working memory capacity tended to obtain a higher global cognitive control score. Because the statistical assumptions of the general linear model were not well respected in this analysis (see Figure 23), we tested the same correlation with Kendall's *tau-a*, a non-parametric correlation test. This test also indicated a significant correlation between working memory capacity and global cognitive control score,  $\tau = .21$ ,  $p < .05$ .

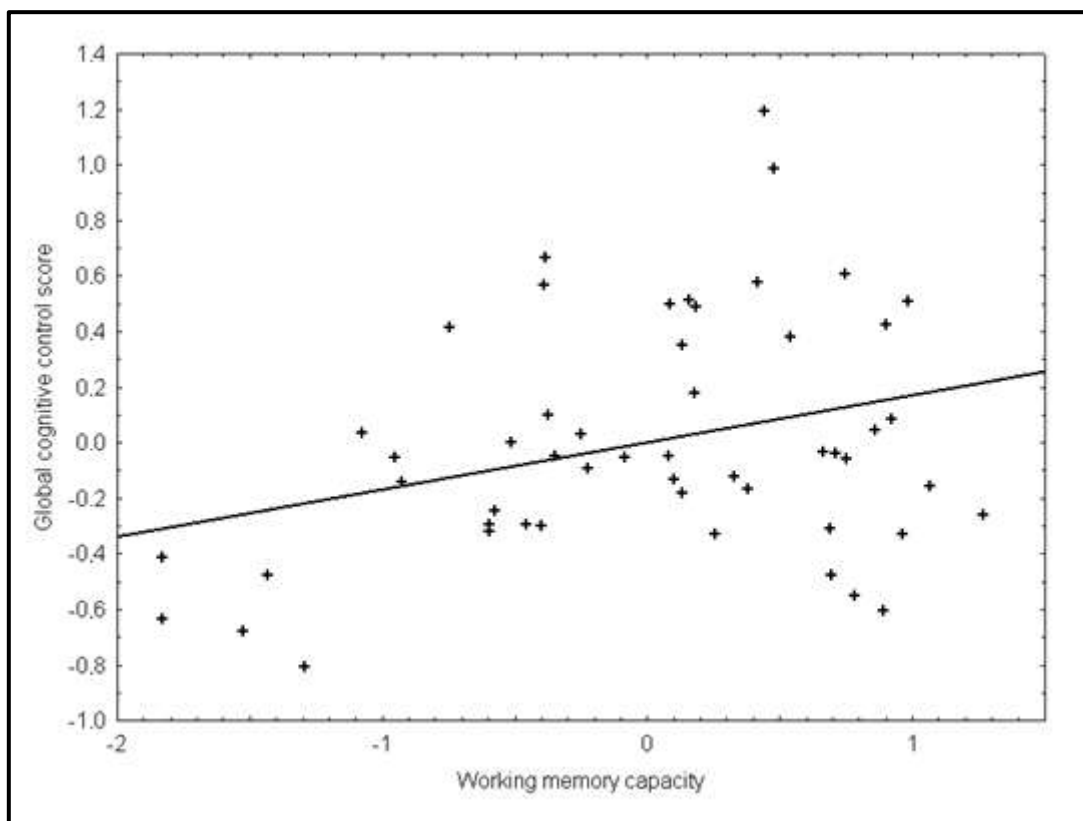


Figure 23. Correlation between working memory capacity and score on the global cognitive control score.

<sup>14</sup> The two Stroop cost indices, the two switching costs and the two mixing costs were reversed so that high values indicated a high tendency to use proactive control, similar to the PBI.



### 3.3.4. Exploratory analyses

The absence of bivariate correlations between working memory capacity and performance in both the AX-CPT and the Stroop task is especially striking, since these relationships have been previously evidenced in the literature. To better understand this discrepancy, exploratory analyses were carried out to examine the correlation between working memory and performance in these tasks in detail.

For the AX-CPT, working memory capacity was not correlated with median response times on any trial type, all  $F_s < 1$ . Participants with high working memory capacity made less errors on AX trials,  $F(1, 49) = 4.21$ ,  $MSE = 0.00101$ ,  $p = .046$ ,  $\eta^2_p = .08$ ,  $r = -.28$ , but working memory capacity was unrelated to error rates on all other trial types, all  $p_s > .20$ . When controlling for performance on BY trials (as in Richmond et al., 2013), working memory capacity was unrelated on performance on all trial types in terms both of RTs and error rates, all  $F_s < 1$  except for error rates on AX trials,  $F(1, 47) = 2.48$ ,  $MSE = 0.000867$ ,  $p = .122$ ,  $\eta^2_p = .05$ . Thus, working memory capacity was not related to a specific pattern of performance related to proactive control in the AX-CPT.

For the Stroop task, the relationship between working memory capacity and performance was tested with a 2 (trial type) x WMC design to facilitate comparison with published studies. For error rates, working memory capacity did not interact with trial type,  $F(1, 49) = 0.72$ ,  $MSE = 0.00168$ ,  $p = .399$ ,  $\eta^2_p = .01$ , indicating that the Stroop effect was not larger for participants with low working memory capacity; the main effect of working memory capacity was not significant,  $F(1, 49) = 0.86$ ,  $MSE = 0.00164$ ,  $p = .358$ ,  $\eta^2_p = .02$ . For RTs, working memory capacity did not interact with trial type either,  $F(1, 48) = 0.35$ ,  $MSE = 1974$ ,  $p = .559$ ,  $\eta^2_p = .01$ , again indicating that the amount of interference did not differ as a function of working memory capacity; the main effect of working memory capacity was not significant either,  $F(1, 48) = 0.04$ ,  $MSE = 15047$ ,  $p = .848$ ,  $\eta^2_p = .00$ .

### 3.4. Discussion

The objective of this study was to estimate a global cognitive control measure on the basis of three classic cognitive control tasks sensitive to the use of proactive control; we expected working memory capacity to correlate with the global cognitive control measure. The data supported this hypothesis: a high working memory capacity was associated with a higher score on the global cognitive control measure, despite working memory capacity being largely uncorrelated with individual proactive control indices estimated in individual tasks.

These results strongly advocate the use of multiple tasks to measure cognitive control and also suggest that our failure to evidence a relationship between working memory capacity and cognitive control in previous studies might be due to measurement problems. Combining scores in several tasks to obtain a more valid estimate of the underlying ability is an elementary principle in psychometrics, but as we have seen, it fits particularly well with the notion that measures of cognitive control are intimately tied with irrelevant task-specific processes. Importantly, the weak correlations involving individual cognitive control scores may also stem from their low reliability. As described in the preliminary analyses, almost none of the reliability coefficients for individual indices of the tendency to use proactive control reached the minimum threshold of .70; the reliability coefficient for the switching cost calculated on RTs even reached a frightening *minus* .07. Although these coefficients are likely to be underestimates – as discussed in Experiment 5a, the split-half procedure combined with the small number of trials probably yields lower values than a test-retest procedure would – they certainly do not vouch for the high validity of the measures. It is noteworthy that all cognitive control indices used in this study were computed as difference scores; the low reliability of difference scores is a well-known problem (see e.g. Thomas & Zumbo, 2012). This is partly because the reliability of difference scores is a function of the two scores used to compute them, and the reliability of individual scores is already low in many cases in the tasks used here. But the biggest problem might be the fact that the reliability of difference scores decreases when the bivariate correlation between the scores used to compute them increases (Thomas & Zumbo, 2012), and these scores are often highly correlated in cognitive control tasks: for example, the correlation between the two average RTs used to compute the switching cost (RTs on trials with switching and RTs on trials without switching) was .89 in this study. In short, combining multiple indices of cognitive control may be a strategy worth generalizing in future studies.

Another striking result in this study is that we again failed to replicate the correlations between cognitive control tasks and working memory capacity reported in the literature. Working memory capacity was not associated with differences in the use of proactive control in the AX-CPT, as in Experiment 2b, Experiment 5a and Experiment 5b; a novel finding is that working memory capacity was not associated with performance in the mostly congruent Stroop task either, contrary to many published findings<sup>15</sup>. Of course, this failure might be

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<sup>15</sup> We also failed to observe a relationship between working memory capacity and a mostly congruent Stroop task in another experiment not reported here, labeled Experiment 6b. This experiment used a picture-word Stroop including 75% of congruent trials and a total of 288 trials; working memory capacity was measured with

attributable to the low sample size and low reliability coefficients; on the other hand, reliability coefficients probably had similar values in published studies for the reasons outlined above, and certain studies have evidenced a correlation between working memory capacity and performance in the Stroop task with even smaller samples (e.g. D. L. Long & Prat, 2002; Experiment 1, who worked with a total of 20 participants). Again, no obvious reason seems to fully explain our failure to replicate the literature.

Although the results were promising in indicating that working memory capacity correlated with a global measure of cognitive control – the first evidence of a relationship between working memory and cognitive control in the studies presented so far –, the small number of participants in the study means these results should be approached with caution. The low sample size posed several problems to the interpretation of the results: it led us to resort to simply averaging the dependent variables, rather than using a more sophisticated approach such as a latent variable analysis – which would have been more appropriate given the design; it was associated with a violation of statistical assumptions in the main analysis of interest; and studies collecting as many variables as ours typically use sample sizes at least twice or thrice larger. Unfortunately, sample size in this study was limited by practical constraints, including the duration of the protocol and the available funding.

Even if we assume that our results were reliable despite the low sample size and that working memory capacity actually correlated with the global cognitive control measure, the biggest limitation of this study remains: there is no way to tell whether the score on the global cognitive control measure actually reflected the use of proactive control. The Stroop task and number-letter task used to index cognitive control in this study were selected for their sensitivity to proactive control, but contrary to the tasks used in Study 2, Study 3, Study 4 and Study 5, they were not designed to specifically assess proactive control. Although the PBIs calculated in the AX-CPT might be hypothesized to uniquely index the tendency to use proactive control, this is definitely not the case for the measures used in the two other tasks: the indices of cognitive control in both the Stroop task and the number-letter task were calculated as the cost in performance when confronted to interference (either created by the Stroop effect or by task-switching), and this cost can be expected to be heavily influenced by mechanisms other than the efficient use of proactive control, such as the ability to resolve interference (see e.g. Kane & Engle, 2003). The notion that the cognitive control score

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the reading span, symmetry span and operation span. Working memory capacity did not correlate with the Stroop cost calculated on error rates, with the Stroop cost calculated on RTs, with the combination of the two, or with any index of performance in the task, all  $F_s < 1$ .

depended on the ability to resolve interference is especially problematic since this ability has been related to working memory in the past (e.g. Engle & Kane, 2004). Thus, the correlation between working memory capacity and the global cognitive control measure observed in this study may be driven by factors other than cognitive control.

In summary, this study represented a step forward when compared to prior research using generic cognitive control tasks: given that the protocol included paradigms chosen for their sensitivity to proactive control, the observed correlation between cognitive control and working memory capacity might reflect a relationship between working memory capacity and the tendency to use proactive control. Since individual cognitive control estimates were entirely uncorrelated with working memory capacity, these results were also informative in suggesting that measuring proactive control with a single indicator is not a promising strategy. However, the contribution of these results to our thesis was limited by the low sample size and most importantly by the fact that the global cognitive control estimate did not uniquely reflect the tendency to use proactive control. In short, Study 6 suffered from the same shortcoming as Study 1b: the results were congruent with our expectations, but they did not provide a critical test of our thesis.

#### **4. Conclusion**

The two studies presented in this chapter were not decisive in establishing a relationship between working memory capacity and the tendency to use proactive control. Three consecutive experiments (not including Experiment 2b) failed to evidence a relationship between working memory capacity and the tendency to use proactive control in the AX-CPT; we also failed to replicate the classic correlation between working memory capacity and performance in a mostly congruent Stroop, and working memory capacity was not related to a cued task-switching paradigm either. Thus, using classic cognitive control tasks did not do much to strengthen the evidence of a relationship between working memory capacity and proactive control. The analysis presented in Appendix C suggested that this replication failure was not due to a difference between French and American samples. Study 6 showed that working memory capacity was correlated with a global measure of cognitive control incorporating measures from multiple tasks, which suggested that our difficulty to evidence a relationship between working memory and proactive control could stem both from the use of individual tasks to measure proactive control and from the low reliability of cognitive control indices; however, this result did not unambiguously indicate a relationship between working memory capacity and the tendency to use proactive control.

Given the lack of unequivocal measures of the tendency to use proactive control with high reliability and demonstrable replicability across studies, correlating behavioural measures of the tendency to use proactive control with working memory capacity does not seem to be a promising strategy. In the next chapter, we tried to overcome the shortcomings of behavioural measures by indexing the tendency to use proactive control through the study of brain activity.

# CHAPTER 7. BRAIN ACTIVITY AS A PROACTIVE CONTROL INDEX

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## 1. Overview

In Chapter 4, Chapter 5 and Chapter 6, we consistently failed to observe a relationship between working memory capacity and the tendency to use proactive control in paradigms new and old. The results of Study 6 suggested that this failure could be due to a fundamental difficulty in obtaining a valid behavioural measure of the tendency to use proactive control, because of the impurity of the tasks and/or because of the low reliability of the measures. This point, combined with the difficulty of devising a specific measure of proactive control, leaves us two alternatives. The first solution would be to run a high-powered study with high sample size and to use a latent variable analysis to extract a global measure of the tendency to use proactive control, with no guarantee that this measure would accurately reflect proactive control (for the reasons outlined in the introduction, pp. 61-65). The second solution is to use indices other than behavioural measures.

One major strength of the DMC framework is that proactive and reactive control are described in association with patterns of brain activity: recall that proactive control is associated with sustained activity in the dorsolateral prefrontal cortex, presumably for active maintenance of contextual information, whereas reactive control is associated with transient activation of the dorsolateral prefrontal cortex and the anterior cingulate cortex when a stimulus requiring control appears (see p. 68). Although both mechanisms are hypothesized to be supported by a much more extensive neural network (see Braver et al., 2007), this separability in terms of neural activations and time dynamics suggests that brain activity can be used to determine whether a participant uses proactive or reactive control. Indeed, a participant who demonstrates sustained activity in the dorsolateral prefrontal cortex throughout the delay of a task can be assumed to use proactive control, whereas a participant who demonstrates transient activity can be assumed to use reactive control.

As we have seen (pp. 71-73), a number of studies have used fMRI to assess the use of proactive and reactive control in participants. Although most of these studies have tested mechanisms of the DMC framework as a function of age (e.g. Paxton et al., 2008), pathology (e.g. Edwards et al., 2010), or features of the task (e.g. G. C. Burgess & Braver, 2010), there is no reason that the same designs cannot be applied to the study of individual differences in working memory capacity: multiple studies have successfully related brain activity to

individual differences within groups of non-pathological young adults (see Braver, Cole, & Yarkoni, 2010). Several authors have studied brain activity associated with cognitive control as a function of individual differences in working memory capacity (e.g. G. C. Burgess et al., 2011); although their works do not provide a critical test of our thesis, they illustrate that neuroimaging can inform us about the relationship between working memory and cognitive control. Generally speaking, neuroimaging seems an especially promising tool to understand the basis of individual differences (see Yarkoni & Braver, 2010). One major advantage of this approach is that brain activity can provide a relatively purer index of cognitive control mechanisms when compared to behavioural tasks: for example, a high performance on AX trials in the AX-CPT may reflect the use of proactive control, but also a high processing speed or a high ability to retrieve contextual information in memory; on the other hand, observing sustained neural activity in the prefrontal cortex unambiguously indicates that proactive control is being implemented.

The two studies presented in this chapter used a neuroimaging approach to test the hypothesis that working memory capacity is related to the tendency to use proactive control. Brain activity was studied with fMRI and with electroencephalography (EEG) to obtain a measure of the tendency to use proactive control, as reflected by the amount of sustained activity – especially in the dorsolateral prefrontal cortex – during the delay period in a task. This measure was then correlated with an independent behavioural measure of working memory capacity. We expected participants with high working memory capacity to demonstrate a pattern of brain activity most congruent with a high tendency to use proactive control.

## **2. Study 7 – Functional MRI and the AX-CPT**

### **2.1. Experiment 7a**

#### **2.1.1. Rationale**

Although the AX-CPT is the paradigmatic task associated with the DMC framework, its relationship with working memory capacity appears questionable at best. Beyond the studies presented in the introduction, which did not provide clear-cut evidence of a specific pattern of proactive control for participants with high working memory capacity (see pp. 80-87), we directly failed to observe a specific relationship between the two constructs in Experiment 2b, Experiment 5a, Experiment 5b and Study 6. These findings contrast with the high success of the AX-CPT in assessing proactive control in neuroimaging studies (e.g.

Barch et al., 2001; A. MacDonald & Carter, 2003; Paxton et al., 2008; Braver et al., 2009; Edwards et al., 2010). As outlined above, however, the failure to observe a relationship between working memory capacity and the AX-CPT may be due to the use of behavioural indices of performance, rather than neuroimaging data.

As we have seen, the main problem with attempts to correlate performance in the AX-CPT with working memory capacity is that participants with high working memory capacity tend to perform generally better on all trial types, which does not provide a critical test of the DMC framework. Interestingly, one study (A. MacDonald & Carter, 2003) encountered a similar problem with schizophrenic patients, who were systematically outperformed by control participants on all trial types; however, the authors successfully used fMRI to show that schizophrenic patients demonstrated lower activity in the dorsolateral prefrontal cortex during the delay period of the AX-CPT, unambiguously indicating that these participants used less proactive control in the task. This study illustrates how investigating neural activity can lead to drawing inferences about cognitive control mechanisms, even when behavioural results are not informative. Measuring brain activity in the task may provide a purer measure of the tendency to use proactive control, relatively unaffected by the usual confounds of cognitive control. In support of this idea, a large proportion of the studies that successfully used the AX-CPT focused on brain activity in the task, rather than on behavioural performance.

The objective of Experiment 7a was simple: measuring brain activity in the AX-CPT through fMRI, and testing the hypothesis that this activity varied as a function of working memory capacity. One group of participants with low working memory capacity and one group with high working memory capacity were invited to complete the AX-CPT while undergoing fMRI scanning. The delay separating cue and probe in each trial was manipulated to create a short-delay and a long-delay version of the AX-CPT. This delay manipulation has been successfully used in past studies to evidence the use of proactive control in the AX-CPT: since proactive control, but not reactive control, relies on sustained neural activity during the delay, increasing the length of the delay elicits different results as a function of the control mechanism, in terms of behavioural performance (e.g. Braver et al., 2005) and most importantly in terms of brain activity (e.g. Barch et al., 2001; Paxton et al., 2008). In one study in particular, Paxton and colleagues (2008; Study 1) used the delay manipulation to evidence a difference in the use of control mechanisms between young and older adults. Young adults, hypothesized to use proactive control, demonstrated increased activity in the dorsolateral prefrontal cortex during the delay of the AX-CPT in a long-delay condition when



compared to a short-delay condition. Comparatively, older adults, hypothesized to use reactive control, demonstrated a reduced activity in the dorsolateral prefrontal cortex in a long-delay condition when compared to a short-delay condition.

In the current experiment, we elected to closely replicate the procedure used by Paxton and colleagues. We expected to observe a similar effect: the length of the delay was hypothesized to interact with working memory capacity, with participants in the high span group demonstrating increased activity in the dorsolateral prefrontal cortex in the long-delay condition and participants in the low span group demonstrating reduced activity. This difference in brain activity as a function of working memory capacity was hypothesized to be restricted to delay-related activity: we did not expect to observe more general differences in task-related activity, such as higher overall activity for participants in the high span group.

### *2.1.2. Method*

This experiment was approved by an ethics committee (Comité de Protection des Personnes Sud-est V) under approval number 13-CHUG-47 and by the competent governmental institution (the Agence Nationale de Sécurité du Médicament [ANSM]) under approval number 131568B-31. All participants provided written informed consent and completed a medical check-up before entering the scanner.

#### *2.1.2.1. Participants.*

A sample of 106 undergraduates at the University of Grenoble participating for course credit completed a working memory pre-test; working memory capacity was measured with the modified version of the CCS replacing the reading span by the alpha span (see Appendix A), and the composite working memory score was computed for each subject. Participants who fell in the upper quartile or the lower quartile of the distribution of working memory scores were invited to participate in the fMRI session for course credit. Participants were included if they met the following criteria: native French speaker, right-handed, no history of neurological disorders, without psychoactive medication, normal or corrected-to-normal vision, and no dental fillings or dental braces. The final sample comprised 20 participants (2 males and 18 females; age ranging from 18 to 26,  $M = 20.92$ ,  $SD = 2.03$ ) divided into a low span group ( $n = 9$ ) and a high span group ( $n = 11$ ). A two-sample  $t$ -test indicated that working memory scores were significantly lower in the low span group ( $M = -0.86$ ,  $SD = 0.44$ ) than in the high span group ( $M = 0.72$ ,  $SD = 0.40$ ),  $t(17) = -8.21$ ,  $p < .001$ .

### 2.1.2.2. *Behavioural task.*

We used a version of the AX-CPT 70 (with 70% of AX trials and 10% of each AY, BX and BY trials) closely based on the work of Paxton and colleagues (2008). Cues and probes were white letters displayed against a black background, presented in 48-point uppercase Helvetica font at the center of the screen. Cues and probes could be any letter in the alphabet (except *B, H, K, V, W, and Y*, as in Paxton et al., and *I* and *O* due to their similarity with the digits *1* and *0*). In each trial, participants were confronted with a cue presented for 300ms, a delay period, a probe presented for 300ms with an additional 1000ms response period, and an ITI. The long-delay condition used a 4700ms delay and a 1200ms ITI, whereas the short-delay condition used a 1200ms delay and a 4700ms ITI; as a consequence, total trial duration was equated across conditions. The delay period and the additional response period were unfilled (i.e., participants only saw a black screen); the message "prepare for the next trial" was displayed during the ITI. Participants were instructed to respond to each stimulus (including both cues and probes) by pressing a "target" button (in yellow) with their index or a "non-target" button (in blue) with their middle finger; they were informed that they always had to respond within 1000ms. The same dependent variables as in Study 2, Study 5 and Study 6 were collected: error rates and median RTs were recorded for each trial type, with median RTs computed on correct trials only; the three PBIs and the  $d'$ -context were also computed.

### 2.1.2.3. *Procedure and paradigm.*

The fMRI session took place one month after the working memory pre-test. Participants were instructed to avoid wearing any makeup or hair conditioner, drinking coffee, smoking, or taking unusual medicine prior to the imaging session. The instructions for the AX-CPT were explained to participants outside the scanner and they completed a few practice trials with the experimenter before entering the scanner. While in the scanner, participants completed a series of 10 practice trials for the long-delay condition and 10 trials for the short-delay condition during the calibration scans; the practice trials were repeated until participants reached 80% of correct answers. The protocol then proceeded to the actual task; participants completed the AX-CPT while the scanner acquired functional images. The AX-CPT was followed by two other tasks not reported here (a  $n$ -back and a reading span), and a structural image was then acquired. Participants were fully debriefed at the end of the protocol. Overall, participants spent approximately 50 minutes inside the scanner.

The paradigm for the AX-CPT was a block design. Participants completed three blocks of 20 trials each (or 60 repetition times [TR]) for the short-delay condition and three blocks of 20 trials each (or 60 TR) for the long-delay condition, in random order. Trials within a task block were presented in the same pseudo-random order for all participants with the constraint that there could never be two consecutive AY, BX or BY trials. In addition, the six blocks of trials were interleaved with seven fixation blocks to provide a baseline measure of brain activity. The fixation blocks were denoted by a centrally presented crosshair; they lasted 30 seconds each (or 12 TR). In total, participants completed 60 trials (180 TR) per condition and 210 seconds of fixation blocks (84 TR). The overall duration of this functional scan was 18.5 minutes.

#### *2.1.2.4. MRI acquisition.*

Whole-brain images were acquired on a Philips 3.0 Tesla Achieva TX system with a standard head coil. High-resolution structural images were acquired using a 3D turbo gradient echo T1-weighted sequence (TR = 25ms, echo time [TE] = 2.93ms, flip angle = 15°). Each structural image consisted of 128 contiguous axial slices (1 x 1 x 1 mm) acquired parallel to the anterior-posterior commissure plane. Functional images were acquired in ascending order using a multi-shot gradient echo echo-planar imaging T2\*-weighted sequence (TR = 2500ms, TE = 30ms, flip angle = 80°) sensitive to blood-oxygen-level-dependent (BOLD) magnetic susceptibility. Each functional image consisted of 44 contiguous axial slices (2.29 x 2.29 mm in-plane x 3 mm thick) acquired parallel to the anterior-posterior commissure plane. The first four images in each scanning run were used to allow the scanner to reach a steady state and were discarded.

#### *2.1.2.5. fMRI data processing.*

All data processing was performed using the SPM8 toolbox ([www.fil.ion.ucl.ac.uk/spm/](http://www.fil.ion.ucl.ac.uk/spm/)) for MATLAB (The MathWorks, Inc.).

**Pre-processing.** The following pre-processing steps were applied for each participant. The first step was to temporally align the different slices composing each functional image through slice-timing correction, so as to control for differences in the timing of the acquisition. Functional images were then realigned onto the mean image of the series using a rigid-body translation and rotation correction, so as to correct for participant movement (Friston, Williams, Howard, Frackowiak, & Turner, 1996). Functional images were registered to the structural image of the participant in order to correct for movement between the

functional and anatomical scans. Structural images were normalized to a MNI template (SPM8 default T1 template), and the same normalization parameters were applied to the functional images. Functional images were then smoothed with a Gaussian filter (8mm width). The resulting images were screened for artifacts for each participant; movement parameters were also checked to ensure that no participant moved more than 1mm during the acquisition. Two participants were excluded from the sample because their functional images were artifacted. The final sample included 18 participants ( $n = 8$  for the low span group and  $n = 10$  for the high span group).

**Statistical analysis.** First-level analyses were performed at the individual level on the pre-processed functional images. Regressors were created for the three experimental conditions: long-delay AX-CPT (LD), short-delay AX-CPT (SD), and fixation blocks (FB). Each regressor was modeled as a boxcar function convolved with the canonical hemodynamic response (Friston et al., 1995). The general linear model was then used to generate parameter estimates of activity for each condition, each voxel and each participant. A high-pass filter of 1/128 Hz was used to correct for slow signal drifts; the structure of error covariance was estimated with an autoregressive AR(1) model to account for temporal autocorrelation of activity.

Using the computed parameter estimates, linear contrasts between the experimental conditions were calculated and the corresponding statistical parametric maps were generated for each participant. Two contrasts were calculated: 1) a contrast testing overall task-related activity, or increased activity in the task blocks when compared to the fixation blocks, computed as  $[(LD + SD) / 2 > FB]$ ; and 2) a contrast testing delay-related activity, or increased activity in the long-delay block when compared to the short-delay block, computed as  $[LD > SD]$ .

The contrast images generated for each participant were then entered into second-level analyses treating subject as a random factor. Three second-level analyses were performed for each of the two contrasts: the first analysis used a one-sample  $t$ -test to describe significant activity across the whole sample, the second analysis used a two-sample  $t$ -test to search for increased activity in the high span group when compared to the low span group, and the third analysis used a two-sample  $t$ -test to search for increased activity in the low span group when compared to the low span group.

Unless noted, all second-level analyses used a statistical significance threshold set at .05 with false discovery rate (FDR) control (Genovese, Lazar, & Nichols, 2002). To further limit the risk of type I errors, a region was considered to be significantly activated only if at

least five contiguous voxels were activated above threshold. Anatomical labels were assigned to activated areas using the Talairach daemon atlas (version 2.4.3.; Lancaster et al., 2000); corresponding Brodmann areas were derived using the nearest coordinate method with the Talairach daemon after conversion into Talairach space. When necessary, MNI coordinates were transformed into Talairach coordinates using the using the WFU PickAtlas toolbox (Maldjian, Laurienti, Burdette, & Kraft, 2003).

### 2.1.3. Results

#### 2.1.3.1. Behavioural results.

Descriptive statistics for the AX-CPT are presented in Table 16 (for performance on each trial type) and Table 17 (for complex indices of the tendency to use proactive control) as a function of task condition.

Table 16

*Descriptive statistics for the AX-CPT as a function of trial type and task condition*

Dependent variable	Trial type	Short delay	Long delay
Average error rate	AX	.039 (.036)	.048 (.038)
	AY	.100 (.157)	.083 (.085)
	BX	.000 (.000)	.133 (.159)
	BY	.017 (.051)	.017 (.051)
Median RT	AX	425 (95)	447 (84)
	AY	554 (107)	583 (78)
	BX	367 (94)	367 (88)
	BY	366 (78)	352 (76)

*Note.* Average values with standard deviations in parentheses.

The first analysis examined the effect of delay length on performance in the AX-CPT. The two-way interaction between trial type and delay length was not significant for response times,  $F(3, 57) = 1.58$ ,  $MSE = 2565$ ,  $p = .204$ ,  $\eta^2_p = .08$ , suggesting that the pattern of response times did not differ as a function of the delay. The two-way interaction between trial type and delay length could not be tested as usual for error rates because all participants had perfect performance on BX trials in the short-delay condition, yielding a dependent variable

without dispersion. When excluding BX trials from the analysis, the two-way interaction was not significant,  $F(2, 38) = 0.47$ ,  $MSE = 0.00347$ ,  $p = .630$ ,  $\eta^2_p = .02$ ; however, the pattern of error rates suggested that participants had a higher tendency to use proactive control in the short-delay condition, with descriptively less BX errors and more AY errors. The analysis of complex indices of the tendency to use proactive control confirmed this idea: delay length had no effect on the PBI calculated on response times,  $F(1, 19) = 0.21$ ,  $MSE = 0.00400$ ,  $p = .651$ ,  $\eta^2_p = .01$ , but the short-delay condition was associated with lower values of the PBI calculated on error rates,  $F(1, 19) = 9.45$ ,  $MSE = 0.0963$ ,  $p = .006$ ,  $\eta^2_p = .33$ , the composite PBI,  $F(1, 19) = 4.72$ ,  $MSE = 0.279$ ,  $p = .043$ ,  $\eta^2_p = .20$ , and the  $d'$ -context,  $F(1, 19) = 21.66$ ,  $MSE = 0.135$ ,  $p < .001$ ,  $\eta^2_p = .53$ , indicating a lower tendency to use proactive control in this condition.

Table 17

*Descriptive statistics for complex indices of performance in the AX-CPT as a function of task condition*

Trial type	Short delay	Long delay
PBI-errors	0.24 (0.28)	-0.06 (0.40)
PBI-RTs	-0.12 (0.11)	-0.11 (0.12)
PBI-composite	0.18 (0.66)	-0.18 (0.83)
$d'$ -context	3.22 (0.36)	2.68 (0.53)

*Note.* Average values with standard deviations in parentheses. PBI-errors = PBI calculated on errors; PBI-RT = PBI calculated on median response times; PBI-composite = average of the two other PBIs after standardization.

The second analysis examined the relationship between working memory capacity and performance in the AX-CPT. For the short-delay condition, no difference emerged between the low span group and the high span group on any of the performance indices, all  $ps > .10$ , except for response times on AY trials, where participants in the high span group ( $M = 506\text{ms}$ ,  $SD = 100$ ) were faster than participants in the low span group ( $M = 611\text{ms}$ ,  $SD = 88$ ),  $t(18) = 2.45$ ,  $p = .024$ , and response times on BY trials, where participants in the high span group ( $M = 328\text{ms}$ ,  $SD = 76$ ) were also faster than participants in the low span group ( $M = 414$ ,  $SD = 51$ ),  $t(18) = 2.90$ ,  $p = .010$ . For the long-delay condition, a difference emerged for response times on BX trials, where participants in the high span group

( $M = 322\text{ms}$ ,  $SD = 51$ ) were faster than participants in the low span group ( $M = 421\text{ms}$ ,  $SD = 95$ ),  $t(18) = 2.99$ ,  $p = .008$ , and response times on BY trials, where participants in the high span group ( $M = 318\text{ms}$ ,  $SD = 44$ ) were also faster than participants in the low span group ( $M = 394\text{ms}$ ,  $SD = 88$ ),  $t(18) = 2.55$ ,  $p = .020$ . No significant difference appeared for the other performance indices, all  $ps > .10$ .

### 2.1.3.2. fMRI results.

**Task-related activity.** The first series of analyses investigated task-related activity, corresponding to the [LD + SD > FB] contrast. Firstly, we examined task-related activity across the whole sample with a one-sample  $t$ -test. Overall, a large portion of the brain was more activated in the task blocks than in the fixation blocks (total area = 15893 voxels). A large subset of the activated regions was located in the frontal cortex (see Table 18); the right dorsolateral prefrontal cortex demonstrated a particularly high level of task-related activity.

Table 18

*Frontal regions showing higher activity in the task block than in the fixation block.*

Anatomical label	Hemisphere	Brodmann area(s)	$k$	$t$ -value	Coordinates		
					x	y	z
Middle frontal gyrus	Right	9/46	946	5.56	45	11	33
Medial frontal gyrus	Left	6/9	537	5.31	-36	-10	66
Inferior frontal gyrus	Left	9/6	178	4.52	-51	3	38
Inferior frontal gyrus	Right	45	28	4.30	40	23	5
Cingulate gyrus	Right	23/24	95	4.85	7	-17	33
Cingulate gyrus	Right	32	115	5.77	15	21	46
Insula	Left	13	14	4.39	-36	16	16

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .05 with FDR control.  $k$  refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's  $t$  and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.

Secondly, we examined differences in task-related activity as a function of working memory group with two-sample *t*-tests. No region demonstrated significantly more task-related activity in the low span group than in the high span group, even when raising the statistical significance threshold to .001 (uncorrected). Conversely, no region demonstrated significantly more task-related activity in the high span group than in the low span group at the fixed threshold. When raising the statistical significance threshold to .001 (uncorrected), a few posterior regions appeared significantly more activated in the high span group than in the low span group (see Table 19), but these regions did not include any area directly relevant to our hypotheses. In other words, the two span groups did not demonstrate any critical difference in task-related activity.

Table 19

*Regions showing higher task-related activity in the high span group.*

Anatomical label	Hemisphere	Brodmann area	<i>k</i>	<i>t</i> -value	Coordinates		
					x	y	z
Supramarginal gyrus	Left	40	27	4.91	-53	-42	38
Superior temporal gyrus	Right	39	22	4.83	55	-55	11
Middle occipital gyrus	Right	19	6	4.20	35	-77	-1
Middle occipital gyrus	Right	19	19	4.79	42	-72	-14
Middle occipital gyrus	Left	37	19	4.60	-43	-70	-9

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .001 (uncorrected). *k* refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's *t* and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.

**Delay-related activity.** The second series of analyses investigated delay-related activity, corresponding to the [LD > SD] contrast. Firstly, we examined delay-related activity across the whole sample with a one-sample *t*-test. A significant number of regions were more activated in the long-delay than in the short-delay condition; these regions included part of the frontal cortex (see Table 20) and – importantly – part of the right dorsolateral prefrontal cortex.



Table 20

*Frontal regions showing higher activity in the long-delay condition than in the short-delay condition.*

Anatomical label	Hemisphere	Brodmann area	<i>k</i>	<i>t</i> -value	Coordinates		
					x	y	z
Superior frontal gyrus	Right	6	6	4.37	27	8	55
Middle frontal gyrus	Right	6	22	5.00	17	1	66
Middle frontal gyrus	Left	6	41	5.59	-28	-10	57
Middle frontal gyrus	Left	6	6	4.52	-46	-2	44
Middle frontal gyrus	Left	10	9	4.74	-36	58	11
Inferior frontal gyrus	Right	9	14	4.63	50	13	22

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .05 with FDR control. *k* refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's *t* and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.

Secondly, we examined differences in task-related activity as a function of working memory group with two-sample *t*-tests. These analyses constituted the critical test of our hypothesis: we expected the high span group to demonstrate increased delay-related activity when compared to the low span group, especially in the dorsolateral prefrontal cortex. Contrary to this hypothesis, no cortical region demonstrated increased delay-related activity in the high span group when compared to the low span group, even when raising the significance threshold to .001 (uncorrected). Conversely, no region demonstrated increased delay-related activity in the low span group than in the high span group at the fixed significance threshold. When raising the significance threshold to .001 (uncorrected), one cortical region did demonstrate increased delay-related activity in the low span group, but this region was limited to a small part of the occipital lobe (cluster size = 8, *t*-value = 4.50, coordinates *x* = 22, *y* = -57, *z* = 5). In other words, no differences in delay-related activity appeared as a function of the working memory group in the prefrontal cortex, contrary to our hypothesis.

**Region of interest analysis.** An exploratory analysis was run to provide an alternative test of our main hypothesis. In the article serving as the basis for the present experiment (Paxton et al., 2008; Study 1), the authors reported that one region of the dorsolateral prefrontal cortex in

particular – corresponding to Brodmann area 46 – demonstrated increased delay-related activity in young adults when compared to older adults. In a region of interest (ROI) analysis, we investigated activity in this region in the present data. An ROI was created with the marsbar toolbox (version 0.43; Brett, Anton, Valabregue, & Poline, 2002) using the coordinates supplied in Paxton et al. (when converted in MNI space,  $x = 36$ ,  $y = 24$ ,  $z = 27$ ; on the basis of the reported  $621\text{mm}^3$  volume, the ROI was defined as a sphere of  $5.29\text{mm}$  radius). The average activity in this region was then extracted for each participant as a function of the experimental condition using the marsbar toolbox. Overall, activity in the ROI was higher in the task blocks than in the fixation blocks,  $t(17) = 2.25$ ,  $p = .019$ ; activity was also higher in the long-delay condition than in the short-delay condition,  $t(17) = 2.73$ ,  $p = 0.007$ , congruent with the idea that this region supported proactive control. On the other hand, further analyses showed that activity in this region did not depend on the working memory group; this was the case both for task-related activity,  $t(16) = -0.17$ ,  $p = 0.566$ , and for delay-related activity,  $t(16) = -0.51$ ,  $p = 0.691$ . In short, neural activity in the region identified by Paxton et al. (2008; Study 1) as one of the regions supporting proactive control did not differ as a function of working memory capacity.

#### *2.1.4. Discussion*

The objective of this experiment was to investigate the neural substrate of performance in the AX-CPT as a function of working memory capacity; we expected to observe a higher level of delay-related activity in the dorsolateral prefrontal cortex for participants in the high span group, consistent with a higher tendency to use proactive control. The data did not support this hypothesis: the only difference between the two span groups was non-specific, with several posterior regions demonstrating more task-related activity in the high span group. No difference in delay-related activity was found in relevant cortical areas as a function of working memory capacity. Thus, participants with high working memory capacity did not seem more likely to use proactive control in the task.

Examining behavioural performance in the task indicated that participants with high working memory capacity performed better than participants with low working memory capacity on both AY and BX trials. This finding was inconsistent with the literature: similar to studies reported in Chapter 4 and Chapter 6, the data was more indicative of a general advantage for participants with high working memory capacity than of a difference in the use of control mechanisms. Two conclusions can be drawn from this pattern of results. First, the fact that it is so unsatisfactory supports our idea of directly studying neural activity rather than

behavioural performance. Second, and more importantly, the fact that working memory capacity was related to performance in the AX-CPT indicates that the task was sensitive to individual differences in working memory capacity. In other words, the absence of differences in delay-related activity as a function of span group cannot be attributed to the absence of a relationship between the task and working memory capacity.

One possible interpretation for the absence of differences in delay-related activity in the dorsolateral prefrontal cortex would be that our version of the AX-CPT did not engage cognitive control, or that the delay manipulation did not actually elicit changes in brain activity related to cognitive control. However, the analysis examining task-related activity found significantly higher activity in the dorsolateral prefrontal cortex in the task blocks than in the fixation blocks, and the analysis examining delay-related activity found higher activity in the dorsolateral prefrontal cortex in the long-delay than in the short-delay condition. These results suggest that the task did engage cognitive control, and more specifically proactive control since the delay manipulation modulated activity in the dorsolateral prefrontal cortex. In other words, the task and the experimental manipulation seemed to function as expected.

Since the AX-CPT engaged cognitive control, the delay manipulation influenced the implementation of cognitive control, and working memory capacity was related to performance in the task, how can we explain the fact that working memory did not interact with the delay manipulation? A first possibility is, of course, that working memory capacity is not related to the use of proactive control. In that case, the difference in behavioural performance between the two span groups ought to be attributed to the global difference in task-related activity as a function of working memory capacity. Among regions demonstrating more task-related activity in the high span group was the supramarginal gyrus (Brodmann area 40); this region is consistently involved in working memory (e.g. Owen et al., 2005), especially for letters (Ravizza, Delgado, Chein, Becker, & Fiez, 2004). This could suggest that the higher performance of participants in the high span group on AY and BX trials was not due to a higher tendency to use the delay to actively maintain the cue and prepare a response, but simply to a higher efficiency at storing or retrieving the cue in working memory highlighted by higher activity in the supramarginal gyrus.

A second possibility is that the experiment lacked statistical power to detect variations in brain activity as a function of working memory capacity. At 18 participants, the sample was noticeably lower than those collected in most individual differences study; the sample collected in the reference study for this experiment (Paxton et al., 2008; Study 1) was also about twice larger. However, the fact that individual differences in working memory capacity

predicted task-related activity in certain regions suggests that the protocol was sensitive enough to detect differences in brain activity related to working memory.

A third possibility is that the delay manipulation was insufficiently sensitive to individual differences in working memory capacity. To our knowledge, only Paxton et al. (2008; Study 1) have directly studied the impact of the delay manipulation on brain activity, which makes it difficult to put its effectiveness in perspective. On the other hand, several prior studies have failed to observe differential effects of delay length on performance as a function of age group (Paxton et al., 2006) and even working memory capacity (Redick & Engle, 2011); it is therefore possible that this manipulation does not produce large effect sizes. The following experiment tried to account for the second and third possibilities.

## **2.2. Experiment 7b**

### *2.2.1. Rationale*

The objective of Experiment 7b was similar to Experiment 7a: investigating brain activity during the delay period of the AX-CPT as a function of working memory capacity. However, this new experiment was designed to control the two main limitations of Experiment 7a by increasing sample size, and by replacing the delay length manipulation with another approach. In their seminal article, Paxton et al. (2008) reported two different studies: Study 1, which manipulated the delay period in the AX-CPT and served as the basis for our own Experiment 7a, and Study 2, which kept the delay period constant and investigated the precise time dynamics of brain activity during the delay. In the present experiment, we elected to replicate this second study: all participants completed a long-delay version of the AX-CPT, and we examined the timecourse of their brain activity throughout a trial. In other words, both Experiment 7a and Experiment 7b were interested in brain activity during the delay period of the AX-CPT, except that Experiment 7a manipulated the delay whereas Experiment 7b kept the delay constant and used a more fine-grained analysis of brain activity. In order to increase statistical power, a new sample of participants was collected for this experiment; importantly, Experiment 7a and Experiment 7b used identical parameters (all trials in Experiment 7b were identical to the long-delay condition in Experiment 7a), which allowed us to combine data from the two experiments so as to significantly increase statistical power.

In their Study 2, Paxton et al. (2008) reported different time dynamics for activity in the lateral prefrontal cortex as a function of cognitive control: participants using proactive control demonstrated higher activity during the delay period and lower activity at the time of the probe, whereas participants using reactive control showed the reverse pattern. We

expected to observe similar results in the present experiment, with participants in the high span group showing higher activity in the dorsolateral prefrontal cortex during the delay period, but lower activity at the time of the probe than participants in the low span group.

### *2.2.2. Method*

This experiment was approved by an ethics committee (Comité de Protection des Personnes Sud-est V) under approval number 13-CHUG-47 and by the competent governmental institution (the ANSM) under approval number 131568B-31. All participants provided written informed consent and completed a medical check-up before entering the scanner.

The method was identical to Experiment 7a unless specifically noted.

#### *2.2.2.1. Participants.*

Participants were recruited among subjects having completed the modified version of the CCS replacing the reading span by the alpha span (see Appendix A), which included two samples: the same sample of 106 participants pre-tested for Experiment 7a, and participants having completed Experiment 10 (see pp. 281-282). As in Experiment 7a, participants falling in the upper or lower quartile of the distribution of composite working memory scores were invited to participate in the fMRI session for course credit. The same inclusion criteria as in Experiment 7a were used, with the additional constraint of not having participated in Experiment 7a. The final sample collected for Experiment 7b comprised 17 participants (2 males and 15 females; age ranging from 18 to 24,  $M = 19.78$ ,  $SD = 1.83$ ) divided into a low span group ( $n = 8$ ) and a high span group ( $n = 9$ ). A two-sample  $t$ -test indicated that working memory scores were significantly lower in the low span group ( $M = -1.24$ ,  $SD = 0.31$ ) than in the high span group ( $M = 0.95$ ,  $SD = 0.25$ ),  $t(15) = -16.13$ ,  $p < .001$ .

#### *2.2.2.2. Procedure and paradigm.*

The procedure was identical to Experiment 7a with the following exceptions. The delay between the working memory pre-test and the imaging session was variable: either one month (for participants recruited in the sample of Experiment 10,  $n = 11$ ) or four months (for participants recruited in the sample pre-tested for Experiment 7a,  $n = 6$ ). Participants only completed 10 practice trials (corresponding to the long-delay condition of the AX-CPT) during the calibration scans; as in Experiment 7a, these trials were repeated until participants reached 80% of correct answers.

In the AX-CPT, participants completed three blocks of 40 trials each (120 TR). To provide a baseline measure of brain activity, each block of trials was followed by a fixation block; the fixation blocks were denoted by a centrally presented crosshair and lasted 30 seconds each (or 12 TR). In total, participants completed 120 trials (360 TR) and 90 seconds of fixation blocks (36 TR). The overall duration of this functional scan was 16.5 minutes.

### 2.2.2.3. *fMRI data processing.*

**Statistical analysis.** First-level analyses were performed at the individual level on the pre-processed functional images. These first-level analyses used finite impulse response (FIR) modeling (e.g. Henson & Friston, 2007). The specifics of the FIR modeling were identical to Study 2 in Paxton et al. (2008): a 25-seconds response epoch was defined for each trial type, and one regressor was created for each TR throughout a response epoch – for a total of ten time points. An additional regressor was created for the fixation block (FB). Overall, the design matrix included forty-one regressors (not counting the constant regressor): ten regressors per time point per trial type, plus one regressor coding for fixation blocks. Each regressor was modeled as a simple boxcar function. The general linear model was then used to generate parameter estimates of activity for each regressor, each voxel and each participant. A high-pass filter of 1/128 Hz was used to correct for slow signal drifts; the structure of error covariance was estimated with an autoregressive AR(1) model to account for temporal autocorrelation of activity. Only trials with a correct behavioural response were taken into account in the analysis.

The parameter estimates for the 10 time points in a response epoch were processed in the same way as in Paxton et al. (2008): pre-cue activity (PC) was defined as the average of activation at the first and second time points of the response epoch (corresponding to 0-5000ms after the onset of the trial), delay-related activity (DA) was defined as the average of activation at the third and fourth time points (or 5000-10000ms after the onset), and probe-related activity (PA) was defined as the average of activation at the fifth and sixth time points (or 10000-15000ms after the onset). Using the computed parameter estimates<sup>16</sup>, linear contrasts were calculated and the corresponding statistical parametric maps were generated for each participant. The following contrasts were calculated: 1) a contrast testing task-related activity when compared to the fixation blocks, computed as  $[(DA + PA) / 2 > FB]$ ; 2) a contrast testing task-related activity when compared to the pre-cue interval, computed as

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<sup>16</sup> Although the parameters were estimated separately for each trial type, the analyses were performed by averaging the parameter values over all trial types (unless noted). The results did not differ when considering only the most frequent AX trials.

[(DA + PA) / 2 > PC]; 3) a contrast testing delay-related activity when compared to the fixation blocks, computed as [DA > FB]; 4) a contrast testing delay-related activity when compared to the pre-cue interval, computed as [DA > PC]; 5) a contrast testing probe-related activity when compared to the fixation blocks, computed as [DA > FB]; 6) a contrast testing probe-related activity when compared to the pre-cue interval, computed as [DA > PC]; 7) a contrast testing delay-related activity when compared to probe-related activity, computed as [DA > PA]; and 8) a contrast testing probe-related activity when compared to delay-related activity, computed as [PA > DA].

Lastly, the contrast images generated for each participant were entered into second-level analyses treating subject as a random factor. As in Experiment 7a, one-sample *t*-tests were used to describe significant activity across the whole sample, and two-sample *t*-test were used to test differences in activity between the high span group and the low span group.

### 2.2.3. Results

#### 2.1.3.1. Behavioural results.

Descriptive statistics for the AX-CPT are presented in Table 21 for the new sample of participants collected for Experiment 7b ( $n = 17$ ) and in Table 22 for the full sample combining Experiment 7a and Experiment 7b ( $N = 35$ ).

The first analysis tested the difference between values observed in the new sample collected for Experiment 7b and values observed in the long-delay condition of Experiment 7a. This analysis used a series of two-sample *t*-tests to test the effect of sample on each dependent variable, including complex indices of the tendency to use proactive control. None of the *t*-tests were significant, all  $ps > .10$ , indicating that participants performed comparably in both experiments. The two samples were therefore combined for the following analyses (total  $N = 35$ ).

The second analysis examined the relationship between working memory capacity and performance in the AX-CPT in the combined samples. On BX trials, participants in the high span group had faster response times ( $M = 324\text{ms}$ ,  $SD = 61$ ) than participants in the low span group ( $M = 444\text{ms}$ ,  $SD = 131$ ),  $t(35) = 3.67$ ,  $p < .001$ . On BY trials, participants in the high span group also had faster response times ( $M = 327\text{ms}$ ,  $SD = 46$ ) than participants in the low span group ( $M = 440\text{ms}$ ,  $SD = 123$ ),  $t(35) = 3.83$ ,  $p < .001$ . No difference appeared for the other trial types or for the complex performance indices, all  $ps > .10$ .

Table 21

*Descriptive statistics for the AX-CPT in the sample of Experiment 7b*

Trial type	Average error rate (SD)	Median RT (SD)
AX	.062 (.043)	458 (119)
AY	.125 (.119)	582 (126)
BX	.106 (.114)	409 (151)
BY	.019 (.046)	425 (137)
PBI	0.033 (0.361)	-0.107 (0.079)
PBI-comp	0.000 (0.461)	
<i>d'</i> -context	2.59 (0.57)	

*Note.* PBI-comp = average of the two other PBIs after standardization. The average value of the composite PBI is necessarily 0 since it is calculated as the average of two standardized measures.

Table 22

*Descriptive statistics for the AX-CPT in the combined samples of Experiment 7a and 7b*

Trial type	Average error rate (SD)	Median RT (SD)
AX	.057 (.040)	449 (100)
AY	.104 (.104)	576 (99)
BX	.123 (.140)	382 (116)
BY	.019 (.049)	381 (106)
PBI	-0.018 (0.393)	-0.105 (0.106)
PBI-comp	0.000 (0.692)	
<i>d'</i> -context	2.60 (0.53)	

*Note.* PBI-comp = average of the two other PBIs after standardization. The average value of the composite PBI is necessarily 0 since it is calculated as the average of two standardized measures.



### 2.1.3.2. fMRI results.

All analyses were performed on the combined samples of Experiment 7a and Experiment 7b; the results were similar when considering only the participants who had completed Experiment 7b. The final sample included 35 participants ( $n = 19$  for the high span group and  $n = 16$  for the low span group).

**Task-related activity.** We began with an examination of task-related activity during the AX-CPT. Similar to Paxton et al. (2008; Study 2), there were two ways to assess overall task-related activity in the current design: comparing activity during the task to activity during the fixation blocks (corresponding to contrast [DA + PA > FB]), or comparing activity during the task to activity during the pre-cue period (corresponding to contrast [DA + PA > PC]).

The first series of analyses tested task-related activity with the first contrast ([DA + PA > FB]). Firstly, we examined task-related activity across the whole sample with a one-sample  $t$ -test. Overall, a large part of the brain was more activated during the task than during the fixation blocks (total area = 12689 voxels). Several of the activated regions were frontal and prefrontal areas (see Table 23), including parts of the right dorsolateral prefrontal cortex. This result suggests that the task was successful in engaging cognitive control. Secondly, we examined differences in task-related activity as a function of working memory group with two-sample  $t$ -tests. No region demonstrated any difference in overall task-related activity as a function of working memory capacity, even when raising the statistical significance threshold to .001 (uncorrected).

The second series of analyses tested task-related activity with the other contrast ([DA + PA > PC]). Firstly, we examined task-related activity across the whole sample with a one-sample  $t$ -test. At the fixed significance threshold, various posterior areas were significantly more activated in the cue and probe intervals than in the pre-cue interval, but this did not include any frontal regions. When raising the significance threshold to .001 (uncorrected), one frontal region belonging to the precentral gyrus and corresponding to Brodmann area 6 appeared more activated during the cue and probe intervals (cluster size = 10,  $t$ -value = 3.92, coordinates  $x = -41$ ,  $y = -20$ ,  $z = 66$ ); however, since this region did not belong to the prefrontal cortex, it was irrelevant to our hypotheses. Although other frontal and prefrontal regions similar to the areas reported in Table 23 were descriptively more activated during the cue and probe intervals, none of them reached statistical significance.

Table 23

*Frontal regions showing higher activity in the task block than in the fixation block*

Anatomical label	Hemisphere	Brodmann area	<i>k</i>	<i>t</i> -value	Coordinates		
					x	y	z
Middle frontal gyrus	Right	46/9	133	4.08	47	33	27
Middle frontal gyrus	Right	6	328	3.99	27	6	46
Medial frontal gyrus	Left	6	11	4.69	-13	6	55
Precentral gyrus	Left	6	641	6.34	-41	-20	66
Cingulate gyrus	Right	31/23	104	4.12	10	-35	30
Cingulate gyrus	Left	32	12	3.27	-13	16	45

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .05 with FDR control. *k* refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's *t* and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.

Secondly, we examined differences in task-related activity as a function of working memory group with two-sample *t*-tests. No cortical region demonstrated increased task-related activity for participants in the high span group when compared to the low span group, even when raising the statistical significance threshold to .001 (uncorrected). On the other hand, several posterior areas demonstrated increased task-related activity for participants in the low span group with an uncorrected .001 threshold (see Table 24); however, none of these were regions directly relevant to cognitive control. In summary, no differences in task-related activity appeared as a function of working memory capacity in relevant prefrontal regions, either when contrasting task-related activity to activity during the fixation blocks or to activity during the pre-cue interval.

**Comparison of delay-related activity and probe-related activity.** The next series of analyses contrasted delay-related activity with probe-related activity, similar to Paxton et al. (2008; Study 2). The analyses searched both for regions with increased delay-related activity when compared to probe-related activity (corresponding to the contrast [DA > PA]), and for regions with increased probe-related activity when compared to delay-related activity (corresponding to contrast [PA > DA]).

Table 24

*Regions showing higher task-related activity when compared to the pre-cue interval in the low span group*

Anatomical label	Hemisphere	Brodmann area	<i>k</i>	<i>t</i> -value	Coordinates		
					x	y	z
Middle temporal gyrus	Right	37/19	26	5.85	47	-67	2
Precuneus	Left	7	48	5.20	-1	-55	41
Superior parietal lobule	Right	7	21	4.14	40	-62	49

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .001 (uncorrected). *k* refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's *t* and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.

Firstly, we compared delay-related activity with probe-related activity across the whole sample with a one-sample *t*-test. Overall, a large number of regions demonstrated significantly more delay-related activity than probe-related activity (contrast [DA > PA]); these included a set of frontal regions (see Table 25) and, importantly, a small part of the left dorsolateral prefrontal cortex. This result suggests that the dorsolateral prefrontal cortex supported a sustained cognitive control process during the delay period. Conversely, several regions demonstrated more probe-related activity than delay-related activity (contrast [PA > DA]); however, these regions only included posterior areas – a large bilateral part of the occipital cortex, presumably reflecting summation of the hemodynamic response throughout a trial, as well as a small part of the parietal cortex. In other words, no frontal region demonstrated more probe-related activity than delay-related activity.

Secondly, we examined differences in probe-related versus delay-related activity as a function of working memory group using two-sample *t*-tests. This analysis constituted the main test of our hypothesis; as per Paxton et al. (2008), we expected the difference between delay-related and probe-related activity to vary as a function of working memory capacity. Participants in the high span group were expected to demonstrate increased delay-related activity versus probe-related activity (corresponding to contrast [DA > PA]) in the dorsolateral prefrontal cortex when compared to participants in the low span group.

Table 25

*Frontal regions showing higher activity for the cue than for the probe*

Anatomical label	Hemisphere	Brodmann area	<i>k</i>	<i>t</i> -value	Coordinates		
					x	y	z
Superior frontal gyrus	Right	10	17	4.59	25	56	22
Superior frontal gyrus	Right	6/8	377	5.54	7	21	57
Middle frontal gyrus	Left	8	21	4.79	-48	6	44
Medial frontal gyrus	Left	9	5	4.03	-3	51	22
Inferior frontal gyrus	Right	47/45	173	5.55	52	18	2
Inferior frontal gyrus	Left	47/45	71	4.71	-31	18	-14
Cingulate gyrus	Left	24	27	5.32	-1	-25	41

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .05 with FDR control. *k* refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's *t* and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.

For the first contrast testing delay-related activity versus probe-related activity ([DA > PA]), no region demonstrated the predicted pattern of increased activity for participants in the high span group, even when raising the significance threshold to .001 (uncorrected). In other words, participants in the high span group did not demonstrate higher delay-related activity in any region, contrary to our hypothesis.

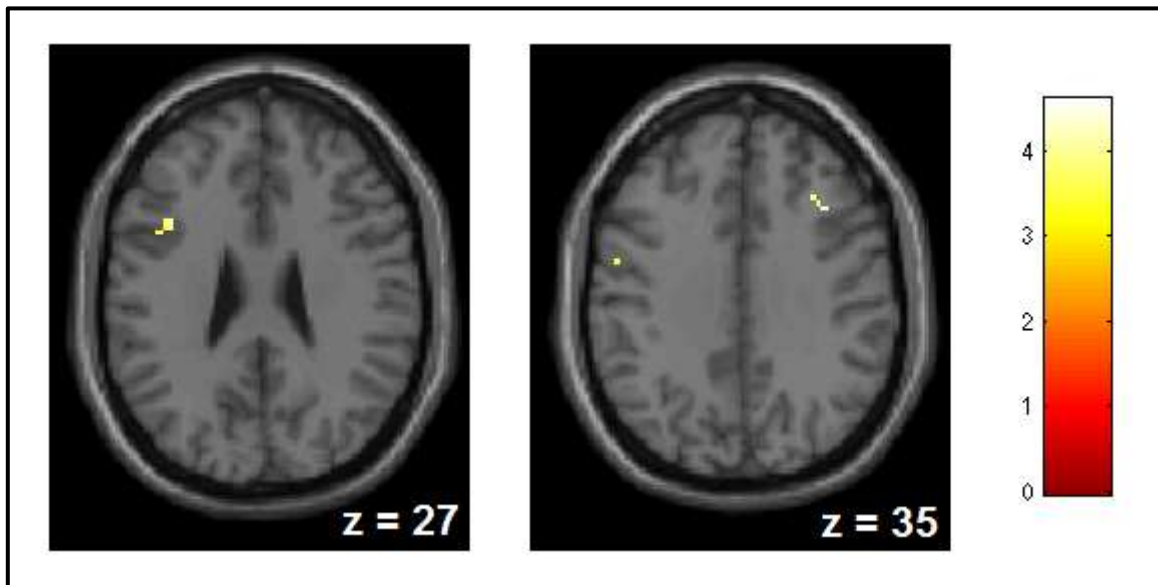
For the reciprocal contrast testing probe-related activity versus delay-related activity ([PA > DA]), however, a number of regions demonstrated the opposite pattern of increased activity for participants in the high span group with an uncorrected .001 significance threshold, contrary to our hypotheses. Several of these regions were frontal areas (see Table 26), including both the left and the right dorsolateral prefrontal cortex (see Figure 24). In other words, participants in the high span group demonstrated more probe-related activity in regions of the dorsolateral prefrontal cortex when compared to participants in the low span group. Another way to phrase this finding would be to say that bilateral regions of the dorsolateral prefrontal cortex demonstrated higher activity at the time of the probe than at the time of the cue, and this effect was more pronounced for participants in the high span group.

Table 26

*Frontal regions showing higher probe-related activity in the high span group when compared to the cue*

Anatomical label	Hemisphere	Brodmann area	<i>k</i>	<i>t</i> -value	Coordinates		
					x	y	z
Middle frontal gyrus	Right	9	9	4.40	37	21	35
Middle frontal gyrus	Left	9	10	3.93	-38	13	27
Precentral gyrus	Left	6/4	27	4.58	-41	-7	60
Precentral gyrus	Left	6	13	3.75	-36	-17	66
Precentral gyrus	Left	6	21	4.35	-51	-5	44
Insula	Left	13	5	4.17	-41	13	19

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .001 (uncorrected). *k* refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's *t* and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.



*Figure 24.* The two regions of the dorsolateral prefrontal cortex demonstrating increased probe-related activity when compared to delay-related activity (corresponding to the contrast [PA > DA]) in the high span group. The colour scale represents the *t*-value of activation. The activation was projected onto the default SPM T1 template in neurological convention.  $p < .001$  uncorrected, extent threshold = 5 voxels, non-frontal regions are masked.

The next two analyses tried to decompose this interaction by specifically examining delay-related activity and probe-related activity.

**Delay-related activity.** This series of analyses focused on delay-related activity. These analyses tested one aspect of our main hypothesis: the higher tendency of participants in the high span group to use proactive control was hypothesized to be revealed by a higher delay-related activity. As per Paxton et al. (2008), we expected participants in the low span group to demonstrate significantly less delay-related activity in the dorsolateral prefrontal cortex than participants in the high span group, and we expected this difference to be especially prevalent for trials starting with a B cue. Similar to the analysis of task-related activity, there were two ways to examine delay-related activity: comparing delay-related activity to activity during the fixation blocks (corresponding to contrast [DA > FB]), or comparing delay-related activity to activity during the pre-cue interval (corresponding to contrast [DA > PC]).

The first series of analyses tested delay-related activity with the first contrast ([DA > FB]). We examined differences in delay-related activity as a function of working memory capacity with two-sample *t*-tests. No cortical regions demonstrated any difference in delay-related activity as a function of working memory capacity, even when raising the significance threshold to .001 (uncorrected). Restricting the analysis to trials starting with a B cue did not change this result.

The second series of analyses tested delay-related activity with the second contrast ([DA > PC]); again, differences in delay-related activity as a function of working memory group were examined with two-sample *t*-tests. No regions demonstrated any difference in delay-related activity as a function of working memory capacity in this analysis, even when raising the significance threshold to .001 (uncorrected). Again, restricting the analysis to trials starting with a B cue did not change this result.

In short, delay-related activity did not differ as a function of working memory capacity. This suggests that the higher probe-related activity versus delay-related activity observed for participants in the high span group in the previous series of analyses was not due to reduced delay-related activity for these participants.

**Probe-related activity.** The following series of analyses examined probe-related activity. These analyses tested another aspect of our main hypothesis: the higher tendency of participants in the low span group to use reactive control was hypothesized to be revealed by a higher probe-related activity. As per Paxton et al. (2008), participants in the low span group were expected to demonstrate higher probe-related activity in the dorsolateral prefrontal

cortex when compared to participants in the high span group, and this difference was expected to be especially prevalent for BX trials. Again, there were two ways to examine probe-related activity: comparing probe-related activity to activity during the fixation blocks (corresponding to contrast [PA > FB]), or comparing probe-related activity to activity during the pre-cue interval (corresponding to contrast [PA > PC]).

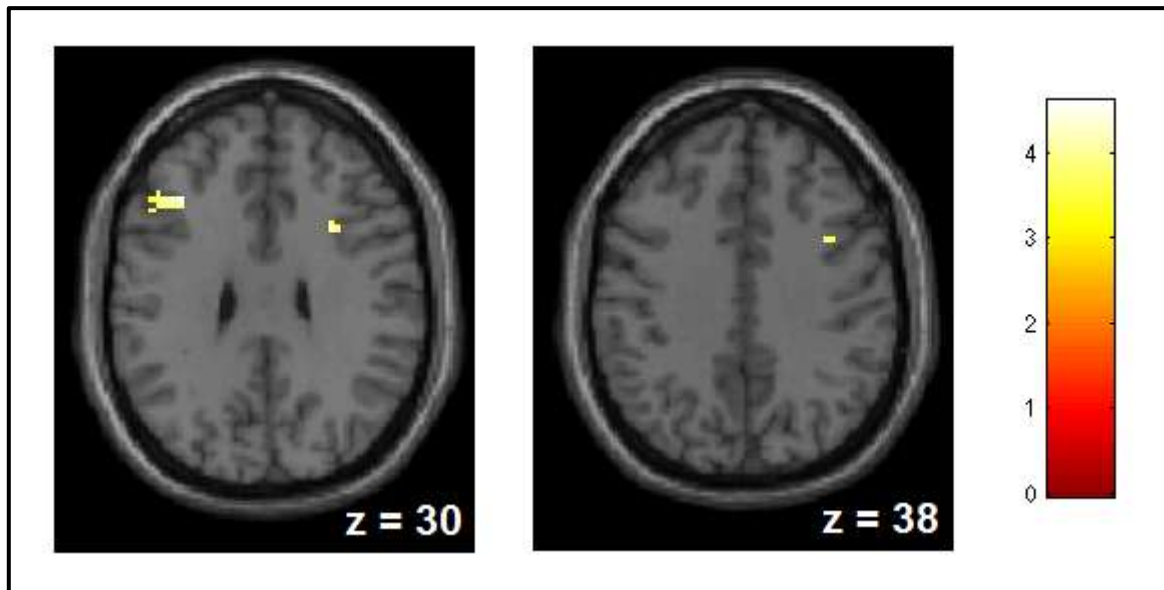
The first series of analyses tested probe-related activity with the first contrast ([PA > FB]). We examined differences in probe-related activity as a function of working memory capacity with two-sample *t*-tests. No region demonstrated increased probe-related activity for participants in the low span group, contrary to our hypothesis, even when raising the significance threshold to .001 (uncorrected). However, several regions demonstrated increased probe-related activity in the high span group with a .001 significance threshold (uncorrected). Several of these were frontal areas (see Table 27 and Figure 25), including bilateral regions of the dorsolateral prefrontal cortex. When restricting the analysis to BX trials, the difference as a function of working memory capacity no longer reached significance in any of the frontal regions, but participants in the high span group still demonstrated descriptively higher probe-related activity in the dorsolateral prefrontal cortex.

Table 27

*Frontal regions showing higher probe-related activity in the high span group when compared to the fixation blocks*

Anatomical label	Hemisphere	Brodmann area	<i>k</i>	<i>t</i> -value	Coordinates		
					x	y	z
Middle frontal gyrus	Left	9	35	4.61	-36	26	30
Middle frontal gyrus	Right	9	5	3.74	37	8	38
Precentral gyrus	Right	6	8	3.70	32	3	35

*Note.* The table includes all significant clusters spanning at least five contiguous voxels, with the statistical significance threshold set at .001 (uncorrected). *k* refers to cluster size, or the number of voxels that reached statistical significance within the cluster. The value of the Student's *t* and the corresponding Montreal Neurological Institute (MNI) coordinates are presented for the voxel with peak activation in the cluster.



*Figure 25.* The two regions of the dorsolateral prefrontal cortex demonstrating increased probe-related activity (corresponding to the contrast [PA > FB]) in the high span group. The colour scale represents the  $t$ -value of activation. The activation was projected onto the default SPM T1 template in neurological convention.  $p < .001$  uncorrected, extent threshold = 5 voxels, non-frontal regions are masked.

The second series of analyses tested probe-related activity with the second contrast ([PA > PC]); again, differences in probe-related activity as a function of working memory group were examined using two-sample  $t$ -tests. The pattern of results was very similar to the previous analysis testing the [PA > FB] contrast: no region demonstrated increased probe-related activity for participants in the low span group, even when raising the significance threshold to .001 (uncorrected), but several regions demonstrated increased probe-related activity for participants in the high span group with an uncorrected .001 threshold. These included two regions of the dorsolateral prefrontal cortex corresponding to Brodmann area 9, one part of the left dorsolateral prefrontal cortex (cluster size = 6,  $t$ -value = 3.73, coordinates  $x = -36$ ,  $y = 21$ ,  $z = 27$ ) and one part of the right dorsolateral prefrontal cortex (cluster size = 21,  $t$ -value = 4.04, coordinates  $x = 37$ ,  $y = 8$ ,  $z = 33$ ). When restricting the analysis to BX trials, the difference still reached significance for the left dorsolateral prefrontal cortex (cluster size = 21,  $t$ -value = 4.58, coordinates  $x = -43$ ,  $y = 26$ ,  $z = 27$ ).

In short, examining probe-related activity revealed that participants with high working memory capacity demonstrated more probe-related activity in the dorsolateral prefrontal cortex, contrary to our hypotheses. In other words, the higher probe-related activity versus delay-related activity observed for participants in the high span group was due to increased probe-related activity for these participants.



**Timecourse analysis.** A series of exploratory analyses was performed to provide another test of our hypotheses. In their seminal article, Paxton et al. (2008; Study 2) studied the timecourse of activity in several regions of the prefrontal cortex, and reported differences as a function of the cognitive control mechanisms. Such an analysis would be especially well-suited to the test of our main hypothesis: a difference in the implementation of cognitive processing during the cue or delay period of the AX-CPT as a function of span group should be visible in a graph plotting percentage signal change in neural activity as a function of time point within a trial. We elected to replicate the same type of analysis by extracting the timecourse of neural activity in several regions of interest. The first two regions of interest were the areas of the dorsolateral prefrontal cortex identified as showing a convergence of cue and probe effects in Paxton et al. (2008; Study 2); the other two were the regions of the dorsolateral prefrontal cortex demonstrating higher probe-related activity versus delay-related activity for participants in the high span group in the present study (see Table 26).

Regions of interest were defined using the marsbar toolbox (version 0.43; Brett et al., 2002) for the areas identified in Paxton et al. (2008; Study 2; for the left dorsolateral prefrontal cortex, radius = 5.85cm; MNI coordinates:  $x = -35$ ,  $y = 44$ ,  $z = 37$ ; for the right dorsolateral prefrontal cortex, radius = 3.87cm; MNI coordinates:  $x = 43$ ,  $y = 22$ ,  $z = 37$ ) and for the areas identified in the present study (for the left dorsolateral prefrontal cortex, radius = 6cm; MNI coordinates:  $x = -38$ ,  $y = 13$ ,  $z = 27$ ; for the right dorsolateral prefrontal cortex, radius = 6cm; MNI coordinates:  $x = 37$ ,  $y = 21$ ,  $z = 35$ ). The average timecourse of neural activity was extracted for each of the ten time points in the 25-seconds response epoch for each participant, and then averaged across all subjects in the same group.

The results of this analysis are presented in Figure 26 (for the Paxton et al. ROI) and in Figure 27 (for the ROI identified in the present study). Overall, no significant difference in neural activity emerged between the two span groups, especially for time points 3 and 4 which represented cue and delay-related activity in the AX-CPT, all  $ps > .20$ . In other words, working memory capacity was not predictive of neural activity during the delay period of the AX-CPT in relevant regions of the dorsolateral prefrontal cortex.

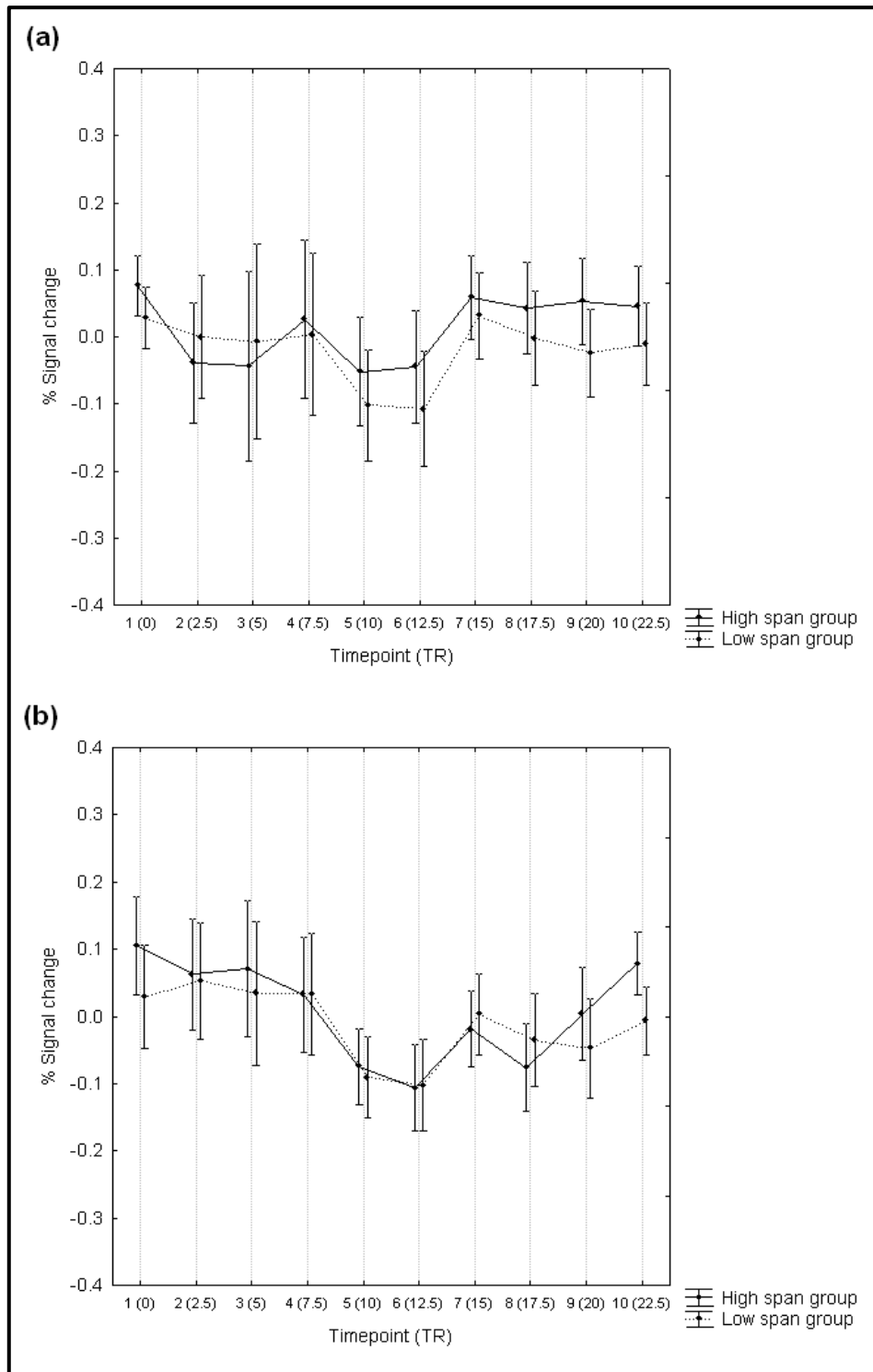
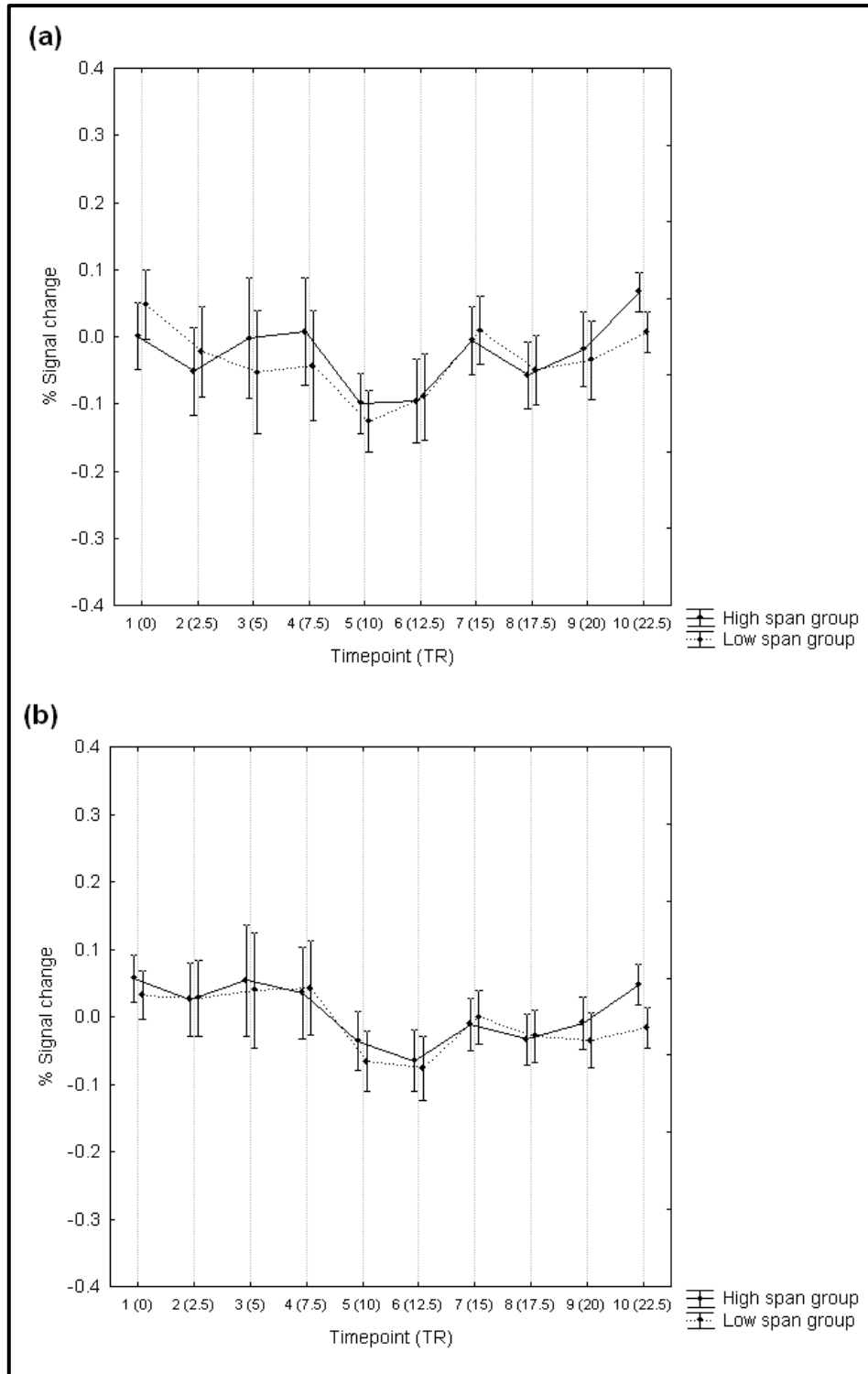


Figure 26. Timecourse of neural activity in regions of (a) the left and (b) the right dorsolateral prefrontal cortex. The analysis used the coordinates of the regions sensitive to proactive control in Paxton et al. (2008; for the left dorsolateral prefrontal cortex, radius = 5.85cm; MNI coordinates:  $x = -35$ ,  $y = 44$ ,  $z = 37$ ; for the right dorsolateral prefrontal cortex, radius = 3.87cm; MNI coordinates:  $x = 43$ ,  $y = 22$ ,  $z = 37$ ).



*Figure 27.* Timecourse of neural activity in regions of (a) the left and (b) the right dorsolateral prefrontal cortex. The analysis used the coordinates of the regions showing a relationship between working memory capacity and probe-related activity in the present study (for the left dorsolateral prefrontal cortex, radius = 6cm; MNI coordinates:  $x = -38, y = 13, z = 27$ ; for the right dorsolateral prefrontal cortex, radius = 6cm; MNI coordinates:  $x = 37, y = 21, z = 35$ ).

#### 2.2.4. Discussion

In this experiment, we endeavoured to evidence that neural activity during performance of the AX-CPT differs as a function of working memory capacity; as per our thesis, we expected to observe higher activity during the cue and delay period for participants with high working memory capacity, consistent with a higher tendency to use proactive control, but higher activity during the probe period for participants with low working memory capacity, consistent with a higher reliance on reactive control. The results ran entirely counter to these predictions. No difference in neural activity in relevant cortical areas appeared during the delay period as a function of working memory capacity, but participants in the high span group demonstrated higher neural activity in the dorsolateral prefrontal cortex during the probe period, suggesting more reactive control in participants with high working memory capacity.

The first major aspect of the results is the absence of a relationship between working memory capacity and neural activity during the cue and delay period. Were there any obvious methodological flaws in the design that could explain this null result? One could argue about statistical power or about the sensitivity of the paradigm to individual differences in working memory capacity as measured with a behavioural task. However, our sample size in this experiment was actually larger than in the original study of Paxton et al. (2008; Study 2); moreover, the analyses did detect reliable differences in neural activity as a function of working memory capacity, albeit during the probe rather than the delay period of the task.<sup>17</sup> The methodology of the present experiment was as close as possible to the methods of the Paxton and colleagues' study that we were attempting to replicate. The only major difference between the two studies was that Paxton and colleagues had included a temporal jitter, with trials being separated by a variable ITI (between 3500ms and 8500ms, when compared to 1200ms in the present study); this temporal jitter was not included in the present experiment to maximize the number of trials and above all to preserve comparability between Experiment 7a and Experiment 7b. However, this difference alone is unlikely to explain the different results across the two studies: the analyses compared activity during the delay

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<sup>17</sup> An additional argument comes from the fact that all participants also completed a *n*-back task during the same fMRI session and that neural activity in the task differed as a function of working memory capacity as measured with the CCS. This further suggests that the absence of differences in delay-related activity was not attributable to a problem with the fMRI procedure, or to a lack of sensitivity of neural activity to behaviourally measured individual differences in working memory capacity. The data for the *n*-back task is presented in Gonthier, Cousin, Pichat, Roulin, & Baciú (2014).

interval to activity during the pre-cue interval and to activity during the probe interval, and the temporal distance between these time points was identical across experiments since only the ITI was varied in the Paxton et al. study. No other methodological discrepancy seems to easily explain the absence of differences in delay-related neural activity as a function of working memory capacity.

On the other hand, it must be noted that the results of Experiment 7b are directly congruent with Experiment 7a, in which no delay-related differences in neural activity as a function of working memory capacity were observed either. In other words, we must reluctantly admit that Study 7 paints a coherent picture of an absence of differences in the use of proactive control as a function of working memory capacity, contrary to our thesis.

If no differences in the use of proactive control appeared during the task, then how can we explain the higher performance of participants with high working memory capacity? In Experiment 7a, we had argued that this difference in behavioural performance was related to the higher task-related activity for participants in the high span group in regions of the parietal lobe associated with working memory, suggesting more efficient maintenance of the cue information throughout the delay for these participants. However, the same results were not found in Experiment 7b: we did observe a difference in task-related activity in a region of the parietal lobe associated with working memory (corresponding to Brodmann area 7; see e.g. Owen et al., 2005), but this difference was in the opposite direction, with a higher level of neural activity for participants in the low span group. Therefore it seems that a difference in task-related activity cannot easily explain the advantage of participants with high working memory capacity.

As a consequence, the most likely source of the difference in behavioural performance resides is the only other difference in neural activity as a function of working memory capacity, namely the higher probe-related activity for participants with high working memory capacity. If we follow the original interpretation for the timecourse of neural activity in the AX-CPT (Paxton et al., 2008), this finding suggests that participants with high working memory capacity relied more on reactive control in the task. Although a higher neural activity does not tell us whether they were more likely to use reactive control, or simply more efficient at using reactive control, the association between reactive control and working memory capacity in the present data is unambiguous.

This constitutes an entirely unexpected finding, although a couple of clues could suggest that participants with high working memory capacity may be more efficient at using reactive control. For example, recall that in Study 5a we observed a selective advantage of

participants with high working memory capacity in the no-go condition, hypothesized to bias all participants towards using reactive control; this finding was discussed in terms of a higher efficiency of participants with high working memory capacity at selectively retrieving contextual information in memory (see pp. 176-177). A recent study reported that neural activity in the dorsolateral prefrontal cortex when confronted with high interference, which might constitute a marker of reactive control, partly mediates the relationship between working memory capacity and fluid intelligence (Burgess et al., 2011); this finding could suggest that participants with high working memory capacity are more efficient at resolving interference through reactive control. The ability to resolve interference is also one of the two functions deemed to be more efficient in participants with high working memory capacity according to the controlled attention framework (Engle & Kane, 2004); this ability bears some conceptual similarity with reactive control, an idea implied by Kane et al. (2007, p. 44), who argued that « [the] executive attention view, emphasizing goal maintenance and competition resolution, parallels the dual mechanisms of cognitive control ». However, these various clues remain very fragmentary and would not have led us to predict a relationship between working memory capacity and reactive control on their own. Interestingly, all these elements also point towards a higher *efficiency* of reactive control in participants with high working memory capacity, not towards a higher tendency to use this mechanism. When applied to the present study, this idea could suggest that all participants used the same mechanisms of cognitive control, but that participants with high working memory capacity were more efficient at using reactive control to retrieve contextual information about the cue, yielding a higher performance in the task.

In summary, Study 7 did not support our hypothesis that participants with high working memory capacity would demonstrate higher neural activity during the delay period of the AX-CPT, which would have indicated a higher tendency to use proactive control; however, the data suggested that participants with high working memory capacity were more prone to (or more efficient at) using reactive control in the task.

### **3. Study 8 – EEG activity during a delay period**

#### **3.1. Rationale**

The rationale of Study 8 was very similar to Study 7. Proactive control is characterized by the implementation of anticipatory or sustained processing in a task; as illustrated by the AX-CPT paradigm, this sustained processing may take the form of preparatory activity during an unfilled delay period. On the other hand, reactive control is thought to be implemented

only when an event requiring control occurs, not during unfilled delay periods. This difference means that the two control mechanisms may be distinguished by the amount of sustained processing taking place during a delay period; since sustained cognitive processing is necessarily subtended by neuronal activations, a difference in sustained activity should be reflected in neural activity. Just as Study 7, Study 8 attempted to evidence a relationship between working memory capacity and the tendency to use proactive control by examining neural activity during the unfilled delay period of a complex task. This is where the similarity between the two studies ends, however.

While Study 7 has used the paradigmatic task for the DMC framework, the AX-CPT, other tasks should conform as well to the predicted pattern of higher activity during a delay period for proactive control. In the original account of the DMC framework (Braver et al., 2007), the authors suggested how proactive control may translate in a short-term memory task: participants may use the delay period separating the presentation of to-be-remembered stimuli within a trial to re-encode these stimuli under a different form. For example, this re-encoding could take the form of elaborative encoding, wherein participants using proactive control would take advantage of the inter-stimulus interval to process to-be-remembered stimuli at a deeper level; this would presumably lead to higher performance. The DMC framework therefore provides an elegant account of how the two mechanisms of control could influence performance in a short-term memory task. Since short-term memory tasks are conceptually closer than the AX-CPT to the working memory construct, studying cognitive control in a short-term memory task might also be an efficient way to maximize individual differences as a function of working memory capacity. For these reasons, the current study used a short-term memory task rather than a cognitive control task such as the AX-CPT.

The results of Study 7 did not indicate any relevant difference in delay-related brain activity in the AX-CPT as a function of working memory capacity. However, fMRI is clearly not the best tool to investigate the time dynamics of cognitive processing, in that the hemodynamic response which serves as the index of neural activity in this technique has a lag of several seconds and activity at any given point of the brain is typically sampled only once every few seconds. Although fMRI was a sound choice for precisely locating neural activity within the dorsolateral prefrontal cortex, its low temporal resolution may partly explain the absence of differences in delay-related activity as a function of working memory capacity. In the current study, we instead elected to measure neural activity using electroencephalography. EEG had two main advantages for our purposes. First, its temporal resolution is excellent, in the range of milliseconds. This excellent temporal resolution comes with poor spatial

resolution, but this did not constitute a major concern in the present study: contrary to Study 7, we did not have specific predictions concerning the precise spatial locus of brain activity during the ISI, since elaborative encoding may take place in various parts of the brain. Second, the sensitivity of EEG activity to mnemonic processes is well-known (for a review, see Gonthier & Hot, 2013). A significant number of studies have evidenced sustained oscillatory activity during the ISI in short-term memory tasks. This sustained activity is especially prominent in the theta frequency band at the frontal and secondarily at the occipital level (e.g. Gevins, Smith, McEvoy, & Yu, 1997; Klimesch, 1999; O. Jensen & Tesche, 2002). The involvement of the theta band in memory tasks seems near ubiquitous; theta activity during the ISI of memory tasks is typically sustained throughout the delay period and increases with memory load (e.g. O. Jensen & Tesche, 2002). Besides the theta band, a sustained activity appears in the beta band on frontal and occipital electrodes (e.g. Tallon-Baudry, Kreiter, & Bertrand, 1999; Hwang et al., 2005); this activity is sometimes hypothesized to represent subvocal rehearsal (Hwang et al., 2005). The gamma band also seems to demonstrate sustained activity during memory tasks (e.g. Tallon-Baudry et al., 1999). Lastly, a decreased oscillatory activity in the alpha band has been reported in memory tasks and is typically interpreted in terms of increased attention or mental effort during the task (e.g. Gevins et al., 1997; Klimesch, 1999).

In the current study, participants completed a short-term memory task with a long ISI; their EEG activity was measured throughout the task. We expected participants with high working memory capacity to demonstrate higher activity during the ISI, indicating the use of proactive control. Since we did not expect the difference in cognitive processing to affect a well-defined, time-locked cognitive process, the data was not subjected to an event-related potential (ERP) analysis. Instead, we simply expected participants with high working memory capacity to demonstrate sustained neural activity during the ISI in the theta band and secondarily in the beta and gamma bands, as well as decreased activity in the alpha band, to a greater extent than participants with low working memory capacity.

### **3.2. Method**

This experiment was approved by an ethics committee (Comité d'éthique recherche de l'Université de Savoie) under approval number 20132.

#### **3.2.1. Participants.**

Participants were recruited among subjects having completed Experiment 5a, which included 95 undergraduates at the University of Savoie; all these participants had performed



the modified version of the CCS replacing the reading span by the alpha span (see Appendix A). Participants who fell in the upper quartile or the lower quartile of the distribution of composite working memory scores were invited to participate in the EEG session for payment (€10.00 an hour). Participants were included if they met the following criteria: native French speaker, right-handed, no history of neurological disorders, without psychoactive medication, and normal or corrected-to-normal vision. The final sample comprised 40 participants (9 males and 31 females; age ranging from 18 to 25,  $M = 20.12$ ,  $SD = 1.77$ ) divided into a low span group ( $n = 20$ ) and a high span group ( $n = 20$ ). A two-sample  $t$ -test indicated that working memory scores were significantly lower in the low span group ( $M = -0.97$ ,  $SD = 0.35$ ) than in the high span group ( $M = 1.04$ ,  $SD = 0.21$ ),  $t(38) = -21.82$ ,  $p < .001$ .

### 3.2.2. Materials.

The main task of interest was a short-term memory task: in each trial, participants were asked to memorize a series of words and to recall them orally at the end of a trial. All words were two-syllable common nouns of six to ten letters with frequency comprised between 5 and 35 per million in French (as defined in the Lexique 3.80 database; New et al., 2001). The complete list of words is presented in Appendix E.

Each trial started with a fixation cross; words were then presented successively at the center of a computer screen. The presentation of each word was separated by an unfilled ISI. A question mark appeared at the end of a trial to prompt participants to recall the words. Participants were instructed that the order of presentation of the words was irrelevant and that they only had to recall all words in any order. The number of words in each trial varied randomly between five and seven, thus modulating the difficulty level from trial to trial; pilot testing indicated that participants in both the low span and high span groups could manage these memory loads with some effort. The fixation cross was presented for 1500ms; words were always presented for 750ms; the delay between words was randomly varied with a temporal jitter and was comprised between 2000ms and 2600ms (in steps of 100ms). The time allowed for recalling the words was not limited. All stimuli were displayed in white, lowercase, 48-point Helvetica font against a black background.

As a control condition, participants also completed trials of a reading task. Reading trials were exactly identical to memory trials; the only difference was that participants were instructed to silently read the words rather than try to memorize them. The instructions stressed the importance of actually reading the word (rather than just looking at the screen)

and of refraining from trying to memorize the word. The series of words were randomly affected to either the memory condition or the control condition for each participant.

### 3.2.3. Procedure.

The EEG session took place one month after the working memory pre-test. Participants were instructed to avoid wearing any makeup or hair conditioner, drinking coffee, smoking, or taking unusual medicine prior to the testing session. All participants provided written informed consent at the beginning of the protocol. They then received basic explanations concerning the EEG recording, along with the instruction not to move too much during the task. Contrary to many EEG experiments, participants didn't receive any instructions concerning blinking and eye movements during the task, since refraining from making eye movements throughout a one-hour task would presumably have placed a high demand on cognitive control.

After the installation of the EEG system, participants completed three practice trials, one for each difficulty level; the practice trials were repeated until participants correctly understood the task. The protocol then proceeded to the actual task; participants completed the short-term memory task while their EEG activity was recorded. Participants completed six blocks of eight trials for the memory condition, interleaved with seven blocks of four trials for the control condition. All trials were presented in random order, with the constraint that there could never be more than three consecutive trials of the same difficulty level. Participants received a short break halfway through the task. In order to obtain a measure of baseline EEG activity, they also completed fixation trials at the beginning, halfway through and at the end of the short-term memory task. The fixation trials were denoted by a centrally presented crosshair and lasted 30 seconds each; participants were simply instructed to look at the cross without performing any particular task. In total, participants completed 48 trials in the memory condition, 28 trials in the control condition and three fixation trials.

An experimenter sat next to the participant throughout the task to record the number of correctly recalled stimuli and to trigger the start of each trial. To ensure that differences in EEG activity were not due to differences in strategy use, participants also completed a short questionnaire after the end of the short-term memory task; the questionnaire simply asked participants to describe which strategies they had used to memorize the words. Overall, the experimental session lasted for approximately an hour and a half per participant, including about one hour for the short-term memory task and half an hour for setting up and taking off the EEG system.

### 3.2.4. EEG acquisition.

EEG activity was recorded with a BioSemi ActiveTwo system using 64 active Ag-AgCl electrodes; the electrodes were mounted on an elastic headcap with a standard 10-20 layout. EOG activity was recorded with four electrodes placed at the outer canthus of each eye and at infra and supra-orbital points around the right eye; the electrodes were aligned with the pupil looking straight. The ActiveTwo system does not use a reference electrode. The conductivity of all electrodes was checked for each participant (*electrode offset* below 40 mV in the BioSemi terminology). Electrical activity was sampled at a rate of 1024Hz.

### 3.2.5. EEG data processing.

The data were pre-processed and analyzed using the fieldtrip toolbox (<http://fieldtrip.fcdonders.nl/>) for MATLAB (The MathWorks, Inc.).

**Pre-processing.** The following pre-processing steps were applied for each participant. In the first step, raw data were visually inspected; channels showing strong and widespread electrical artifacts (such as a flat signal for the whole duration of the recording) were rejected. The signal in each channel was then re-referenced to the grand average of the signal (calculated over all channels) at each time point. The signal was filtered with a low-pass filter at 200Hz, a high-pass filter at 3Hz, and a notch filter at 50Hz to decrease line noise. The continuous EEG recording was then broken down into multiple response epochs. The onset of each epoch corresponded to the moment when a word disappeared from the screen; each epoch lasted for 2000ms, corresponding to the lowest possible ISI in the task<sup>18</sup>. This procedure yielded 288 response epochs in the memory condition and 166 response epochs in the control condition for each participant. The signal in the baseline trials was also independently extracted in this step (yielding three baseline response epochs of 30 seconds each). In the next step, the signal was demeaned; in other words, the average of the signal in a channel was subtracted at each time point. The following step used a semi-automatic artifact rejection procedure: response epochs where either the variance or the absolute maximal value of the signal were more than 1.2 standard deviations above the mean were rejected; this rejection procedure was applied iteratively until no epoch exceeded the threshold. No more than 20% of the response epochs were excluded for any participant. In the next step, an

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<sup>18</sup> Response epochs actually started 500ms before and finished 500ms after the values reported here; this form of padding was used to avoid edge effect artifacts in subsequent analyses. The additional 500ms at each end of a response epoch were not analyzed.

independent component analysis (ICA) was applied to the signal so as to extract electro-oculographic activity. Components were removed using an automated procedure based on topographic distribution: the extracted components were checked against two templates representing the typical topographic signature of vertical and horizontal eye movements. Components with a correlation higher than .70 with one of the templates were labeled as reflecting eye movements; the signal was corrected to remove these components. This procedure removed either one or two components for all participants. Lastly, the signal in missing channels was interpolated as the average of the neighbouring channels.

**Data analysis.** A time-frequency analysis using the wavelet decomposition method was performed on the pre-processed data. This analysis first computed the power in each frequency bin comprised between 3Hz and 200Hz (in steps of 0.5Hz) for each time bin comprised between 0ms and 2000ms (in steps of 50ms). In the following step, the power in each time-frequency bin was transformed into a *z*-score using the mean and standard deviation of power in the same frequency bin during the baseline trials. The individual frequency bins were then regrouped in frequencies of interest corresponding to theta (4 – 8Hz), alpha (8 – 13Hz), beta (13 – 30Hz), and gamma (36 – 200Hz; Cacioppo, Tassinari, & Berntson, 2007); the power was averaged over all bins within a frequency band. The different response epochs in the same condition were averaged; lastly, the data was averaged across all participants within the same group. These steps yielded an estimate of power in each frequency band at each time point for each of the two groups. Examining the data revealed that the signal in the gamma band was heavily contaminated by high frequency muscular activity in more than 50% of trials; as a consequence, the gamma band was dropped from all analyses.

### **3.3. Results**

#### **3.3.1. Behavioural results.**

A two-sample *t*-test indicated that short-term memory scores were significantly lower in the low span group ( $M = 186$ ,  $SD = 17$ ) than in the high span group ( $M = 230$ ,  $SD = 21$ ),  $t(37) = -7.27$ ,  $p < .001$ . Most participants reported using subvocal rehearsal as their dominant strategy ( $n = 31$ ); five participants reported integrating the words into sentences, three participants created mental pictures of the words, and one participant classified the words into meaningful groups. No participant reported using no strategy at all. A polytomous logistic regression indicated that the likelihood of using a particular strategy did not differ as a function of span group,  $\chi^2(3) = 1.96$ ,  $p = .581$ . In short, the short-term memory task was

sensitive to individual differences in working memory capacity, and all participants tended to use similar strategies independently of their working memory capacity.

### 3.3.2. EEG results.

**Method of analysis.** All statistical analyses were performed using the fieldtrip toolbox (<http://fieldtrip.fcdonders.nl/>) for MATLAB (The MathWorks, Inc.). We used nonparametric cluster-based permutation tests (see Maris & Oostenveld, 2007), a procedure analogous to a bootstrap analysis for behavioural data; these analyses were performed in three steps. In the first step, *t*-tests were computed to compare the average power across conditions at each time point for each electrode; these *t*-tests contrasted either the memory and control conditions (with paired *t*-tests) or the high span and low span groups (with unpaired *t*-tests). Data points with *t*-tests significant at the .05 level (two-tailed) were selected; temporally or spatially adjacent data points with significant *t*-tests were regrouped into clusters; and the test statistic of interest was computed for each cluster by calculating the sum of all *t*-values within the cluster. The second step used the Monte Carlo method; all response epochs were randomly assigned to one of two subsets (the sizes of the subsets being the same as the sizes of the conditions being compared), the procedure described for step one was performed on this random partition, and the values of the test statistic of interest were collected. This procedure was repeated 1100 times to construct a distribution of the test statistic of interest under the null hypothesis. In the third step, the test statistic of interest actually observed in the data was compared with the null distribution generated in step two; a cluster was considered statistically significant if its test statistic was greater than 95% of test statistics under the null distribution. The analysis was performed separately for the theta, alpha and beta frequency bands.

**Memory-related activity.** The first statistical analysis tested the difference in oscillatory activity between the memory and control conditions, collapsed over all participants. The average time-frequency maps for the control and memory conditions are presented in Figure 28. When compared to the baseline, these maps descriptively indicated increased power in the alpha band in the control condition (Figure 28a) and increased power in the theta and beta bands in the memory condition (Figure 28b).

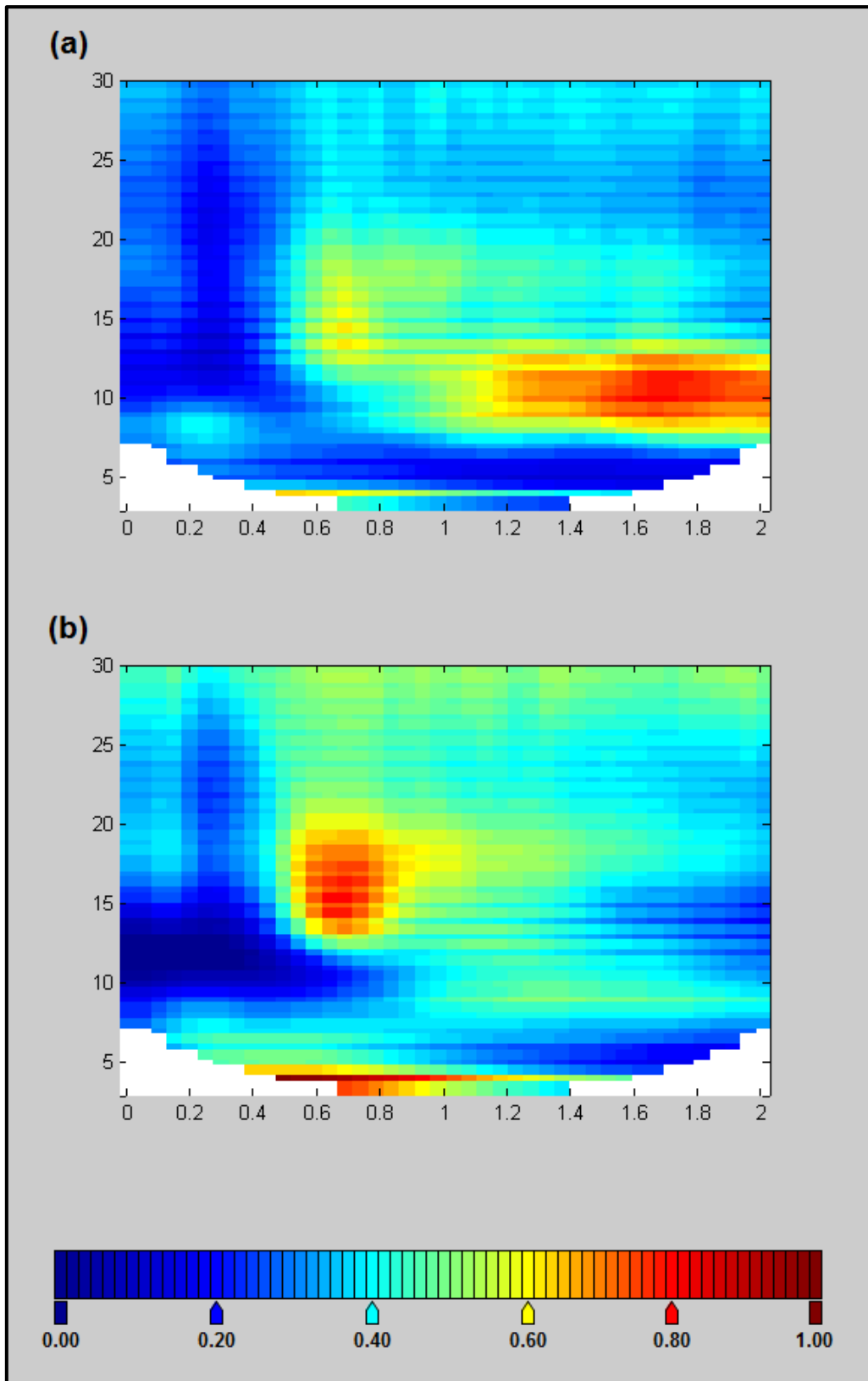


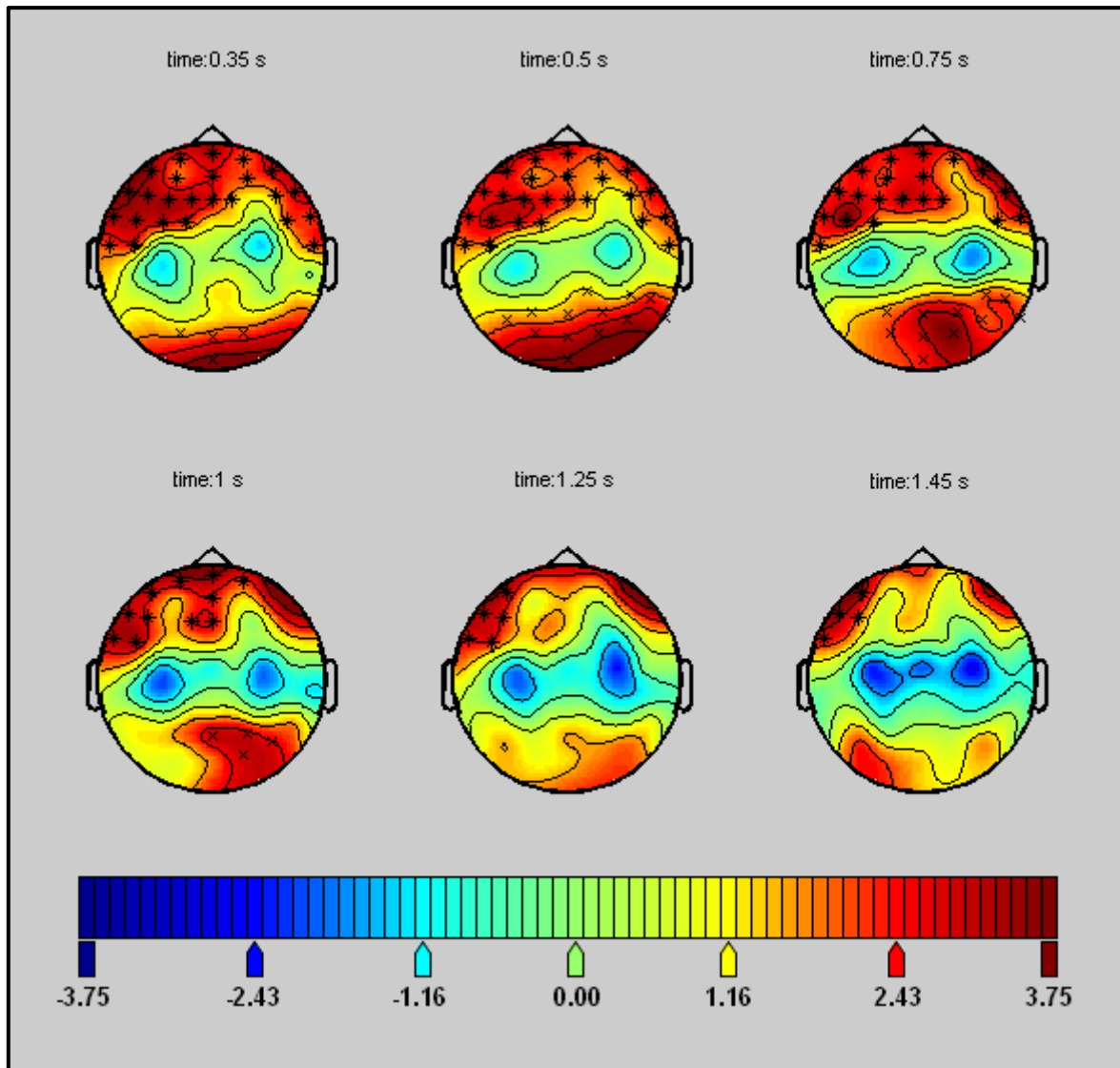
Figure 28. Power as a function of time and frequency in the control condition (a) and in the memory condition (b), averaged over all electrodes. The colour scale represents z-scores; positive indicates higher activity in the corresponding condition when compared to the baseline.

In the theta band, we expected to observe higher activity in the memory condition over frontal and occipital regions. The results were congruent with our hypotheses (see Figure 29): as expected, participants demonstrated increased oscillatory activity in the theta band in the memory condition. This activity was mainly located in frontal regions and secondarily in occipital regions; it was sustained throughout about half the ISI, from approximately 300ms to 1500ms post-word offset. In short, we observed memory-related sustained oscillatory activity in the theta band across frontal and occipital sites, suggesting that the paradigm functioned correctly and that the short-term memory task did engage mnemonic processes.

In the alpha band, we expected to observe lower activity in the memory condition across the whole brain, indicating increased mental effort in the memory condition. This is precisely what the data indicated (see Figure 30): participants demonstrated higher activity in the alpha band across the whole scalp throughout the entirety of the ISI, indicating that they engaged more attention or mental effort in the memory task than in the reading task.

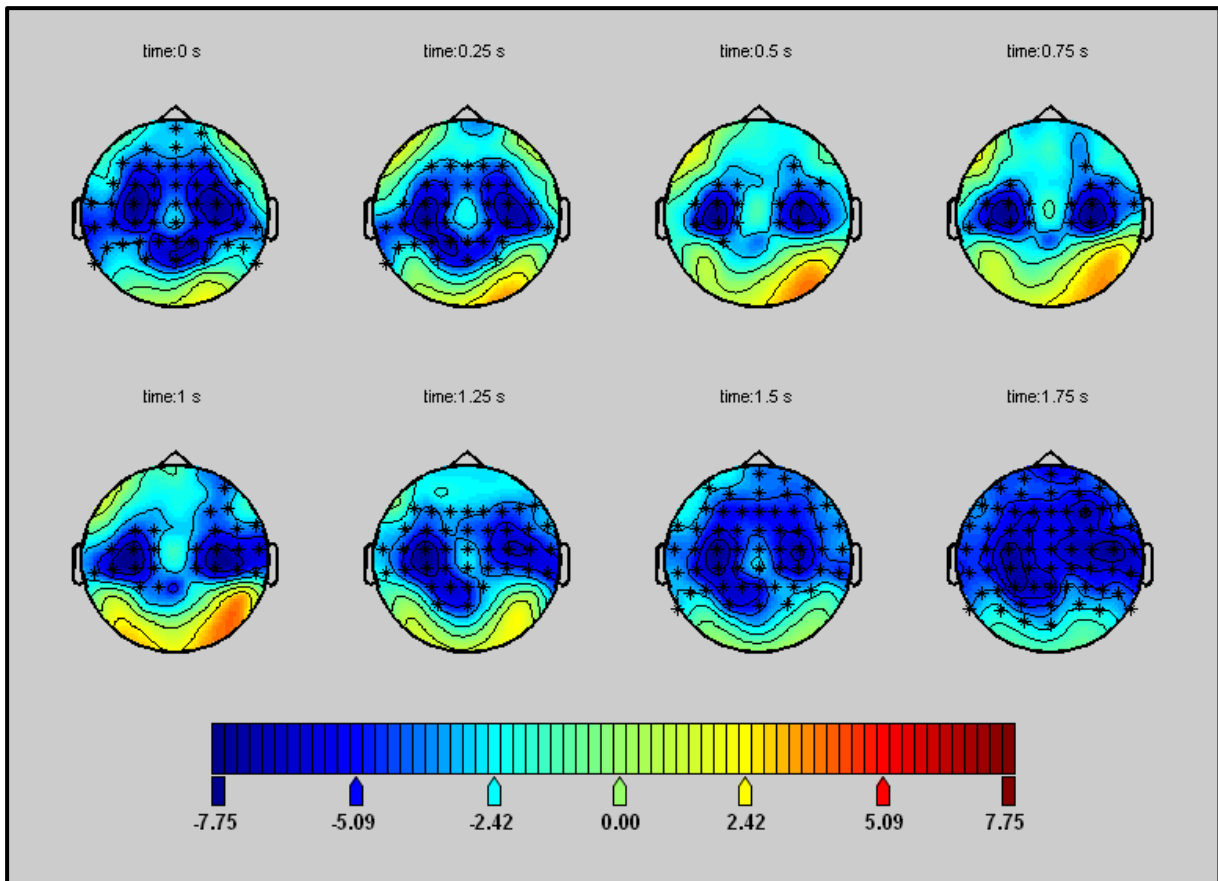
In the beta band, we expected to observe higher activity in the memory condition over frontal and occipital regions, presumably indicating subvocal rehearsal. Overall, the results were rather congruent with this prediction (see Figure 31). The participants demonstrated increased activity in the beta band in the memory condition in occipital and frontal regions, although this activity tended to be more prevalent in temporal sites than in frontal sites; this increased activity was observable from 0ms to 2000ms. This result was congruent with the use of subvocal rehearsal in the memory condition. Activity in the beta band also significantly decreased in centro-parietal sites in the memory condition; this decrease was sustained from 0ms to 2000ms. Although we had not predicted this result, decreased power in the beta band on central electrodes is reliably observed when participants make movements or imagine making movements (e.g. McFarland, Miner, Vaughan, & Wolpaw, 2000); it is therefore likely that this finding was due to the articulatory component of subvocal rehearsal.

In summary, the short-term memory task elicited the predicted patterns of oscillatory activity: in the memory condition, participants demonstrated the predicted increase in theta activity in frontal and occipital regions associated with memory activity, the predicted decrease in alpha activity associated with increased mental effort, and the predicted increase in beta activity in frontal and occipital regions associated with subvocal rehearsal. Activity in the beta band also decreased in central electrodes, congruent with subvocal rehearsal during the memory task.

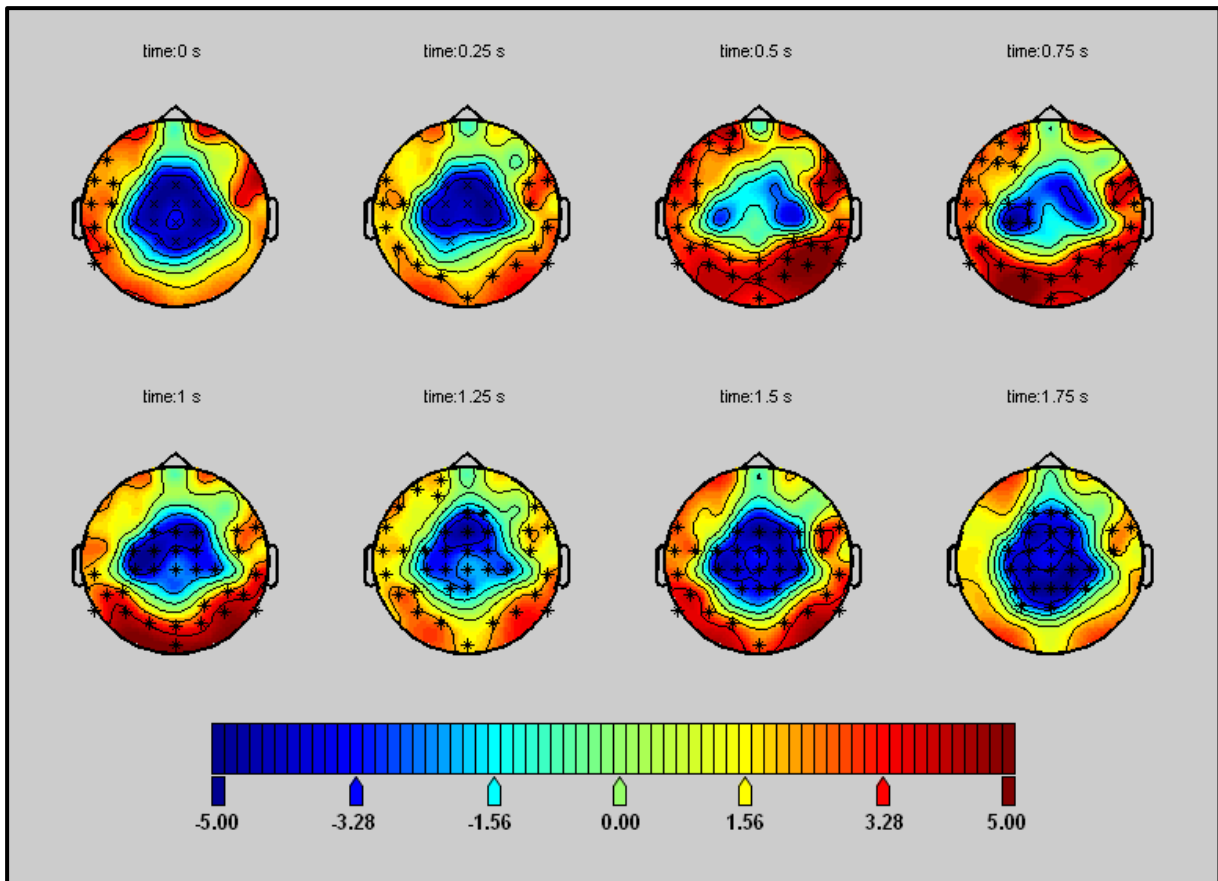


*Figure 29.* Differences in oscillatory activity in the theta band between the memory and control conditions for all participants. The colour scale represents  $t$ -values corresponding to the test of the difference between the two conditions; positive indicates higher activity in the memory condition. \*  $p < .05$ , \*  $p < .01$ . All statistically significant clusters are comprised between the first and last plotted time points.





*Figure 30.* Differences in oscillatory activity in the alpha band between the memory and control conditions for all participants. The colour scale represents  $t$ -values corresponding to the test of the difference between the two conditions; negative indicates higher activity in the control condition. \*  $p < .01$ .



*Figure 31.* Differences in oscillatory activity in the beta band between the memory and control conditions for all participants. The colour scale represents  $t$ -values corresponding to the test of the difference between the two conditions; positive indicates higher activity in the memory condition. \*  $p < .05$ , \*  $p < .01$ .

**Memory-related activity and working memory capacity.** The second analysis tested the interaction between working memory span group and experimental condition for each frequency band. We expected participants in the high span group to demonstrate more memory-related activity during the ISI, consistent with a higher tendency to use proactive control; this difference was expected to translate into a larger increase in theta and beta activity and a larger decrease in alpha activity in the memory condition when compared to the control condition.

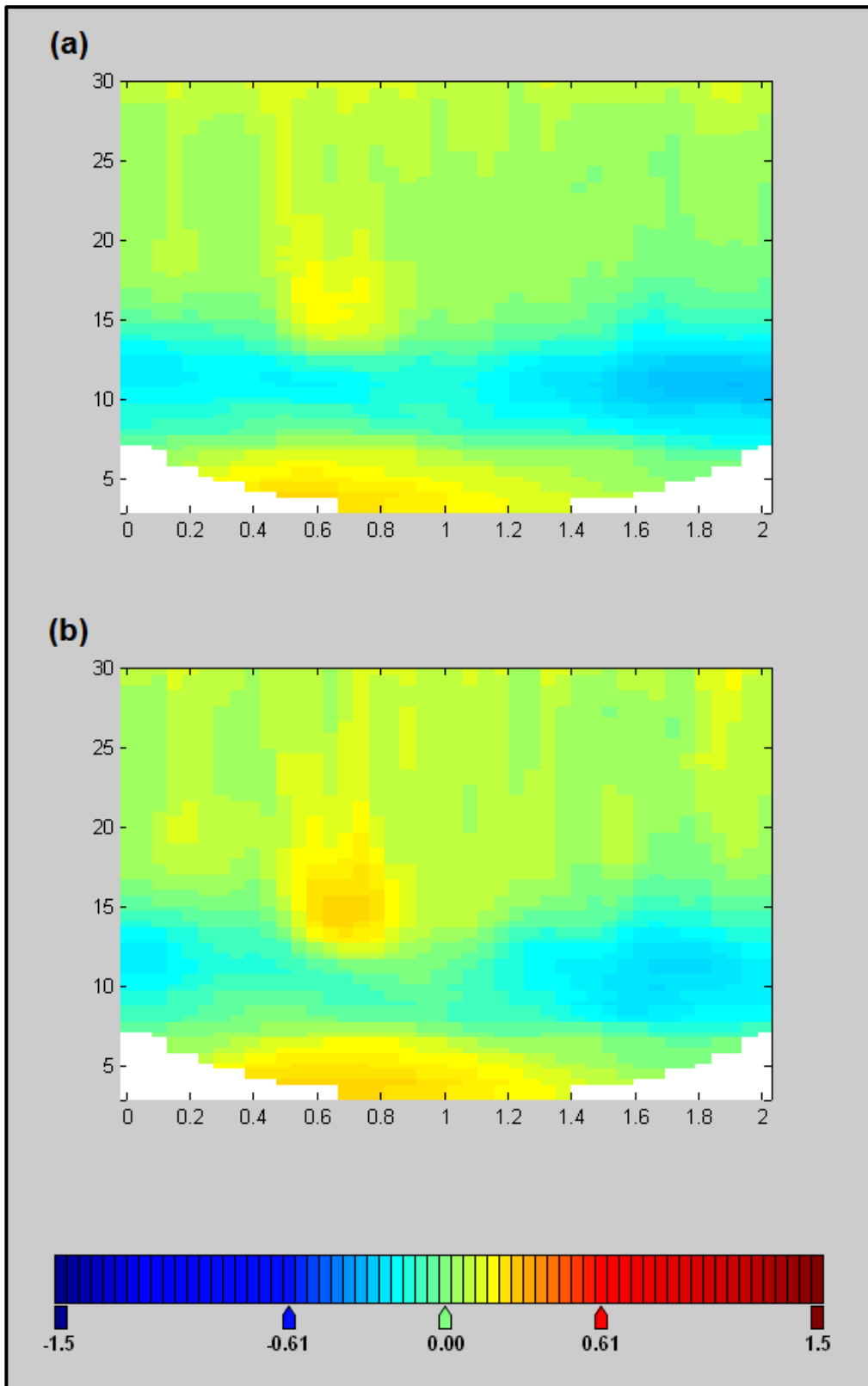
The average time-frequency maps representing the difference between the memory and control conditions as a function of span group are depicted in Figure 32. Overall, the results were entirely incongruent with our hypotheses. No significant difference between the two groups appeared for either the theta, alpha or beta frequency bands. In other words, the difference between the memory and control conditions did not depend on the working memory span group: all participants demonstrated a comparable increase in activity in the

theta and beta bands and a comparable decrease in activity in the alpha band in the memory condition when compared to the control condition.

For reference, the difference in activity in the theta band between the memory and control conditions is represented in Figure 33 separately for participants in the high span and low span groups. As can be seen, memory-related activity in the theta band was similar for the two span groups; if anything, memory-related activity was descriptively more intense, more widespread and lasted approximately 250ms longer in the low span group. In short, sustained neural activity was similar across working memory span groups, and this null result was not due to insufficient statistical power since the difference of activity in the theta band was descriptively in the wrong direction.

**Theta activity as a function of memory load.** As an exploratory analysis, we tested the difference in sustained oscillatory activity in the theta band as a function of memory load, as indexed by the position of the ISI in a trial. In other words, the following analysis tested whether neural activity differed as a function of whether the ISI followed the first, second... or fifth word in a trial. The delay periods following the sixth and seventh words were not included in the analysis, since not all trials included more than five words due to the variable difficulty level. The analysis averaged theta activity over all frontal and fronto-polar electrodes. Since oscillatory activity in the theta band typically increases with memory load in frontal regions, we expected theta activity to increase throughout the course of a trial. As predicted, theta activity descriptively increased as a function of memory load in the memory condition (except for a sharp plunge for the fourth word in a trial), whereas it remained approximately constant throughout a trial for the control condition (see Figure 34).

On the other hand, the increase in theta activity as a function of memory load was similar for the two working memory span groups: *t*-tests indicated that theta activity did not differ across the groups at any point for either the control condition, the memory condition or the difference between the two, all *ps* > .30. In short, all participants demonstrated an increase in memory-related theta activity when the memory load increased within a trial, but this effect was comparable in magnitude across the two working memory groups. This result suggests that all participants, whatever their working memory capacity, tended to implement sustained activity during the delay period as a means to perform the memory task; of secondary interest, it also indicates that participants with a high working memory capacity did not demonstrate a specific difference in memory-related activity when the memory load was high, which rules out one possible interpretation for our null results.



*Figure 32.* Difference in power between the memory and control conditions as a function of time and frequency in the low span group (a) and in the high span group (b), averaged over all electrodes. The colour scale represents z-scores; positive indicates higher activity in the memory condition.

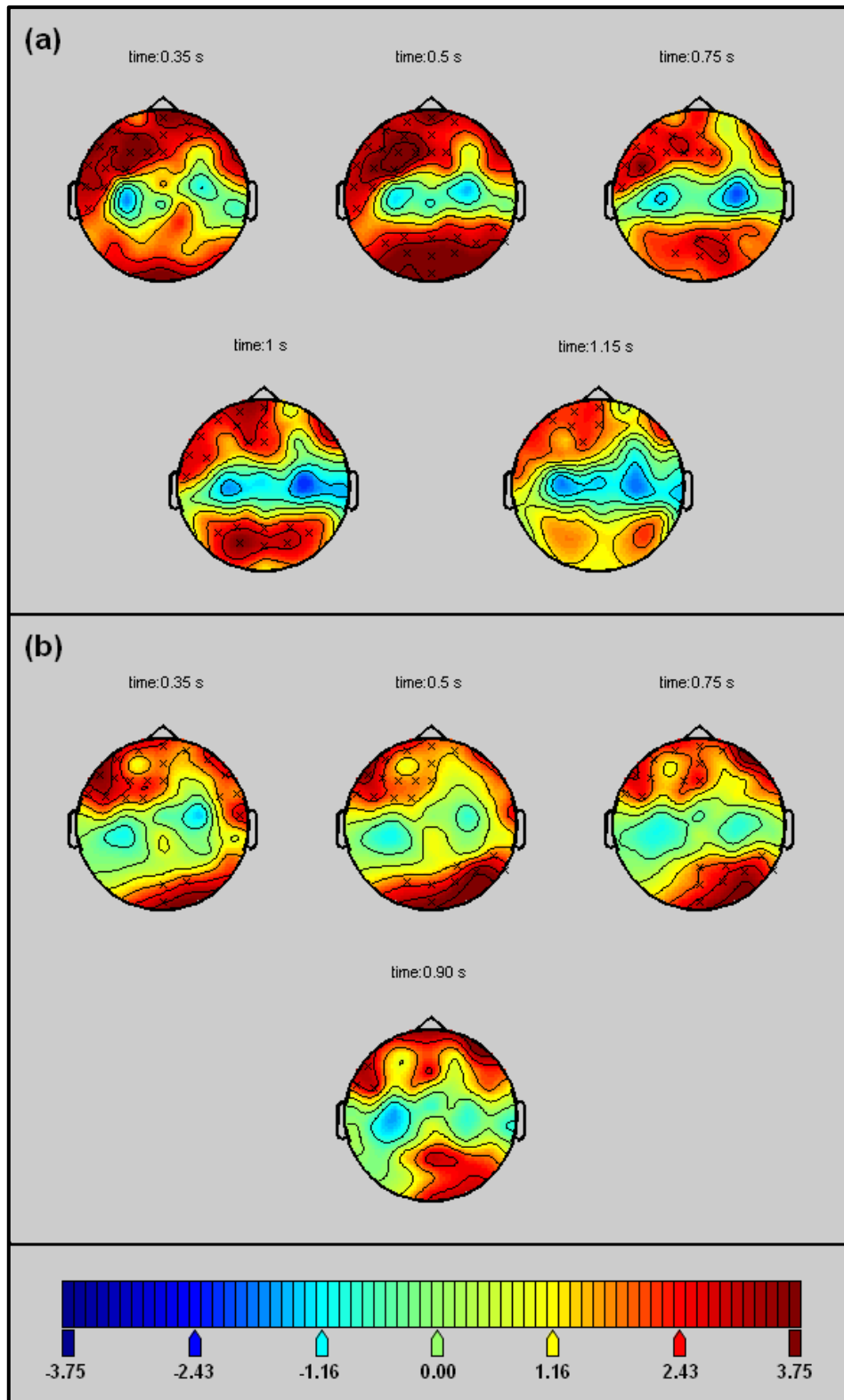


Figure 33. Differences in oscillatory activity in the theta band between the memory and control conditions, depicted for participants in the low span group (a) and the high span group (b). The colour scale represents  $t$ -values corresponding to the test of the difference between the two conditions; positive indicates higher activity in the memory condition. \*  $p < .05$ . All statistically significant clusters are comprised between the first and last plotted time points.

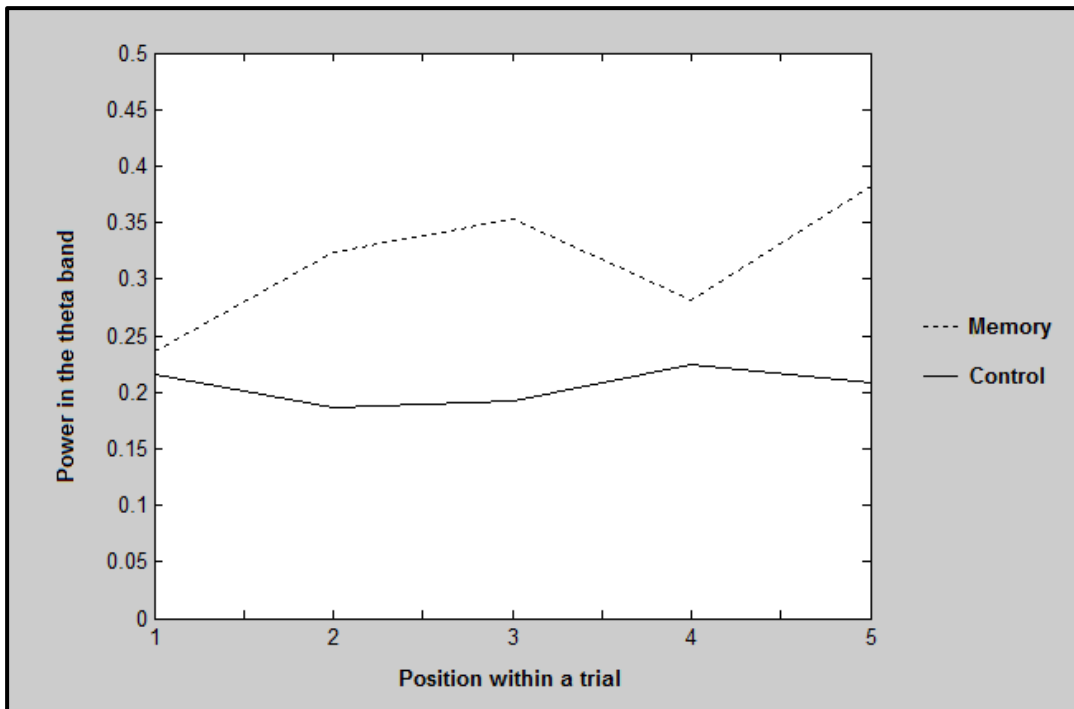


Figure 34. Average power in the theta frequency band as a function of position within a trial and experimental condition across all participants. The difference between conditions is significant for positions 2, 3 and 5.

### 3.4. Discussion

In this experiment, we expected to observe sustained oscillatory activity in the theta, beta and gamma bands and decreased activity in the alpha band in the memory condition; we expected all these effects to be more pronounced for participants with high working memory capacity, indicating a higher tendency to use proactive control. The first part of these hypotheses was well supported by the data: although activity in the gamma band could not be tested, we observed sustained activity in the theta and beta bands over frontal and occipital sites and decreased activity in the alpha band in the memory condition, entirely congruent with the literature. An unexpected decrease in beta activity over central electrodes was also congruent with the use of subvocal rehearsal in the memory condition. However, none of these effects were modulated by working memory capacity. An exploratory analysis indicated that theta activity increased throughout a trial, also congruent with the literature; however, this effect was not modulated by working memory capacity either.

When considering the average neural activity over all participants, the pattern of results was entirely consistent with the literature. All predicted effects appeared in the data, suggesting that the experimental paradigm was successful in isolating memory-related neural activity. The emergence of sustained oscillatory activity throughout the ISI indicated that participants engaged in active memory-related cognitive processing such as subvocal

rehearsal or attentional refreshing of stimuli in memory; thus, the task was more specifically successful in eliciting sustained activity reminiscent of proactive control.

On the other hand, none of the effects involving working memory capacity were significant; if anything, participants with low working memory capacity demonstrated more sustained memory-related activity throughout the ISI than participants with high working memory capacity, contrary to our hypotheses. This absence of significant effects was not due to a lack of sensitivity of the task at the behavioural level: the difference in short-term memory performance as a function of working memory capacity was highly significant, indicating that participants with high working memory capacity did perform better in the task. Although activity in the gamma band was excluded from the analyses, the probability is slim that participants differed only in this frequency band without a concurrent difference in the theta band prominently associated with mnemonic processes. We can therefore conclude that no difference in sustained neural activity appeared as a function of working memory capacity, despite both the behavioural task and the EEG procedure demonstrating adequate sensitivity.

Two possible conclusions could be drawn on the basis of these results. The first possibility is that the higher performance of participants with high working memory capacity is not supported by a difference in brain activity. In other words, participants with high working memory capacity would carry out the exact same cognitive operations as participants with low working memory capacity, but the end result would be different with better remembrance for participants with high working memory capacity. It is unclear what exactly would drive the higher performance of these participants in that account. Maybe the difference between participants could be adequately described in terms of efficiency: all participants would implement qualitatively similar processes, but participants with high working memory capacity would do so more efficiently. Of course, this account is completely antagonistic to our thesis that participants with high working memory capacity use a qualitatively different cognitive control mechanism.

The second possibility is that there is actually a difference in neural activity as a function of working memory capacity in our experiment, but that this difference is not found during the maintenance period of the task. Recall that our analyses only searched for differences in neural activity during the delay period separating the presentation of two words, not during the 750ms period when a word was presented or during the retrieval period at the end of a trial; therefore, a difference in neural activity could have gone undetected in one of these periods. Oscillatory neural activity during these two phases of the trials could not be examined in our study, since the signal was heavily contaminated by electromyographic

activity (corresponding to eye movements associated with reading during the word presentation period, and to vocalizing movements associated with recalling the words out loud during the retrieval period); thus, the possibility remains open that there exists a true difference in memory-related neural activity between participants as a function of working memory capacity, but that this difference is restricted to the encoding or retrieval period. This possibility is supported by the fact that multiple memory-related effects reflected in neural activity are known to exist during the encoding and retrieval periods of a trial (for a review, see Gonthier & Hot, 2013; D. Friedman & Johnson, 2000); it is also congruent with the main finding of Experiment 7b using the AX-CPT paradigm, namely the fact that participants differ in terms of probe-related or retrieval activity. Importantly, however, this account is also entirely incongruent with our thesis: neither encoding-related, nor retrieval-related differences in activity as a function of working memory capacity would indicate a difference in the use of proactive control, since such a difference should specifically appear in the delay period. In short, no possible interpretation of the results seems to indicate that a high working memory capacity was associated with a higher tendency to use proactive control in a short-term memory task.

#### **4. Conclusion**

The two studies presented in this chapter attempted to use a neuroimaging approach to index the cognitive control mechanisms used by participants without contamination by behavioural confounding factors; in both cases, proactive control was operationalized as the amount of sustained activity during the delay period of a task. The two studies used very different paradigms but they came to remarkably similar conclusions: participants do not demonstrate any difference in delay-related neural activity as a function of working memory capacity. If a difference does exist, it does not seem to be attributable to proactive control; in fact, the higher probe-related activity observed in Study 7 for participants with high working memory capacity suggested that these participants actually use more reactive control (or do so more efficiently). In short, Study 7 and Study 8 offered compelling evidence against our own thesis. In the final chapter of this experimental section, we abandoned the idea of measuring an association between working memory capacity and the tendency to use proactive control. Instead, we elected to test the predictive value of our thesis by directly manipulating proactive control requirements in a fluid intelligence task, with the objective of modulating the relationship between working memory capacity and fluid intelligence.



# CHAPTER 8. THE EXPLANATORY VALUE OF PROACTIVE CONTROL

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## 1. Overview

In the previous chapters, we tried to test the first part of our thesis – the idea that participants with high working memory capacity have a higher tendency to use proactive control. This attempt met little success: measures of proactive control were generally uncorrelated with working memory capacity. This failure could be considered as the death-knell of the second part of our thesis – namely, the idea that the higher tendency of participants with high working memory capacity to use proactive control is what drives their higher performance in fluid intelligence task. However, it may also be the case that there is a true relationship between working memory and proactive control, but that this relationship is difficult to evidence in laboratory tasks: actual differences in control mechanisms could exist without directly impacting performance, making experimental validation difficult (see pp. 63-64 for a similar argument). It could also be the case that the three-way relationship between working memory capacity, cognitive control and fluid intelligence is more apparent in fluid intelligence tasks; the fact that a relationship between working memory and fluid intelligence is reliably observed means that there is significant variability to work with, which could make any effect of cognitive control easier to evidence in this context.

For these reasons, we elected to put the second part of our thesis directly to the test. The two studies presented in this chapter tried to assess the explanatory value of the DMC framework in the relationship between working memory capacity and fluid intelligence; as per our thesis, the higher tendency of participants with high working memory capacity to use proactive control was expected to drive their higher performance in fluid intelligence tasks. Contrary to Chapters 4 to 7, the studies presented in this chapter directly measured performance in fluid intelligence tasks and tried to test the relationship between this measure and working memory capacity in the context of the DMC framework. In other words, we did not try to evidence a correlation between working memory capacity and the tendency to use proactive control as in previous chapters; instead, we tried to understand whether the hypothesized relationship between working memory capacity and proactive control explains the relationship between working memory and fluid intelligence.

As we have seen, the correlational method gave poor results in previous chapters. Consequently, the two studies presented in this chapter tried to manipulate rather than

measure proactive control, using the combined experimental-correlational approach presented in Chapter 6 (Study 5; p. 163). Contrary to Study 5, proactive control was directly manipulated within a fluid intelligence task rather than within a cognitive control task. More specifically, the next two studies tried to decrease the role of proactive control in fluid intelligence tasks. The rationale was as follows: if performance in fluid intelligence tasks is related to working memory capacity because these tasks benefit from proactive control, then reducing the advantage procured by proactive control in a fluid intelligence task should decrease its relationship with working memory. In other words, working memory capacity should be more related to performance in a standard fluid intelligence task where proactive control brings a lot of benefit than to performance in a modified fluid intelligence task where cognitive control plays a limited role.

In the introduction, we have proposed that proactive control benefits performance in a fluid intelligence task by helping the participant organize his thoughts in a goal-driven manner and systematically navigate through the task by following a hierarchy of goals and sub-goals (p. 76). Reducing the advantage procured by proactive control in a fluid intelligence task was slightly more of a challenge. Fortunately, modifying a task to limit the role of cognitive control has been successfully done in the past, in the context of clinical neuropsychology. Two seminal studies investigated deficits in goal-driven behaviour in patients with a frontal lesion (Luria & Tsvetkova, 1964; Luria & Tsvetkova, 1967; see also Seron, 2009). One of these studies focused on Kohs' blocks, a test requiring participants to manipulate coloured cubes so as to reproduce a visual pattern; one patient, *Urb*, was completely unable to reproduce simple structures in this task (Luria & Tsvetkova, 1964). Patient *Urb* reportedly carried out actions in a quasi-random sequence, helplessly manipulating the blocks around without a clear direction; the authors interpreted this deficit in terms of an inability to subordinate his activity to a plan – in other words, a failure of top-down cognitive control. Critically, Luria and Tsvetkova tried to help the patient perform the task by reducing the importance of cognitive control. They proceeded by decomposing the task into a sequence of operations to be carried out successively, and by simply passing on this walkthrough to the patient. As a result, the performance of patient *Urb* improved tremendously to the point that he was able to complete the task. Importantly, the walkthrough only detailed which steps to perform in which order; it did not provide the patient with any supplementary information. The second study reported the same result with an arithmetic task: patients with a cognitive control deficit were unable to solve arithmetic problems because they computed random operations instead of following the task goal; however,

providing them with a detailed procedure to follow led them to successfully solve the problems (Luria & Tsvetkova, 1967). These two studies suggest that a deficit in cognitive control may be compensated by having participants follow a predetermined hierarchy of goals and sub-goals that they are unable to define independently.

In their article, Luria and Tsvetkova (1964) presented an example of the program provided to patient *Urb*:

I. [Analyze the pattern.]

1. Look at the pattern.
2. Count how many squares there are in all the figure given.
3. Look what colours there are in the figure.
4. Try to single out the structure and draw the figure.

II. Begin to construct [the pattern].

1. Find out the necessary number of blocks.
2. Begin to construct the figure from the top, lay the blocks from left to right.

[...]

This program is strikingly similar in its structure to the hierarchy of goals and sub-goals that participants use in the APM, as described by Carpenter and colleagues (1990, p. 412 and p. 419; see also p. 51-53, this work). This is not surprising since both the APM and the Kohs' blocks task are based on the systematic spatial analysis of a complex figure and the construction of an answer; Kohs' blocks are sometimes used as an intelligence measure, although this use is debatable. This similarity suggests that the procedure used by Luria and Tsvetkova may be successfully applied to the APM. In other words, providing participants with a plan to follow in the APM should reduce the cognitive control demands of the task. Importantly, this should have different effects on participants as a function of their working memory capacity: participants with high working memory capacity are hypothesized to use proactive control and to already complete the task by following a definite hierarchy of goals and sub-goals; consequently, providing them with a walkthrough should have little effect on their performance. On the other hand, participants with low working memory capacity are hypothesized to use reactive control and to complete the task without relying on a systematic hierarchy of goals and sub-goals, eliciting their lower performance; as a consequence, providing these participants with a walkthrough should improve their performance.

In the two studies presented here, we used this rationale to test the hypothesis that the relationship between working memory capacity and fluid intelligence is due to a differential use of proactive control. Two fluid intelligence tasks were modified with a procedure similar to the work of Luria and Tsvetkova (1964, 1967), so that participants did not need to independently define a step-by-step procedure to follow. In each study, half the participants completed the standard version of the task and the other half completed the modified version with reduced cognitive control demands. Participants with high working memory capacity were hypothesized to use proactive control, to efficiently follow a hierarchy of goals whether explicitly provided with this hierarchy or not, and to perform efficiently in both versions of the task. On the other hand, participants with low working memory capacity were hypothesized to use reactive control and to complete the task without following an internally generated hierarchy of goals; as a consequence, they were expected to perform better in the modified version of the task.

## **2. Study 9 – Modified progressive matrices**

### **2.1. Experiment 9a**

#### *2.1.1. Rationale*

In this experiment, we tried to apply the logic of reducing the contribution of cognitive control to performance by modifying Raven's APM (Raven et al., 1998), with a procedure similar to Luria and Tsvetkova's work (1964, 1967). Two reasons motivated the choice of the APM: they are frequently described as the experimental measure with the highest loading on fluid intelligence (e.g. Carpenter et al., 1990), and their relationship with working memory capacity has been documented in a very large number of works (Ackerman et al., 2005; Redick et al., 2012). An additional advantage of the APM is that several researchers have tried to create modified versions of the test to assess its relationships with other constructs, with fruitful results (e.g. Wiley, Jarosz, Cushen, & Colflesh, 2011; Jarosz & Wiley, 2012).

Providing participants with a step-by-step procedure to follow in order to solve the task required precisely defining such a procedure. Fortunately, Carpenter and colleagues (1990), in their study of the APM using eye-tracking and verbal reports, have provided a directly usable account of the hierarchy of goals and sub-goals that participants tend to follow in the task: participants usually start with the top left corner and proceed by systematic pairwise comparison between elements of the matrix; they generalize this procedure to the second and third lines of the matrix; using this information, they generate a representation of

the form that the missing piece should take; and they compare this representation to the possible answers. This description is sufficiently detailed that it can be used to generate a step-by-step procedure for participants to follow.

Luria and Tsetkova (1964, 1967) provided participants with a written walkthrough to read and to apply; this procedure functioned correctly for lesioned patients, but it could have posed compliance problems in non-pathological participants and would have been harder to systematically apply for a large number of trials in the APM. As a result, instead of asking participants to follow a written procedure, we elected to create a modified version of the task by decomposing each item into several parts presented successively. The decomposition was carried out so as to mimic the procedure naturally followed by participants according to Carpenter and colleagues (1990). In other words, instead of providing participants with a written walkthrough whose first entry would be "compare the first two elements of the matrix", we modified the task so that participants had to compare the first two elements of the matrix before viewing the rest of the item.

For example, the first step that participants typically follow is to compare the top left and top middle elements of the matrix to detect regularities and differences; accordingly, the first part of the matrix that participants saw in the modified version of the task included only the top left and top middle elements. The second step that participants follow is to look at the top right element of the matrix to generalize the conclusions they have drawn on the first two elements; accordingly, the second part that participants saw included the top left, top middle and top right element – and so on. The final part presented the full matrix along with the possible answers, exactly the same as it appears in the standard version of the task. Importantly, our modified version of the APM did not provide participants with any supplementary information, did not point out their mistakes and did not provide any help for the abstraction of logical rules themselves (see Luria & Tsvetkova, 1964, for a similar point). The only change between the standard and the modified version was that the matrix was not presented all at once, but one step at a time.

Participants completing the modified version of the APM only had to follow predetermined steps to solve the problems; this modification was hypothesized to reduce the need for participants to generate their own hierarchy of goals and sub-goals – in other words, to reduce the benefit of using proactive control. As a consequence, participants with low working memory capacity were expected to perform better in the modified version than in the standard version, whereas participants with high working memory were expected to perform at the same level in both versions of the task. Another way to phrase this hypothesis is that the

correlation between working memory capacity and performance in the APM was expected to be lower in the modified version than in the standard version.

### 2.1.2. Pre-test experiment

Our modification of the APM raised two major issues. Firstly, decomposing the presentation of the items into multiple steps was bound to increase the total time participants spent on the task. This was a source of concern, as the difference in performance between participants as a function of working memory capacity could have been due to time-on-task differences; for example, one could imagine that participants with low working memory capacity tend to spend less time on the task. Secondly, matrices in the APM are based on several types of logical rules, which are not necessarily affected in the same way by modifications of the task. Two types of rules in particular, distribution-of-two and distribution-of-three rules (see Carpenter et al., 1990), can only be inferred with a global view of the matrix: comparing two figures, or even considering a whole row, does not allow unambiguous extraction of the rule, as is the case for example for addition and subtraction rules. Our modification of the APM seemed ill-suited to these rules because decomposing the items encouraged participants to focus on the features of individual elements within the matrix. In order to eliminate this problem, our version of the APM excluded items following a distribution-of-two or a distribution-of-three rules. This restriction should not affect the relationship of the task with working memory, because working memory capacity is predictive of performance on problems with all rule types (Salthouse, 1993; Unsworth & Engle, 2005) and because items from all difficulty levels were still present in the task (see Appendix F, Table F1, for a list of retained items); however, the restriction in rule types could still have affected the psychometric properties of the task.

A pre-test experiment was set up to control for both these possible problems. A sample of 89 participants completed the operation span as well as an unmodified version of the APM restricted to certain items; more specifically, the task included 20 of the 36 items in set II of the APM (Raven et al., 1998), excluding items following a distribution-of-two or a distribution-of-three rule (see Appendix F, Table F1 for the list of 20 items). Our objectives were to ensure that working memory capacity predicted performance despite the restriction in rule types, but did not predict time spent on the task.

Working memory capacity predicted neither median response times in the APM,  $F(1, 87) = 0.01$ ,  $MSE = 85365112$ ,  $p = .915$ ,  $\eta^2_p = .00$ ,  $r = .01$ ; nor total time on task,  $F(1, 87) = 0.40$ ,  $MSE = 44399530172$ ,  $p = .527$ ,  $\eta^2_p = .00$ ,  $r = .07$ . However, we did observe a

significant correlation between working memory capacity and performance in the APM,  $F(1, 86) = 6.71$ ,  $MSE = 11.603$ ,  $p = .011$ ,  $\eta^2_p = .07$ ,  $r = .27$ , as expected. In other words, any effects of our experimental manipulation in the main experiment should not be due to an effect on response times or to the restriction of the task to certain rule types.

### 2.1.3. Method

This experiment was approved by an ethics committee (Comité d'éthique recherche de l'Université de Savoie) under approval number 20148.

#### 2.1.3.1. Participants.

A sample of 83 participants completed the experiment (10 males and 73 females; age ranging from 17 to 29,  $M = 20.61$ ,  $SD = 1.99$ ). All participants were undergraduate students from the University of Grenoble 2 or the University of Savoy participating for course credit. Participants were included if they met the following criteria: native French speaker, never completed the APM, no history of neurological disorders, and without psychoactive medication.

#### 2.1.3.2. Materials.

**Working memory task.** Working memory capacity was measured with the CCS (see Appendix A). The dependent variable on the task was the composite working memory score.

**Standard APM.** Participants completed set II of Raven's APM (Raven et al., 1998). As described previously, the APM comprises a series of logical problems in the form of incomplete matrices. Each matrix is composed of 9 black-and-white figures arranged in a 3x3 rectangular display (see Figure 3 in the introduction, p. 52). The succession of figures within the matrix is governed by logical rules; each matrix includes one to five rules. On each matrix, the bottom right figure is missing; the participant's task is to select, among 8 possible alternatives, the figure that correctly completes the matrix.

The unmodified condition of the task presented the items as they appear in the original version of the test (Raven et al., 1998). Items successively appeared on a computer screen; participants had to select one figure to complete the matrix by pressing the corresponding key on the keyboard. Time on task was not limited so as to limit the contribution of processing speed to scores (Ackerman et al., 2005) and to increase the validity of the measure (Raven et al., 1998). Participants completed 20 of the 36 items in set II, as in the pre-test (see

Appendix F, Table F1 for the items list); the dependent variable in the task was simply total accuracy.

**Modified APM.** The modified condition of the APM included the same items as the standard condition. The only difference between the two versions was the format of presentation of the items. In order to mimic the typical sequence of analysis (Carpenter et al., 1990), the presentation of each item was decomposed into 4 main sections, each with different instructions and each comprising a different number of steps. The images corresponding to these steps were presented sequentially. Although participants were allowed to spend as much time as desired on each image, a minimal examination time of 3 seconds per image was imposed. Participants had to press the spacebar to end the presentation of each image.

In the first section, the participant was encouraged to « try and understand the rules governing the matrix ». The first image presented only the first two elements of the top row. The second image presented the whole first row. The third image presented only the first two elements of the middle row, and the fourth image presented the whole middle row. The fifth image presented the first two items in the bottom row. In the second section, the instruction was to « check whether these rules were correct throughout the whole matrix ». The only image in this section presented the whole matrix (but not the possible answers). In the third section, the participant had to « decide whether each figure could correctly complete the matrix ». Images one to eight presented the whole matrix and a single possible answer. In the fourth section, the instruction was to « choose the one correct answer from among the eight possibilities ». The only image in this section presented the complete item, identical to the way it appeared in the standard version: the whole matrix and the eight possible answers.

### *2.1.3.3. Procedure.*

Participants completed the experimental session in groups of 4 to 8 individuals, in a university computer room equipped with identical computers, 19 inches LCD screens, and headphones for phonic isolation. All participants provided written informed consent prior to the experimental session. Participants completed the CCS followed by one of the two versions of the APM; the whole process took approximately 60 minutes. All participants in a testing session completed the same version of the APM, with conditions alternating from one session to the next. The APM were preceded by two practice trials – standard practice trials for the standard condition and modified practice trials for the modified condition.



## 2.1.4. Results

### 2.1.4.1. Preliminary analyses.

Working memory scores were normally distributed and close to the population average ( $M = 0.04$ ,  $SD = 0.77$ , skewness = -0.20, kurtosis = -0.32). The distribution of working memory scores was similar in the standard condition ( $M = 0.04$ ,  $SD = 0.82$ , skewness = -0.17, kurtosis = -0.53) and in the modified condition ( $M = 0.05$ ,  $SD = 0.72$ , skewness = -0.25, kurtosis = 0.06) of the APM.

To ensure that both versions of the APM had comparable reliability, Cronbach's alpha coefficients were calculated for each condition; internal consistency was similar for the standard version ( $\alpha = .74$ ) and for the modified version ( $\alpha = .72$ ). APM scores were normally distributed on both the standard version ( $M = 11.86$ ,  $SD = 3.61$ , skewness = -0.42, kurtosis = -0.60, range = 5 – 18) and the modified version ( $M = 13.41$ ,  $SD = 2.95$ , skewness = 0.20, kurtosis = -0.70, range = 8 – 19) of the task, without any indication of a ceiling effect. On average, performance was higher in the modified version than in the standard version of the APM,  $t(81) = -2.15$ ,  $p = .034$ . Power (or difficulty) indices, computed as the percentage of participants correctly answering an item, were comparable across versions of the task, indicating that the task modification did not disproportionately affect certain items (see Appendix F, Figure F1). On average, participants spent more time-on-task in the modified condition ( $M = 23.17$  minutes,  $SD = 5.20$ ) than in the standard condition ( $M = 12.84$  minutes,  $SD = 6.72$ ) of the APM,  $t(103) = -8.81$ ,  $p < .001$ .

### 2.1.4.2. Main analyses.

Our hypothesis was that working memory capacity would predict performance in the standard, but not in the modified version of the APM. Congruent with our hypothesis, working memory capacity correlated with performance in the standard APM,  $F(1, 40) = 5.80$ ,  $MSE = 11.640$ ,  $p = .021$ ,  $\eta^2_p = .13$ ,  $r = .36$ , but not in the the modified APM,  $F(1, 39) = 0.06$ ,  $MSE = 8.908$ ,  $p = .807$ ,  $\eta^2_p = .00$ ,  $r = .04$ . These correlations are represented in Figure 35. A statistical test using Fisher's  $z$ -transformation revealed that the difference between the two correlations was marginally significant,  $p = .074$  (one-tailed).

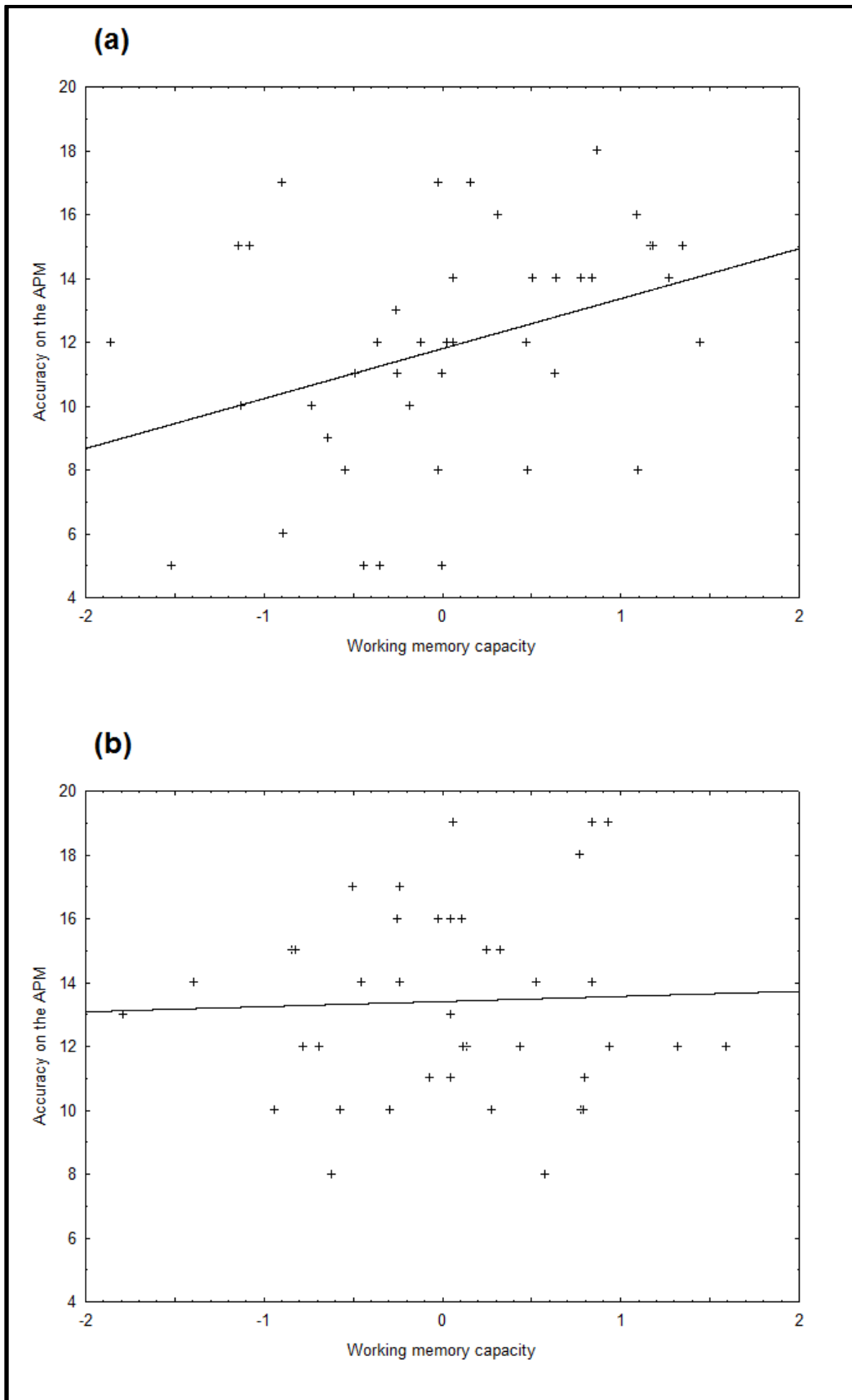


Figure 35. Scatterplots for the correlation between (a) working memory capacity and performance in the standard APM and (b) working memory capacity and performance in the modified APM.

While this correlational analysis provides some support for our hypotheses, it provides no insight into the differential effects of the two task versions on performance as a function of working memory capacity; in particular, it does not allow to test the hypothesis that the task modification selectively increased the performance of participants with low working memory capacity. In order to test this hypothesis more fully, we re-analyzed the data using an extreme-group procedure. This classical analysis in individual differences studies of working memory consists in contrasting two groups of participants with extreme working memory scores. For the following analysis, working memory was considered as a two-modality categorical variable, with participants falling in the upper quartile of the distribution forming the high span group ( $n = 21$ ), and participants falling in the lower quartile forming the low span group ( $n = 21$ ). Low spans who completed the standard APM had a working memory capacity ( $M = -0.99, SD = 0.42$ ) similar to low spans who completed the modified APM ( $M = -0.89, SD = 0.40$ ),  $t(19) = -0.55, p = .588$ . High spans who completed the standard APM also had a WM score ( $M = 1.07, SD = 0.25$ ) similar to high spans who completed the modified APM ( $M = 0.96, SD = 0.27$ ),  $t(19) = 0.93, p = .365$ .

We expected high spans to demonstrate a comparable performance in both versions of the APM, and we expected low spans to perform worse than high spans in the standard version, but not in the modified version. These hypotheses were tested via a set of orthogonal planned comparisons. Firstly, the performance of low spans in the standard APM ( $M = 10.73, SD = 3.80$ ) was lower than the mean of the other three conditions,  $F(1, 38) = 5.87, MSE = 10.36, p = .020, \eta^2_p = .13$ . Secondly, the performance of low spans in the modified APM ( $M = 12.60, SD = 2.76$ ) did not differ from the mean of the performance of high spans in both task conditions,  $F(1, 38) = 1.10, MSE = 10.36, p = .302, \eta^2_p = .03$ . Thirdly, the performance of high spans in the standard APM ( $M = 14.09, SD = 2.51$ ) did not differ from their performance in the modified APM ( $M = 13.70, SD = 3.62$ ),  $F(1, 38) = 0.08, p = .783, \eta^2_p = .00$ . These results suggest that the modified version of the APM improved the performance of low spans to the level of high spans, but had no effect on the performance of high spans themselves, congruent with our hypotheses (see Figure 36 for a graphical summary of the results).<sup>19</sup>

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<sup>19</sup> Because the extreme-design procedure excludes participants who do not fall either in the high span group or the low span group, one may be concerned about their performance. These participants as a group performed better than low spans but worse than high spans in the standard APM ( $M = 11.25, SD = 3.63$ ); their performance was roughly equivalent to both high spans and low spans in the modified APM ( $M = 13.67, SD = 2.76$ ).

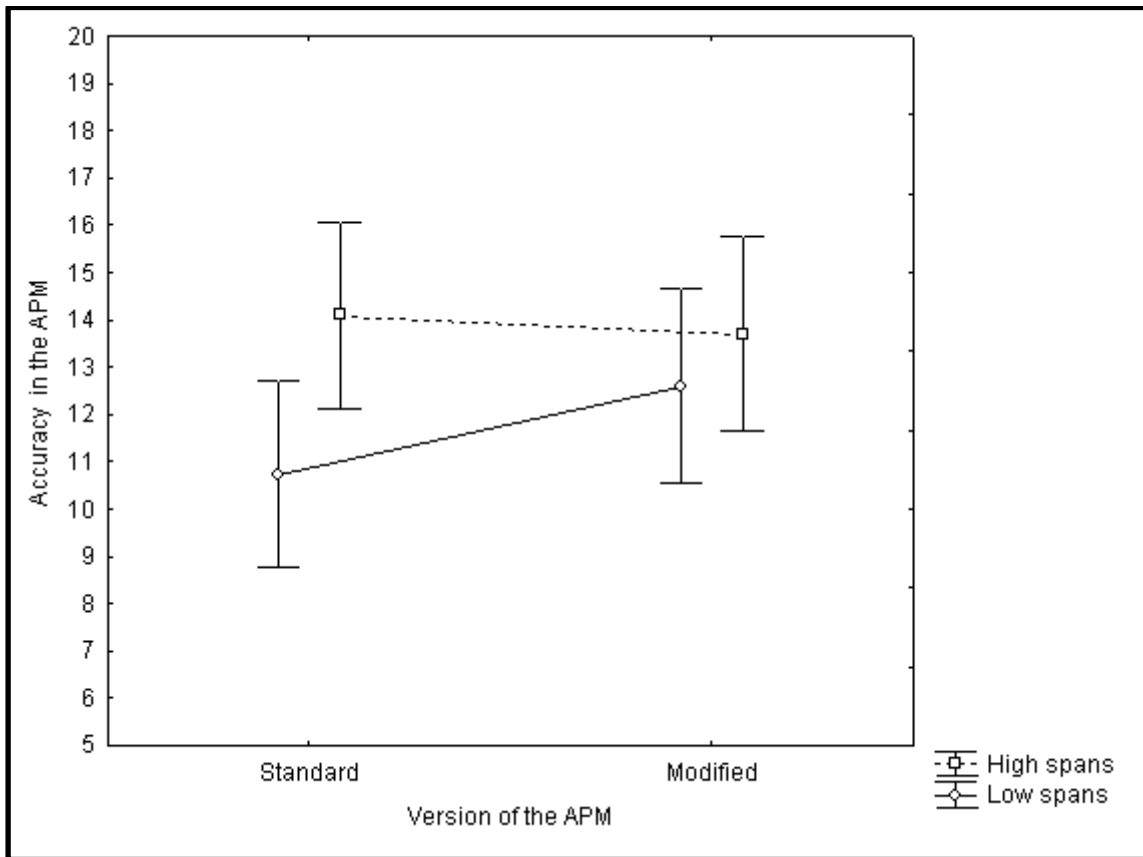


Figure 36. Performance in the APM as a function of the task version and the working memory group. Error bars represent standard errors of the mean.

### 2.1.5. Discussion

The goal of this study was to determine whether the correlation between working memory capacity and fluid intelligence can be attributed to the higher tendency of participants with high working memory capacity to use proactive control. We modified Raven's APM to reduce the cognitive control demands of the task; participants with high working memory capacity no longer performed better than participants with low working memory capacity in the modified version. These results suggest that cognitive control explains part of the shared variance between working memory capacity and fluid intelligence.

These results are certainly more encouraging than those of Chapters 4 through 7. The significant influence of cognitive control on the relationship between working memory capacity and fluid intelligence may mean two things: either the role of cognitive control is easier to observe in the context of a fluid intelligence task, or experimentally manipulating cognitive control is a better way to test its influence on behaviour. Although the two solutions are believable, there should be more irrelevant sources of variance in fluid intelligence tasks than in cognitive control tasks, which should contribute to blur the role of cognitive control;

thus, the possibility that manipulating the construct is more efficient than just measuring it seems more likely.

Our findings imply that cognitive control mechanisms play a role in determining performance in Raven's APM; of course, they do not mean that cognitive control is the sole determinant of performance in the APM (Ackerman et al., 2005). Instead, it is extremely likely that differences also exist in the ability to extract and understand the rules present in the problems, an "abstraction skill" of sorts that is probably closer than cognitive control to the notion of reasoning abilities that the APM intend to measure. In fact, performance in fluid intelligence tasks probably results from the combination of individual differences in several processes, including both abstraction and cognitive control (Carpenter et al., 1990). In any case, however, the fact that participants with low working memory capacity demonstrated the same performance as participants with high working memory capacity in the modified version of the task suggests that difference in fluid intelligence as a function of working memory capacity are not related to true differences in the ability to abstract rules.

Importantly, these results can hardly be interpreted in terms of processing speed, short-term or secondary memory, three confounds often called upon to explain the relationship between working memory and fluid intelligence: none of the three variables was targeted by our experimental manipulation, which only affected processes related to the control of performance. On the other hand, "processes related to the control of performance" do not only include cognitive control; the modification of the APM partially changed the nature of the task, which may have affected other components of performance. For example, the modification may have qualitatively affected the way participants perform the task by altering the use of the two possible strategies in the APM, constructive matching and response elimination (Vigneau et al., 2006; see pp. 79-80). Breaking down the presentation of the matrices encouraged participants to consecutively consider each figure in an item, then each possible answer to the item; it is possible that this modification made the constructive matching strategy easier or more prevalent. As we have seen, these two strategies are conceptually related to the DMC framework in that proactive control may be a requirement for the efficient use of constructive matching, but they are not identical to cognitive control mechanisms either. In the absence of an accurate functional model of the determinants of performance in the APM, it is difficult to speculate further on the effect of our modification.

Despite the encouraging findings of this study, the sample size of 40 participants per group is still relatively small, and the results certainly deserve replication. This consideration led to Experiment 9b.

## **2.2. Experiment 9b**

### *2.2.1. Rationale*

The objective of Experiment 9b was simply to replicate the findings of Experiment 9a in a different sample. Rather than carrying an exact replication, this was the occasion to tie a few loose ends in Experiment 9a. Firstly, because all participants in the same testing session completed the same condition of the APM, the possibility of a sample bias existed in the previous experiment; in Experiment 9b, experimental conditions were assigned at random for each participant, solving this problem. Secondly, one reviewer of Experiment 9a raised the concern that working memory capacity was measured using only complex span tasks. It was argued that more diverse tasks might have yielded a more accurate estimate of working memory capacity by eliminating method-related variance (see Redick et al., 2012, for a similar point), and that a working memory estimate based on different tasks might have responded differently to the experimental manipulation. To control for this problem, Experiment 9b used more varied working memory tasks. Third, one problem with Experiment 9a was that participants received different initial information as a function of the experimental condition. The modified version of the APM instructed participants on what to do at the beginning of each section; for example, participants were told to « try and understand the rules governing the matrix » by comparing pairs of stimuli in the first section, and to « check whether these rules were correct throughout the whole matrix » in the second section. By contrast, the standard version of the APM only instructed participants to try and select the most appropriate piece to complete the matrix. Thus, participants completing the modified version of the APM not only completed a different task, they were also instructed in the most efficient way to complete the task by following the procedure defined by Carpenter and colleagues (1990). In Experiment 9b, the two practice items used the modified procedure for all participants, so that participants were all trained to use the goal hierarchy procedure.

### *2.2.2. Method*

This experiment was approved by an ethics committee (Comité d'éthique recherche de l'Université de Savoie) under approval number 20148.

#### *2.2.2.1. Participants.*

A sample of 104 participants completed the experiment (15 males and 89 females; age ranging from 18 to 28,  $M = 22.37$ ,  $SD = 2.28$ ). All participants were undergraduate students

from the University of Grenoble 2 participating for course credit. The inclusion criteria were the same as in Experiment 9a.

#### *2.2.2.2. Materials.*

The materials were identical to Experiment 9a with the exception of the working memory tasks. Participants completed three working memory tasks: an operation span, an alpha span, and a spatial working memory task; as in the CCS, the working memory score was calculated as the average of z-scores for all three tasks. The operation span was the third subtest of the CCS, used in all other experiments (see Appendix A). The alpha span confronted participants with a series of words and asked them to recall the first letter of each word in alphabetical order; the task is presented in detail in Appendix A.

The spatial working memory task was loosely based on a task developed by Oberauer and colleagues (Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000). As in the original task, participants had to memorize visual patterns represented by grids in a matrix and to transform these patterns before recall. However, the original version of the task, involving mental rotation, appeared much too difficult for our sample in pilot testing; in our final version of the task, participants had to recall the mirror image of the patterns instead. In each trial, participants were confronted with a 5x5 grid in which certain squares were lit in red, forming a visual pattern; they were instructed to memorize this pattern. The grid was presented for 5000ms. At the end of this delay, an empty recall grid appeared; participants were to click on squares of the recall grid so as to form a mirror image of the pattern. Participants completed 12 trials in the main task. The difficulty was randomly varied from trial to trial by changing the number of squares in a pattern; set sizes ranged from five to eight, with three trials per set size. Participants first completed five practice trials with set sizes of two to eight.

#### *2.2.2.3. Procedure.*

The procedure was identical to Experiment 9a with two exceptions. First, participants completed either the standard or the modified version of the APM, defined at random. Second, the two practice items preceding the APM used the modified procedure for all participants; participants completing the standard version of the APM were instructed that the modified procedure used for the practice items simply presented an efficient way to solve the task, but that they did not have to follow this procedure throughout the task.

### 2.2.3. Results

#### 2.2.3.1. Preliminary analyses.

Besides the alpha span and operation span tasks (already validated in Appendix A), the spatial working memory task yielded scores with a satisfying distribution ( $M = 41.31$ ,  $SD = 7.95$ , skewness = -0.38, kurtosis = -0.47, range = 22 – 56 out of a total of 63 stimuli to recall). Overall, working memory scores were normally distributed ( $M = -0.02$ ,  $SD = 0.71$ , skewness = 0.10, kurtosis = -0.37). The distribution of working memory scores was similar in the standard condition ( $M = -0.12$ ,  $SD = 0.72$ , skewness = 0.36, kurtosis = 0.27) and in the modified condition ( $M = 0.09$ ,  $SD = 0.69$ , skewness = -0.17, kurtosis = -0.75) of the APM.

Manipulation checks on both versions of the APM gave results similar to Experiment 9a: the distributions of APM scores were normal on both the standard version ( $M = 11.76$ ,  $SD = 3.61$ , skewness = -0.01, kurtosis = -0.04, range = 4 – 20) and the modified version ( $M = 14.14$ ,  $SD = 2.42$ , skewness = -0.22, kurtosis = -0.22, range = 8 – 19), and both distributions were very close to values observed in Experiment 9a. As in Experiment 9a, performance was on average higher in the modified version than in the standard version of the APM,  $t(102) = -3.91$ ,  $p < .001$ .

#### 2.2.3.2. Main analyses.

We carried out the same analyses as in Experiment 9a. Firstly, we expected working memory capacity to correlate with performance in the standard, but not in the modified version of the APM. This hypothesis was not supported by the data: working memory predicted scores in the APM for both the standard condition,  $F(1, 52) = 13.59$ ,  $MSE = 10.519$ ,  $p < .001$ ,  $\eta^2_p = .21$ ,  $r = .46$ , and the modified condition,  $F(1, 47) = 13.21$ ,  $MSE = 4.145$ ,  $p < .001$ ,  $\eta^2_p = .22$ ,  $r = .47$  (see Figure 37); a statistical test using Fisher's  $z$ -transformation indicated that these correlations were not statistically different,  $p = .476$  (one-tailed).

As in Experiment 9a, participants were divided into high spans ( $n = 26$ ) and low spans ( $n = 26$ ) for the second part of the analysis. Low spans who completed the standard APM had a working memory capacity ( $M = -0.92$ ,  $SD = 0.31$ ) similar to low spans who completed the modified APM ( $M = -0.96$ ,  $SD = 0.22$ ),  $t(24) = 0.35$ ,  $p = .726$ , and high spans who completed the standard APM also had a WM score ( $M = 0.98$ ,  $SD = 0.48$ ) similar to high spans who completed the modified APM ( $M = 0.85$ ,  $SD = 0.28$ ),  $t(24) = 0.90$ ,  $p = .376$ .



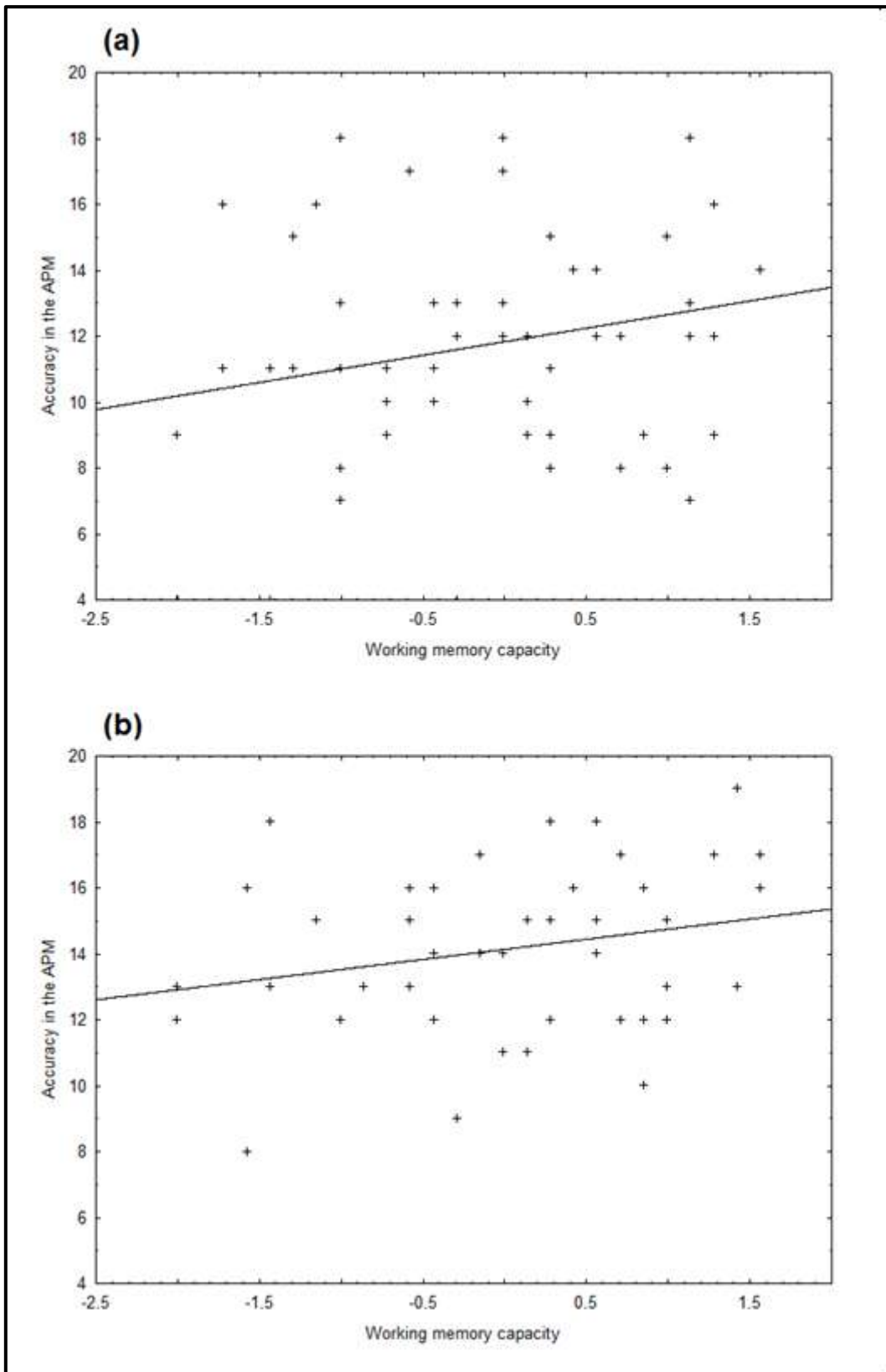


Figure 37. Scatterplots for the correlation between (a) working memory capacity and performance in the standard APM and (b) working memory capacity and performance in the modified APM.

As in Experiment 9a, we expected high spans to demonstrate a comparable performance in both versions of the APM, and we expected low spans to perform worse than high spans in the standard version, but not in the modified version. The data were not fully compatible with our hypotheses: the performance of low spans in the standard APM ( $M = 10.59$ ,  $SD = 3.81$ ) was lower than the mean of the other three conditions,  $F(1, 48) = 15.49$ ,  $MSE = 8.48$ ,  $p < .001$ ,  $\eta^2_p = .24$ , and the performance of high spans in the standard APM ( $M = 14.67$ ,  $SD = 3.24$ ) did not differ from their performance in the modified APM ( $M = 15.53$ ,  $SD = 3.24$ ),  $F(1, 48) = 0.52$ ,  $p = .476$ ,  $\eta^2_p = .01$ , but contrary to our expectations, the performance of low spans in the modified APM ( $M = 11.89$ ,  $SD = 1.53$ ) differed from the mean of the performance of high spans in both task conditions,  $F(1, 48) = 7.90$ ,  $MSE = 8.48$ ,  $p = .007$ ,  $\eta^2_p = .14$  (see Figure 38). In other words, the difference in performance between low spans and high spans was not eliminated by the modification of the APM.<sup>20</sup>

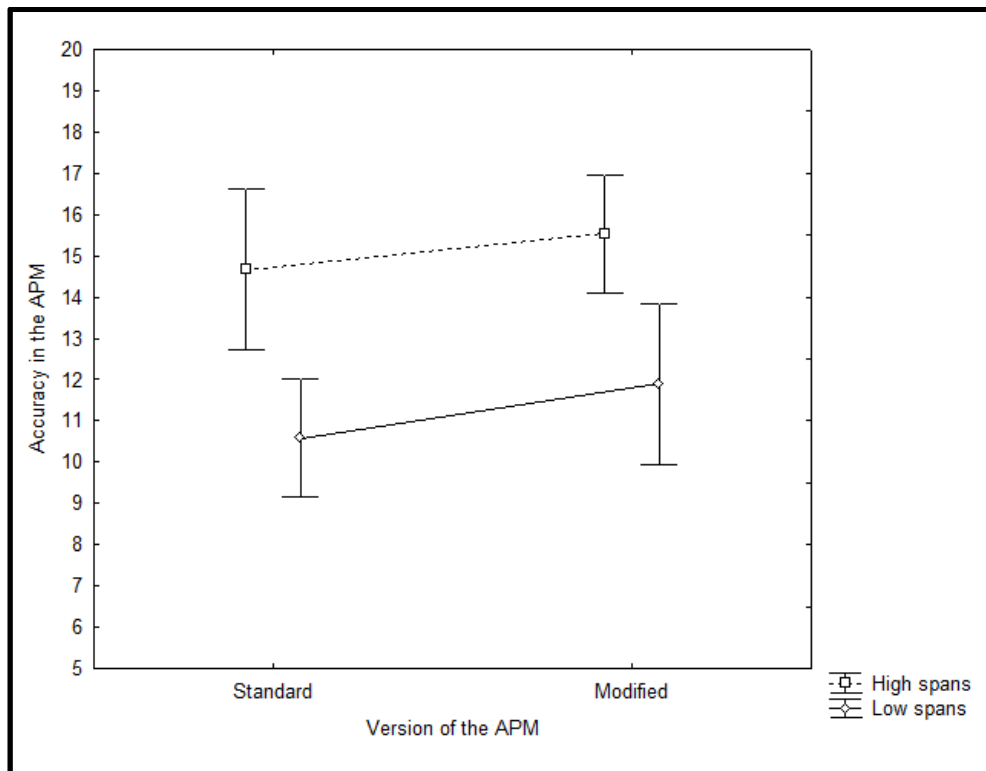


Figure 38. Performance in the APM as a function of the task version and the working memory group. Error bars represent standard errors of the mean.

<sup>20</sup> As for participants who did not fall in either the low span or the high span group, on average, they performed better than low spans but worse than high spans in both the standard condition ( $M = 11.54$ ,  $SD = 3.18$ ) and the modified condition ( $M = 14.00$ ,  $SD = 2.27$ ).

### 2.2.3.3. Exploratory analyses.

Two additional analyses were conducted in order to understand the discrepancy between Experiment 9a and Experiment 9b. A first analysis tested whether performance in each experimental condition differed between the two experiments. A series of *t*-tests revealed that there were no significant differences in performance on the APM between Experiment 9a and Experiment 9b for low spans in the standard condition, low spans in the modified condition, and high spans in the standard condition, all  $ps > .60$ . High spans in the modified condition performed slightly better in Experiment 9b, but the effect did not reach significance,  $t(25) = -1.66, p = .136$ .

As proposed for Experiment 2a and Experiment 2b (p. 136), the difference between the two samples could be caused by a sample bias at the level of working memory, such as a lower average working memory capacity in one of the samples. A second analysis tested this idea by comparing the distribution of scores on the operation span task which was completed by participants in both samples. On average, scores on the operation span were equivalent in Experiment 9a ( $M = 0.04, SD = 0.77$ ) and in Experiment 9b, ( $M = -0.02, SD = 0.71$ ),  $t(185) = 0.57, p = .569$ . A Levene test indicated that the variability of scores in both samples was also equivalent,  $F(1, 185) = 1.38, p = .242$ . Thus, there were no significant differences in the sampling of working memory capacity between the two experiments.

In a third analysis, we elected to combine the datasets of Experiment 9a and Experiment 9b so as to maximize statistical power. This combination posed no particular problems because the two experiments used the same procedure, except for working memory tasks. Since the operation span was the only working memory task common to the two experiments, scores on this task were used as a working memory capacity estimate. The main analyses were then repeated on this combined dataset, with the sample as a controlled variable. Overall, working memory capacity predicted performance in the APM both in the standard condition,  $F(1, 94) = 6.02, MSE = 12.23, p = .016, \eta^2_p = .06, r = .25$ , and in the modified condition,  $F(1, 89) = 4.78, MSE = 6.91, p = .031, \eta^2_p = .05, r = .23$ , as in Experiment 9b and contrary to our hypotheses. These two correlations were not statistically different,  $p = .444$  (one-tailed).

Unexpectedly, dividing the participants into low spans ( $n = 47$ ) and high spans ( $n = 47$ ) yielded results congruent with our hypotheses and with Experiment 9a: the performance of low spans in the standard APM ( $M = 11.13, SD = 4.12$ ) was lower than the mean of the other three conditions,  $F(1, 90) = 7.04, MSE = 11.25, p = .009, \eta^2_p = .07$ , the performance of low spans in the modified APM ( $M = 12.74, SD = 2.45$ ) did not differ from

the mean of the performance of high spans in both task conditions,  $F(1, 90) = 0.74$ ,  $MSE = 11.25$ ,  $p = .391$ ,  $\eta^2_p = .01$ , and the performance of high spans in the standard APM ( $M = 12.78$ ,  $SD = 3.72$ ) did not differ from their performance in the modified APM ( $M = 14.17$ ,  $SD = 2.82$ ),  $F(1, 90) = 2.00$ ,  $p = .161$ ,  $\eta^2_p = .02$  (these results are depicted in Figure 39). In other words, the correlational analysis was incompatible with our hypothesis and indicated that the correlation between working memory capacity and performance was similar in both conditions of the task, whereas the extreme design analysis supported our hypothesis.

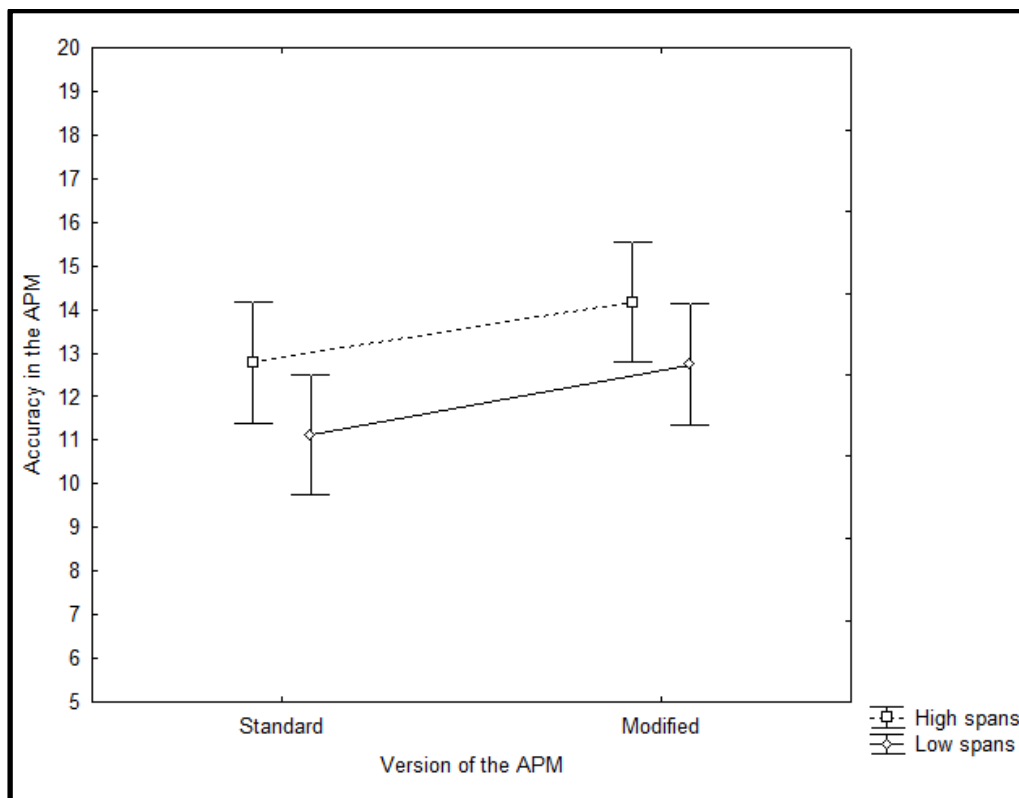


Figure 39. Performance in the APM as a function of the task version and the working memory group. Error bars represent standard errors of the mean.

Closer inspection of the results of the extreme design analysis explains the source of this discrepancy. Examining descriptive statistics and Figure 39 indicates that although the effect of task condition failed to reach significance in the high span group, the modification of the APM did improve their performance to the same extent as that of low spans: on average, low spans scored 1.61 points higher in the modified APM whereas high spans scored 1.39 points higher in the modified APM. Furthermore, the difference in performance between the two groups was similar for the two experimental conditions: on average, the performance of high spans was 1.66 points higher in the standard condition and 1.43 points higher in the

modified condition. In other words, the fact that the extreme design analysis supported our hypotheses seems mainly due to the reduction of statistical power that stemmed from restricting the analysis to half the sample. The results of this analysis descriptively converge with the correlational analysis in suggesting that our hypotheses were incorrect: overall, the modification of the APM improved the performance of all participants to the same extent and did not reduce the relationship between working memory capacity and fluid intelligence.

#### *2.2.4. Discussion*

Experiment 9b was a simple replication of Experiment 9a, with minor modifications: different working memory tasks were used and participants completing the standard version of the APM received the same training using the modified procedure as participants completing the modified version of the task. We expected to observe the same results as in Experiment 9a. However, contrary to our hypothesis and in direct contradiction with Experiment 9a, the modification of the APM did not increase the performance of low spans to the level of high spans; working memory capacity was predictive of performance in both versions of the task.

There does not seem to be an obvious explanation for the discrepancy between Experiment 9a and Experiment 9b. The change in working memory tasks is certainly not to blame: participants assigned to the low span and high span groups in the extreme design analysis demonstrated similar APM performance in both samples, and restricting the analysis to the operation span task, completed by all participants, also yielded comparable results in both samples. Thus the difference is to be sought elsewhere. The only other significant change between the two experiments was the fact that participants completing the standard version received the training for the modified version in Experiment 9b. Could it be the case that these participants strived to use the efficient procedure proposed in the modified version of the task, leading them to perform better despite completing the standard version of the APM? If this hypothesis was true, then participants in the standard condition of Experiment 9b should have performed better than participants in the standard condition of Experiment 9a; complementary analyses indicated that this was not the case, invalidating this explanation.

The only easy explanation left is random variation between the two experiments. Complementary analyses indicated that the only difference approaching significance between the samples concerned high spans in the modified condition, who performed slightly worse in Experiment 9a. This small difference was sufficient to make the results conform to our hypotheses in Experiment 9a: had high spans performed better in the modified condition of

Experiment 9a, the correlation between working memory capacity and performance might have reached statistical significance in the modified version, contrary to our predictions. In other words, the discrepancy between the conclusions of the two experiments rests entirely on the lower performance of a handful of participants in Experiment 9a. Due to the low sample size, it is possible that this lower performance was simply the result of chance; the fact that combining the samples of Experiment 9a and Experiment 9b yielded a correlation between working memory capacity and performance in the modified condition, in opposition to Experiment 9a and to our hypotheses, supports this interpretation. In short, close inspection of the data suggests that the results of Experiment 9a were a false positive; overall, the results of Study 9 tend to indicate that our hypotheses were incorrect and that the modification of the APM did not selectively improve the performance of participants with low working memory capacity.

As with several other studies presented in this work, it is difficult to tell whether this failure is due to our thesis being wrong or to our experimental paradigm being inadequate. There could be several plausible reasons for a problem with the paradigm itself. To our knowledge, this study constituted the first attempt to manipulate cognitive control in a high-level cognitive task outside of the realm of clinical neuropsychology. Even if participants with low working memory capacity do suffer from a lower cognitive control ability than their counterparts, they are most certainly more efficient than a patient with a pre-frontal lesion; thus, it is very possible that the procedure used by Luria and Tsvetkova (1964, 1967) is too rough to affect the performance of non-pathological participants. This idea may seem to run counter to the finding that participants performed better in the modified condition; however, one should not forget that the modified procedure affected several other parameters such as the time participants spent on the task, which was about twice as long in the modified condition. The higher performance in this condition could be explained by the greater time participants spent looking at the items, rather than by an effect of the modification on cognitive control.

At a more conceptual level, another possibility is that there is no direct match between mechanisms of the DMC framework and the control of performance in the APM as defined by Carpenter and colleagues (1990): although our hypothesis seemed compatible with the literature, there is a significant conceptual distance between cognitive control and rule abstraction in fluid intelligence tasks. To date, the DMC framework has mostly been used in the context of relatively low-level cognitive tasks involving attention, memory or cognitive control itself; thus, no well-defined translation of the framework exists for fluid intelligence

tasks, and it is possible that proactive control is not intimately tied with the ability to follow a hierarchy of goals and sub-goals in the APM as defined by Carpenter and colleagues.

In summary, Study 9 did not generally support the hypothesis that the contribution of cognitive control to performance in a fluid intelligence task can be reduced to selectively improve the performance of participants with low working memory capacity. Although the results of Experiment 9a were encouraging, these results could not be reproduced in Experiment 9b and were likely to represent a false positive. However, the tenuous possibility remained that the results of Experiment 9a legitimately indicated that the modification of the APM selectively improved the performance of participants with low working memory capacity; to account for this possibility, a conceptual replication was carried out in Study 10.

### **3. Study 10 – Modified Culture Fair test**

#### **3.1. Rationale**

Study 9 produced ambiguous results: in Experiment 9a, the data matched the predicted pattern of decreased correlation between working memory capacity and performance in the modified version of the APM with low cognitive control demands, but this was not the case in Experiment 9b or when combining the two samples. Although the result of Experiment 9a was likely to be a false positive, the ambiguity could only be resolved with a second replication attempt. Instead of running an exact replication of Study 9, we elected to seize this opportunity to extend our hypotheses to another paradigm. A frequent concern for researchers is that Raven's APM have been used in many, if not the majority of studies testing the relationship between working memory capacity and fluid intelligence; the use of this task is in fact so frequent that some have argued that working memory is specifically associated with performance in the APM, rather than with fluid intelligence in general (see Ackerman et al., 2005). This argument is difficult to justify in the face of the evidence of a general relationship between working memory and high-level cognition, but it illustrates the need to extend experimental studies beyond Raven's matrices. A related issue is that the role of cognitive control may be very different in the APM and in other fluid intelligence tasks: as outlined by Carpenter and colleagues (1990), the APM are typically solved with a sequential and very systematic procedure, which may not be true for different tasks.

The APM may be an excellent fluid intelligence task, but they are in no way the only one. Another classic fluid intelligence task is Cattell's Culture Free (or Culture Fair) Test (CFT; Cattell, 1940). The CFT is constituted of four different subtests. The first subtest requires participants to complete a series of pictures following logical rules, the second

subtest requires them to find the two intruders in sets of five pictures, the third subtest is a matrix completion task analogous to the APM, and the fourth subtest requires participants to analyze the spatial relations between different elements in a picture and to select a matching picture where the elements bear the same relations. This test has demonstrated good psychometric properties over the years and has been validated in a French sample (Cattell, 1986). Importantly, the CFT has been used to assess the relationship between working memory capacity and fluid intelligence in several studies; it typically correlates with working memory tasks, with correlation coefficients similar in magnitude to those observed with the APM (e.g. Engle et al., 1999; Conway et al., 2002).

Study 10 constituted a conceptual replication of Study 9. The procedure of Study 9 was transposed to the CFT: participants completed either the standard version of the test, or a modified version where they only saw small parts of the stimuli at once. No model of the control of performance existed for the CFT, contrary to the APM; we consequently elected to adapt the procedure described by Carpenter and colleagues (1990): participants were hypothesized to look at parts of the stimuli one piece at a time to try and abstract logical rules, then at the whole stimuli to generalize these rules and construct a representation of the answer, and then at the possible answers to pick the most appropriate. Our predictions were identical to Study 9. Participants with high working memory capacity were expected to perform better than their counterparts in the standard condition, whereas all participants were expected to demonstrate similar performance in the modified condition.

## **3.2. Method**

### **3.2.1. Participants**

A sample of 43 participants completed the experiment (9 males and 34 females; age ranging from 19 to 27,  $M = 22.12$ ,  $SD = 1.87$ ). All participants were undergraduate students from the University of Grenoble 2 participating for course credit. Participants were included if they met the following criteria: never completed the Cattell test, not participated in Experiment 9a or Experiment 9b, native French speaker, right-handed, no history of neurological disorders, and without psychoactive medication.

### **3.2.2. Materials**

**Working memory task.** Working memory capacity was measured with the modified version of the CCS replacing the reading span by the alpha span (see Appendix A). The dependent variable on the task was the composite working memory score.



**Standard CFT.** The French version of the CFT was used for this study (Cattell, 1986). Participants completed the form A of Scale 2 and the form B of Scale 4. In the perspective of extending the results of Experiment 9a to a truly different paradigm, Scales 1 and 3 were not used because of their conceptual similarity of the APM. As in Study 9, time-on-task was not restricted so as to reduce the contribution of processing speed to performance.

As described above, the objective of Scale 2 is to find two intruders in sets of five pictures. Intruders are pictures that do not match the others; in the easiest trials, all pictures are perceptually identical except for the intruders, whereas in the hardest trials the intruders are pictures belonging to different semantic categories or following different logical rules. Scale 2 includes 14 trials; the total score in this scale was calculated as the number of correctly identified intruders.

The objective of Scale 4 is to analyse the spatial relations between the elements of a reference picture, and to select the matching picture among a set of five possible answers. The reference picture is constituted of geometric shapes (such as lines and squares) and one or several dots. Spatial relations are defined in reference to the dots; for example, in one reference picture the dot may be "inside the triangle and below the line". The participant would then have to select among the five possible answers the picture where the dot is also inside the triangle and below the line. Scale 4 includes 10 trials; the dependent variable in this scale was simply the total number of correct answers.

**Modified CFT.** As in Study 9, the only difference between the standard and the modified conditions of the CFT was the format of presentation of the items. This format was slightly different for Scale 2 and Scale 4. Items in Scale 2 are simply composed of five pictures; the pictures are unitary and cannot be decomposed like the matrices in the APM. If the procedure described by Carpenter et al. (1990) extends to this task, participants should proceed with successive pairwise comparisons of all items, followed by generalization over the whole set. As a consequence, items of Scale 2 were presented in five steps. The first four steps included only two adjacent pictures (*ab*, *bc*, *cd* and *de*); participants were instructed to compare all pairs of pictures to try and understand their differences and similarities. The fifth and final step included all pictures at once, identical to the standard condition.

As for Scale 4, each item is composed of a reference picture and five possible answers. In order to select the correct answer, participants have to list the spatial relations between the dot(s) and all geometric shapes in the spatial picture, then to successively examine all possible answers. The presentation of the items was broken down into four sections. The first section presented only the reference picture and comprised several steps; in each step, participants

saw the dot(s) and one of the geometric shapes. For example, if the reference picture included one dot, a triangle and a line, participants saw the dot and the triangle in the first step and the dot and the line in the second step. Participants were instructed to take advantage of this section to extract the spatial relations one by one. In the second section, participants saw the entirety of the reference picture; they were instructed to integrate and rehearse all the spatial relations found in the first section. The third section comprised five steps; in each step, participants saw the whole reference picture along with one of the possible answers. They were instructed to decide whether each possible answer matched the reference picture. In the fourth and final step, participants saw the reference picture and all five possible answers, identical to the standard condition.

### *3.2.3. Procedure*

Participants completed the modified CCS and the CFT, in order; the whole procedure lasted approximately 60 minutes. Half the participants ( $n = 21$ ) completed the standard condition of Scale 2 followed by the modified condition of Scale 4, whereas the other half ( $n = 22$ ) completed the standard condition of Scale 4 followed by the modified condition of Scale 2. This procedure ensured that the results could not be explained by sample differences since all participants completed the standard version of one scale and the modified version of the other; it also ensured that participants could not learn and generalize the modified procedure from one scale to the other, since the modified condition was always completed last. Both Scale 2 and Scale 4 were preceded by practice items (two items for Scale 2 and three for Scale 4); participants completed a version of the practice items matching their experimental condition, as in Experiment 9a (in other words, participants completing the standard version of a scale completed the standard version of the practice items and vice versa).

## **3.3. Results**

### *3.3.1. Preliminary analyses*

Working memory scores were normally distributed although slightly above the population average ( $M = 0.18$ ,  $SD = 0.76$ , skewness =  $-0.58$ , kurtosis =  $-0.07$ ). However, the distribution of working memory scores tended to vary as a function of the experimental condition: scores were more normally distributed and more dispersed in the group of participants who completed the standard condition of Scale 2 first ( $M = 0.07$ ,  $SD = 0.90$ , skewness =  $-0.34$ , kurtosis =  $-0.52$ , range =  $-1.63 - +1.46$ ) than in the group of participants

who completed the standard condition of Scale 4 first ( $M = 0.28$ ,  $SD = 0.60$ , skewness =  $-0.67$ , kurtosis =  $-0.03$ , range =  $-1.16 - +1.05$ ). A Levene test indicated that the dispersion of scores was marginally higher for participants who completed the standard condition of Scale 2 first,  $F(1, 41) = 3.54$ ,  $p = .067$ .

The second series of preliminary analyses concerned performance in the CFT. In Scale 2, scores were normally distributed on both the standard version ( $n = 22$ ,  $M = 20.48$ ,  $SD = 2.48$ , skewness =  $-0.39$ , kurtosis =  $-0.35$ , range =  $15 - 25$  out of a possible 28) and the modified version ( $n = 21$ ,  $M = 21.77$ ,  $SD = 2.37$ , skewness =  $-0.53$ , kurtosis =  $0.28$ , range =  $16 - 25$  out of a possible 28). In Scale 4, the same was true for the standard version ( $n = 21$ ,  $M = 7.24$ ,  $SD = 1.61$ , skewness =  $-0.27$ , kurtosis =  $-0.54$ , range =  $4 - 10$  out of a possible 10) and the modified version ( $n = 22$ ,  $M = 7.14$ ,  $SD = 1.08$ , skewness =  $0.20$ , kurtosis =  $-0.36$ , range =  $5 - 9$  out of a possible 10). No ceiling effect appeared in either subscale. The average performance on Scale 2 was marginally higher in the modified condition than in the standard condition,  $t(41) = -1.75$ ,  $p = .087$ ; however, this was not the case for Scale 4, where participants demonstrated comparable performance in both conditions,  $t(41) = -0.24$ ,  $p = .808$ , contrary to our hypotheses.

Cronbach's alpha coefficients were calculated to ensure that both standard and modified versions of the CFT scales had comparable reliability. The alphas could not be computed separately for each version of each subscale, as this would have left too few items per scale to obtain an adequate estimate of internal consistency; instead, one alpha coefficient was calculated for participants who completed the standard version of Scale 2 and the modified version of Scale 4, and a second coefficient was calculated for participants who completed the modified version of Scale 2 and the standard version of Scale 4. Internal consistency was similar for participants in the first condition ( $\alpha = .49$ ) and for participants in the second condition ( $\alpha = .50$ ). These alpha coefficients are quite low; this problem stems from the fact that the test included few items and that scores were at ceiling on many of these items; for example, the average accuracy was 100% on four of the ten items in Scale 4.

As in Experiment 9a, power indices were computed to ensure that the modification of the CFT did not differentially affect certain items. The results are presented in Appendix G, in Figure G1 for Scale 2 and in Figure G2 for Scale 4. Overall, the difficulty of the items was comparable across the two versions of each scale.

As in Study 9, participants spent on average significantly more time on the modified version of Scale 2 ( $M = 5.83$  minutes,  $SD = 1.44$ ) than on the standard version ( $M = 2.29$  minutes,  $SD = 0.79$ ),  $t(25) = -5.25$ ,  $p < .001$ . The same was true for Scale 4: participants spent

more time on the modified version ( $M = 9.30$ ,  $SD = 1.83$ ) than on the standard version ( $M = 6.06$ ,  $SD = 1.81$ ),  $t(26) = -4.06$ ,  $p < .001$ .

### 3.3.2. Main analyses

As in Experiment 9a and Experiment 9b, we expected working memory capacity to be predictive of performance in the standard, but not in the modified version of the CFT. This hypothesis was tested separately for Scale 2 and Scale 4.

For Scale 2, working memory capacity was not predictive of performance in either the standard condition,  $F(1, 19) = 0.73$ ,  $MSE = 6.246$ ,  $p = .403$ ,  $\eta^2_p = .04$ ,  $r = .19$ , or the modified version,  $F(1, 19) = 0.50$ ,  $MSE = 4.253$ ,  $p = .487$ ,  $\eta^2_p = .03$ ,  $r = -.16$  (see Figure 40). A test using Fisher's  $z$ -transformation indicated that these two correlations were not significantly different,  $p = .151$  (one-tailed).

For Scale 4, working memory capacity was not predictive of performance in the standard condition,  $F(1, 20) = 0.34$ ,  $MSE = 1.209$ ,  $p = .567$ ,  $\eta^2_p = .02$ ,  $r = .13$ ; it was, however, positively correlated with performance in the modified condition,  $F(1, 18) = 12.19$ ,  $MSE = 1.61$ ,  $p = .003$ ,  $\eta^2_p = .40$ ,  $r = .64$  (see Figure 41), in direct contradiction with our hypotheses. A test using Fisher's  $z$ -transformation indicated that the difference between these two correlations was statistically significant,  $p = .034$  (one-tailed). These results deserved a follow-up analysis aiming to describe the relative performance of high spans and low spans as a function of experimental condition, as was done in Experiment 9a and Experiment 9b: the higher correlation between working memory capacity and performance in the modified condition could be due to high spans performing higher, to low spans performing lower, or both. Unfortunately, the sample size was too low in this study to run an extreme-group analysis; however, some useful descriptive information could still be gained by examining the equations of the regression lines. In the standard condition of Scale 4, the regression predicted a score of 7.30 for participants at +1  $SD$  from the mean working memory capacity, and a score of 6.84 for participants at -1  $SD$  from the mean working memory capacity. In the modified condition of Scale 4, the predicted score was 8.19 for participants at +1  $SD$  from the mean working memory capacity and 5.73 for participants at -1  $SD$  from the mean working memory capacity. In other words, the modified version of Scale 4 elicited both higher performance from high spans and lower performance from low spans when compared to the standard version.

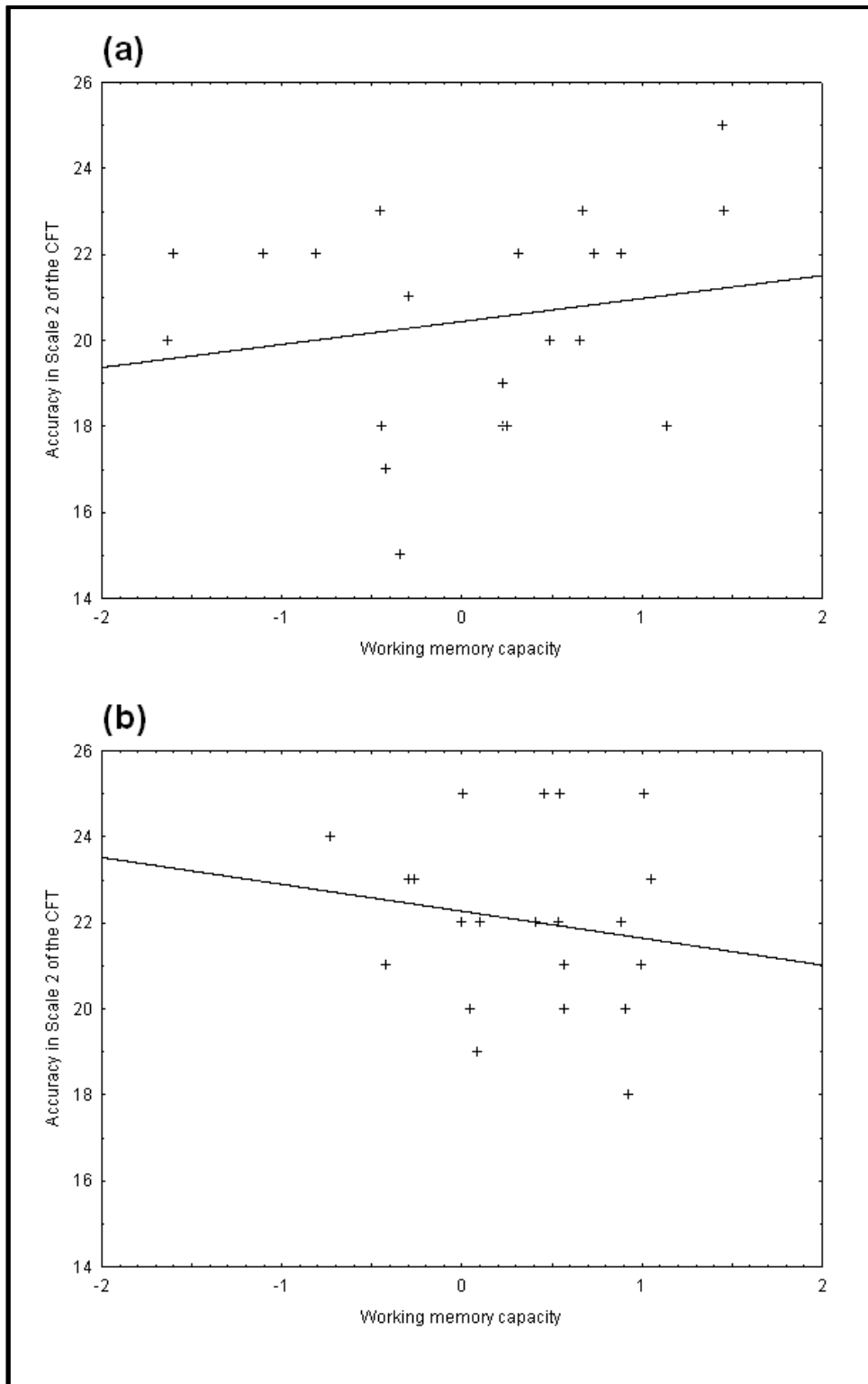


Figure 40. Scatterplots for the correlation between working memory capacity and Scale 2 of the CFT in (a) the standard condition and (b) the modified condition.

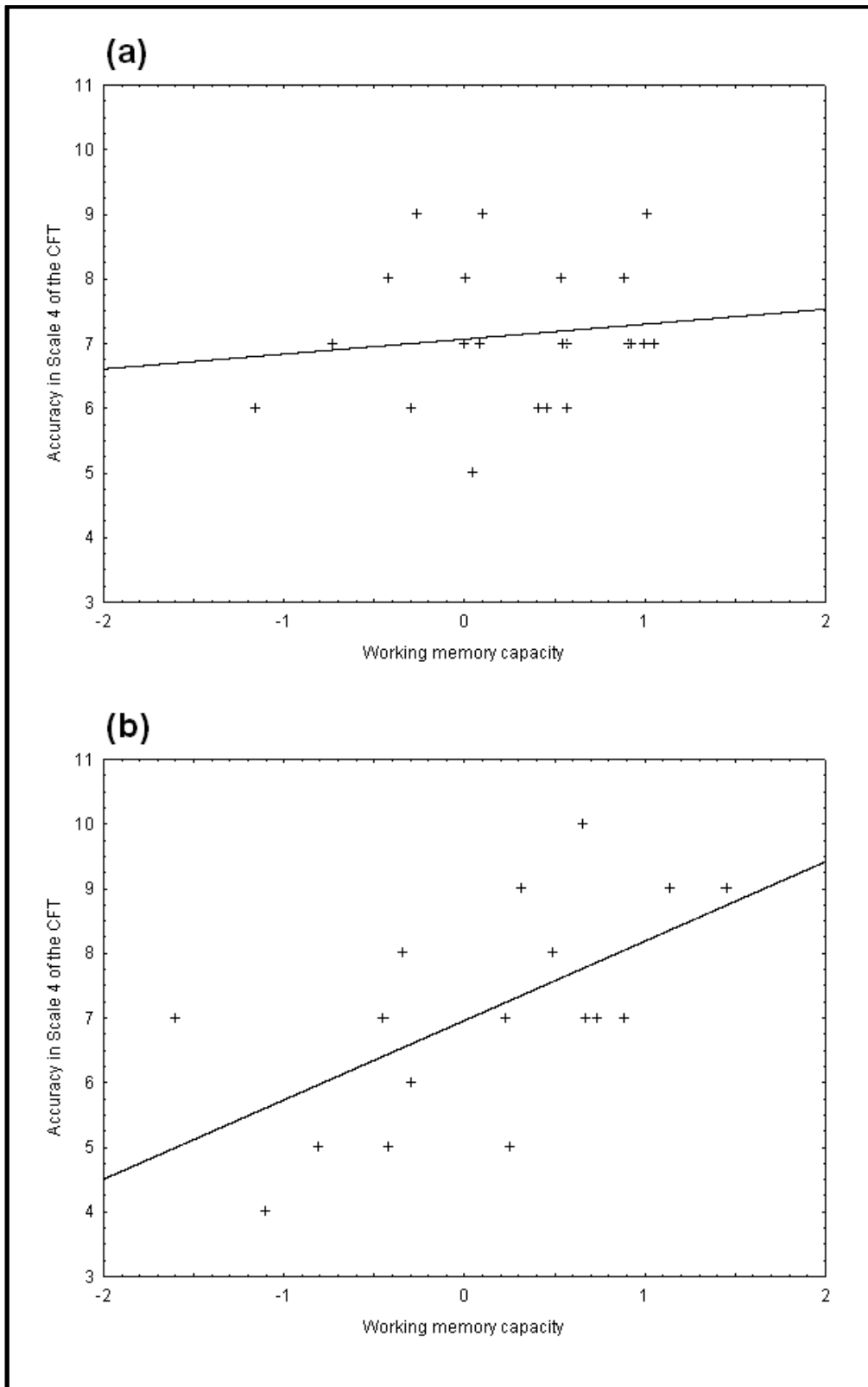


Figure 41. Scatterplots for the correlation between working memory capacity and Scale 4 of the CFT in (a) the standard condition and (b) the modified condition.

### **3.4. Discussion**

Similar to Study 9, the objective of Study 10 was to modify a fluid intelligence task, the CFT, so as to reduce the contribution of cognitive control to performance. We expected to observe a decrease of the relationship between working memory capacity and performance in the modified version of the task. The results were not congruent with our expectations: working memory capacity was not correlated with performance in either version of Scale 2 of the CFT, and it was only correlated with the modified rather than the standard version of Scale 4. In other words, modifying the CFT did not weaken the relationship between working memory capacity and cognitive control.

There are three surprising aspects to these results. The first is the fact that working memory capacity did not correlate with performance in Scale 2 of the CFT. Although multiple studies have reported correlations between the CFT and working memory tasks, these studies typically calculate a single CFT score by aggregating performance in all subscales (e.g. Engle et al., 1999; Conway et al., 2002). In other words, we know that working memory capacity usually correlates with the CFT, but there is no guarantee that this is true for Scale 2 in particular. The four scales of the CFT are based on different principles, and it is entirely possible that working memory capacity is differentially related to each subscale. Scale 1 and scale 4 are conceptually very similar to the APM, which is precisely why they were excluded from the present study; hence it is possible that the reported correlations between working memory capacity and performance on the CFT are primarily driven by these two scales. This idea may explain the discrepancy between our results and the literature, but the question remains of why working memory capacity would be unrelated to scale 2 of the CFT, despite this scale clearly constituting a measure of fluid intelligence. We can only speculate on this issue, but one possible lead is the fact that scale 2 differs from the other three scales in the way the response has to be constructed. In scales 1, 3 and 4, participants have to select one picture that adequately answers a set of constraints – logical rules in scales 1 and 3 and spatial relationships between geometric shapes in scales 4; by contrast, scale 2 requires participants to select pictures that do not match the others. Due to this methodological difference, it may be the case that scales 1, 3 and 4 primarily require participants to construct a mental representation of the correct answer by systematically integrating all constraints, which corresponds to a constructive matching strategy (Carpenter et al., 1990; Vigneau et al., 2006), whereas scale 2 may be much more reliant on response elimination (as defined by Vigneau et al., 2006). Recall that we expected the constructive matching strategy to depend on proactive control, but we did not specifically expect the response elimination strategy to benefit from

proactive control more than reactive control (pp. 79-80). Thus, a correlation between working memory capacity and performance in all sub-scales of the CFT with the exception of scale 2 could be indicative of the fact that scale 2 depends on a response elimination process, which is not as related to working memory and cognitive control as the constructive matching strategy used in the rest of the CFT.

The second surprising aspect of the results is the fact that the modification of the CFT did not elicit a reliable increase in performance; performance was unaffected by the experimental manipulation in Scale 4 and was only marginally better in the modified version of Scale 2. As discussed for Experiment 9b, a plausible explanation is that the procedure of Luria and Tsvetkova (1964) is too rough to have an effect on the performance of participants without a clear deficit in cognitive control. Another noteworthy point is that we did not have at our disposal a clear account of the involvement of cognitive control in the CFT, contrary to the APM. Although we speculated that participants would proceed with the same kind of systematic process as in the APM, this speculation might be wrong. This is especially true for Scale 2 since, as discussed above, this scale differs in the others in that it does not require participants to construct a mental representation of the answer by integrating a set of constraints, which means it may be less dependent on the use of a systematic procedure.

The third remarkable aspect of the results was the finding that the modification of Scale 4 actually increased the correlation with working memory capacity, at the exact opposite of our hypotheses. The significant increase of the correlation (from .13 to .64) suggests that this result represents more than a chance variation. Could it be the case that breaking down the presentation of the items into several steps selectively interfered with the processes used by low spans while helping high spans perform the task? It seems difficult to come up with a mechanism matching this idea and, besides, the fact that the modification of Scale 4 did not on average improve performance suggests that it did not have a sufficient effect on performance to create such a high difference in correlation coefficients. A much simpler explanation may be found in the specifics of the experimental paradigm. Recall that all participants completed the standard version of one scale first and the modified version of the other scale second; this control was necessary to ensure that participants would not generalize the modified procedure to the other scale. However, it also means that all participants who completed the modified version of Scale 4 did so at the very end of the protocol, whereas participants who completed the standard version of the scale did so earlier in the testing session; in other words, the experimental condition was perfectly confounded with the order of the tasks. Thus, we could rephrase the astonishing finding that working



memory capacity was more correlated with performance in the modified version of Scale 4 by saying that working memory capacity was more correlated with performance of Scale 4 when it was completed later in the testing session. This effect could be easily explained by a higher motivation of participants with high working memory capacity, or simply a higher resistance to the build-up of cognitive fatigue throughout the protocol. Although the current data are not sufficient to validate this interpretation, a lower ability of participants with low working memory capacity to maintain a consistent level of performance could constitute an interesting finding in and of itself, which may deserve closer examination.

One obvious caveat in interpreting these results is that with about 20 participants per condition, the sample size in this study was especially small. This is particularly true for participants who completed the standard version of Scale 4 first, because the distribution of working memory scores presented a lesser spread in this condition than in other, bigger samples. The small sample size could explain the absence of a significant correlation between working memory capacity and the CFT, at least in its standard version; correlations between the two variables have typically been reported with samples of at least 120 subjects (Engle et al., 1999; Conway et al., 2002). However, it is much harder to blame the sample size or the distribution of working memory scores for the very high correlation between working memory capacity and performance in the modified version of Scale 4, a correlation which runs entirely counter to our hypotheses. The present study only intended to yield preliminary data, and it is not impossible that a larger sample would have yielded different results; on the other hand, the fact that the only significant correlation was observed in one of the conditions where no correlation was expected prompted us to discontinue using this paradigm altogether.

#### **4. Conclusion**

The two studies presented in this chapter aimed to test the hypothesis that modifying fluid intelligence tasks so as to reduce their demands on proactive control would selectively improve the performance of participants with low working memory capacity. Results were once again mixed. Although the data supported our hypothesis in Experiment 9a, Experiment 9b and Study 10 suggested that modifying the fluid intelligence tasks did not selectively improve the performance of participants with low working memory capacity.

There is no obvious theoretical reason that could explain our failure. As in Chapter 4 and Chapter 5, however, it is difficult to decide whether to attribute this failure to inadequate experimental paradigms or to a wrong thesis. The three experiments presented in this chapter generalized a paradigm intended for use in clinical neuropsychology and in constructive and

arithmetic tasks to a population of control participants and to fluid intelligence tasks; this may be too much generalization at once, and there is a reasonably high probability that the modifications of the fluid intelligence tasks did not function as expected. In other words, a success would have been interesting, but our failure does not necessarily tell us much about the hypothesis that working memory capacity is related to fluid intelligence through cognitive control. At any rate, the absence of a promising way to alter and improve the paradigms led us to abandon this research line entirely.

# GENERAL DISCUSSION

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## CHAPTER 9: GENERAL DISCUSSION

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### 1. Synthesis

In the experimental section, we presented a series of studies attempting to provide evidence that a high working memory capacity is associated with a higher tendency to use proactive control and that this association drives the relationship between working memory capacity and fluid intelligence. A summary of our main findings is presented in Table 28; several conclusions can be drawn from this table.

First, almost all of our studies found a relationship between working memory capacity and performance in complex cognitive tasks. In virtually all experiments, participants with high working memory capacity responded faster or more accurately than their counterparts. The only exceptions were Study 3 and Study 4, where participants had to identify as quickly as possible the objects represented in simple pictures. Many researchers agree that working memory capacity is only related to tasks that are sufficiently complex, not to elementary visual processing (e.g. Kane, Poole, Tuholski, & Engle, 2006; Poole & Kane, 2009), although there are some exceptions (see Barrouillet, L epine, & Camos, 2008); it is therefore not too surprising that working memory capacity was not associated with performance in these two studies. Apart from these two exceptions, working memory capacity was positively correlated with performance in all experiments, thus replicating the ubiquitous finding of a relationship between working memory capacity and high-level cognition.

Finding correlations between working memory capacity and performance with such consistency firmly establishes that there were no major flaws in our working memory measure. This consideration is of particular interest since all experiments (except Experiment 9b) used the CCS to assess working memory capacity: had the task been invalid, the entirety of our experimental procedure would have been compromised. Additionally, the existence of these correlations suggests that our samples of undergraduate psychology students contained sufficient variability to obtain sound estimates of individual differences in working memory capacity.

Two of the observed correlations were especially important to ensure the validity of our work. The first was the association between working memory capacity and performance in the AX-CPT: participants with high working memory capacity performed better in the task throughout our experiments, and also demonstrated differences in brain activity during the task in Experiment 7b. The only exception was Experiment 5b, where performance in the AX-CPT

did not differ as a function of working memory capacity; with only 35 participants in the sample, however, this null result is unlikely to be reliable. The second important finding was the correlation between working memory capacity and fluid intelligence, which was evidenced in both Study 9 and Study 10. The correlation ranged between .36 and .64, congruent with the values reported by Ackerman et al. (2005). In short, working memory capacity demonstrated a reliable association with the paradigmatic task of the DMC framework and with fluid intelligence tasks.

Table 28

*Summary of the results for each experiment*

Experiment	Design	N	Was working memory capacity associated with a...		
			higher overall performance?	higher AX-CPT performance?	higher tendency to use proactive control?
Experiment 1a	Correlational	89	Yes		No
Experiment 1b	Correlational	62	Yes		Possibly
Experiment 2a	Experimental	77	Yes		No
Experiment 2b	Experimental	83	Yes	Yes	No
Experiment 3	Correlational	74	No		No
Experiment 4	Correlational	64	No		No
Experiment 5a	Experimental	95	Yes	Yes	No
Experiment 5b	Experimental	35	Yes	No	No
Experiment 6	Correlational	52	Yes	Yes	Possibly
Experiment 7a	Neuroimaging	18	Yes	Yes	No
Experiment 7b	Neuroimaging	35	Yes	Yes	No
Experiment 8	Neuroimaging	40	Yes		No
Experiment 9a	Experimental	83	Yes		No
Experiment 9b	Experimental	104	Yes		No
Experiment 10	Experimental	43	Yes		No

*Note.* Design = methodology used by the study to test the relationships between the constructs, with "correlational" = fully correlational, "experimental" = combined correlational-experimental approach, and "neuroimaging" = fMRI or EEG. N = sample size included in the study.

In stark contrast with these conclusions, none of our experiments managed to provide strong evidence that working memory capacity is related to the tendency to use proactive control. Whatever the operationalization of proactive control – whether defined as the use of contextual information or as preparatory activity or as the implementation of goal-driven processing, whether measured or manipulated, assessed with a classic or new paradigm, with a cognitive control or a high-level cognitive task, with neuroimaging or behavioural indices – our experiments consistently failed to observe the predicted association between the two constructs. In two cases, Experiment 1a and Experiment 6, the patterns of results did conform to our hypotheses and working memory capacity did correlate with a performance measure hypothesized to depend on proactive control; however, these were precisely the two cases where the tasks had not been specifically designed to assess proactive control and where performance could be influenced by a large number of other factors. These two studies are therefore insufficient to tip the scale in favour of our thesis. In fact, the only association between working memory capacity and a cognitive control mechanism to be reliably evidenced in the present work was with reactive control, in Experiment 7b.

It is worth lingering over the special case of the AX-CPT, since this task has been used and validated in a large number of experiments. Examining the relationship between the AX-CPT and working memory capacity was not a prime focus of the present work, but enough data was incidentally collected over several experiments that we can step back and look at the whole picture. Recall that according to our thesis, working memory capacity was expected to be positively correlated with performance on BX and possibly AX trials, and negatively correlated with performance on AY trials; both reactive and proactive control were expected to lead to comparable performance on BY trials (see p. 80). The AX-CPT was used in Experiment 2b, Experiment 5a, Experiment 5b, Experiment 6, Experiment 7a and Experiment 7b. Working memory capacity was positively correlated with performance on AX trials in three cases, with AY trials in two cases, with BX trials in three cases, and with BY trials in four cases. This pattern of results is not at all consistent with the thesis that working memory capacity is associated with a higher tendency to use proactive control. Interestingly, this conclusion is fully supported by the neuroimaging data collected in Experiment 7a and Experiment 7b, which indicate that all participants demonstrate similar sustained activity during the delay period of the task. The negative relationship with AY trials, predicted by our thesis and reported in Richmond et al. (2013), was never observed; similarly, the complete pattern of a specific advantage of participants with high working memory capacity on AX, BX and BY trials, as reported by Redick et al. (2009; 2011; 2014), did not appear in any experiment. In other words, none of our

experiments using the AX-CPT made a case that participants with high working memory capacity specifically demonstrate a pattern of performance congruent with a higher tendency to use proactive control, despite their higher performance overall. Instead, the results were more congruent with a general advantage of participants with high working memory capacity in all trials of the AX-CPT. Interestingly, this is also what several previous studies observed with other cognitive control tasks (see Keye et al., 2009; Wilhelm et al., 2013).

Apart from the well-known publication bias<sup>21</sup>, it is difficult to find a solid explanation for the discrepancy between our results and prior studies using the AX-CPT. The experiments were comparable in terms of materials, design, procedure and sample sizes; the analysis of differences between sample reported in Appendix C did not indicate critical differences between French and American samples. The only obvious explanation left would be random variation from experiment to experiment, leading to errors in the literature. In support of this idea, the correlations between working memory capacity and the AX-CPT have demonstrated considerable instability from one study to another – both in the present work and in published studies – with working memory capacity in turn predicting performance in each trial type. The critically low values of internal consistency indices for performance in the AX-CPT (see Appendix C, Table C4 in particular) may also cast doubt on the validity of the previously reported patterns of correlations.

It should be noted that Study 9 and Study 10 also failed to provide evidence for a role of proactive control in the relationship between working memory capacity and fluid intelligence. These results contradict the second part of our thesis, namely the idea that the tendency to use proactive control mediates the relationship between working memory capacity and high-level cognition. Interestingly, however, these results are rather congruent with the literature since cognitive control is typically observed to have a small to non-existent mediating role (see p. 61), and they also fit well enough with the results of all our other experiments failing to observe a relationship between working memory and proactive control.

In summary, the results presented in the experimental section actually paint a rather coherent picture. Working memory consistently correlated with performance in high-level cognitive tasks and in the AX-CPT, thus ensuring the validity of our measure and replicating the literature. On the other hand, working memory was consistently uncorrelated with the tendency to use proactive control, and proactive control did not mediate the relationship between working memory capacity and fluid intelligence, which fully contradicted our thesis; instead, a high working memory capacity was simply predictive of a general advantage in most situations. The

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<sup>21</sup> Culminating at approximately 96% in the field of psychology (Sterling, Rosenbaum, & Weinkam, 1995).



next sections will examine three possible explanations for this surprising conclusion and offer a few suggestions for future research.

## **2. A measurement problem?**

A first possible explanation for the absence of a relationship between working memory capacity and proactive control in the present data would be that the relationship does exist, but that we failed to measure it. In other words, it is possible that participants with high working memory capacity do possess a higher tendency to use proactive control, as per our thesis, but that our experiments consistently failed at observing this relationship. It seems difficult to question the validity of every one of our tasks: although some of our experimental paradigms were new and possibly inadequate (e.g. Study 2, Study 3 and Study 4), most of the tasks that we used were closely based on published studies, behaved as expected and/or used manipulation checks which demonstrated coherent results. Provided the tasks were not to blame, there are essentially two factors that could have caused a systematic failure in our experiments.

### **2.1. Statistical power**

Firstly, it is possible that our studies lacked sufficient statistical power to detect the relationship: after all, it is a well-known fact that experimental studies in the field of psychology are consistently underpowered (see e.g. Rossi, 1990). If the magnitude of the correlation between working memory capacity and proactive control is small, then the sample sizes in our studies may have been insufficient to detect it. The average sample size in our experiments was  $N = 64$  (or  $N = 72$  when excluding the three neuroimaging studies), which is certainly not a large number by the standards of differential psychology. A problem of insufficient statistical power would be compounded by the low internal consistency of many of the measures used in the present experiments (in full agreement with Rabbitt, 1997, who claimed that most cognitive control tasks have poor psychometric properties), which could make a small relationship even more difficult to detect.

Further speculating on the power achieved by our experiments would require an estimate of the effect size of the relationship between working memory capacity and proactive control. Fortunately, there are two clues that could help us estimate this number. The first is the negative correlation between working memory capacity and performance on AY trials reported by Richmond et al. (2013), since this negative correlation is presumably relatively unaffected by confounds such as processing speed; the average value of the correlation was  $r = -.176$  in their data. The second clue is the magnitude of the correlation between working

memory capacity and fluid intelligence, given that – according to our thesis – this correlation stems partly from the role of proactive control. In their meta-analysis, Ackerman et al. (2005) reported an average value of  $r = .479$ ; this is probably an over-estimate for the effect size of the correlation between working memory capacity and proactive control since other factors can be expected to contribute to the correlation between working memory capacity and fluid intelligence. These two values provide an upper and a lower bound for the correlation between working memory capacity and proactive control. Using these effect sizes and our mean sample size of  $N = 64$ , a power calculation suggests that the effective power attained by each of our studies was comprised between .29 and .99; in other words, the most pessimistic estimate is that we had on average a one in three chance to reject the null hypothesis in each experiment. This suggests that our experiments may have actually been underpowered; however, with a one in three chance to reject the null, a consistent failure over fifteen different experiments remains surprising.

The idea that our experiments lacked statistical power also hardly explains our consistent failure to observe a proactive control pattern of results in the AX-CPT for participants with a high working memory capacity. Three aspects of the results are especially problematic: one, several of our samples were comparable in size to prior studies (Redick, 2009; Redick & Engle, 2011; Richmond et al., 2013); two, the neuroimaging data in Experiment 7b did demonstrate an association between working memory capacity and a cognitive control, but this association concerned reactive rather than proactive control; and three, several of our experiments found a positive relationship between working memory capacity and performance on AY trials, a finding that contradicts both the theory and prior studies reporting a negative correlation (Experiment 1 and Experiment 2 in Richmond et al., 2013) and that can hardly be explained in terms of low statistical power.

In short, although it is a certainty that more statistical power is always desirable, that cognitive control measures do not appear to be overly reliable and that our sample sizes were not enormous, insufficient power does not seem to fully explain why our results contradicted our thesis. It may nonetheless be interesting in the future to run a high-powered study including a large number of participants and a large number of proactive control measures to obtain more reliable data, although such an endeavour would first require the validation of more proactive control tasks and a detailed examination of their reliability with methods more appropriate than a split-half.

## **2.2. Sampling and the variability of cognitive control strategies**

A second possible culprit for our systematic failure is the very nature of the sample of participants. The sample is actually one of the few features common to all of our studies: in each experiment the participants were undergraduate psychology students, aged between 18 and 25 years on average, with no history of neurological or psychological disorders. Although criticizing the composition of the sample in the discussion of a research work is a little clichéd, this point does bear a special importance for the DMC framework, in particular in the context of a differential approach. As mentioned in the introduction (see pp. 70-73), the majority of studies validating the DMC framework have used different populations to contrast proactive and reactive control; a shift towards reactive control is typically observed in populations with less efficient functioning of the dorsolateral prefrontal cortex, which includes persons with neural dysfunction such as schizophrenic patients (e.g. Barch et al., 2001; A. MacDonald & Carter, 2003; Edwards, Barch, & Braver, 2010), children (Chatham et al., 2009; Brahmabhatt et al., 2010) and older adults (e.g. Braver et al., 2001, 2005, 2009; Paxton et al., 2006, 2008). Importantly, most of these studies have considered young, healthy adults as a "proactive control group". In other words, published studies validating the DMC framework directly indicate that young healthy adults are the group where the tendency to use proactive control is at its highest. These studies did not discriminate between ability levels among young adults, which means they included participants with low working memory capacity; this suggests that young healthy adults are, on average, particularly likely to use proactive control, whatever their working memory capacity.

In practice, our data tend to support the interpretation that all participants had a strong tendency to use proactive control. In all experiments reported here, participants were on average disproportionately slowed on AY trials when compared to BX trials, congruent with a generalized tendency to use proactive control. The same was true in prior studies investigating the relationship between working memory capacity and the AX-CPT in the same types of samples (Redick & Engle, 2011; Richmond, 2013; Redick, 2014). Importantly, not all samples are slower on AY trials: participants who use primarily reactive control are slower on BX trials than on AY trials, as is the case for example in older adults (e.g. Braver et al., 2005) and in schizophrenic patients (e.g. A. MacDonald & Carter, 2003). Additionally, Study 7 indicated that on average, our participants demonstrated sustained activity during the delay period of the AX-CPT; similarly, Study 8 indicated that all participants demonstrated sustained activity during the delay period of a memory task. All these data converge to suggest that overall, our participants tended to use proactive control, independently of their working memory capacity. This point

constitutes an obvious problem in testing our thesis. If all participants included in a sample tend to use proactive control no matter what, then the range restriction will necessarily make it very difficult to evidence an association between individual differences in the use of proactive control and other constructs.

Interestingly, this limitation only questions the validity of our experiments, not the validity of our thesis; indeed, it is possible that working memory capacity is associated with proactive control but that our experiments and our samples did not constitute an adequate framework to study this association. This idea indirectly refers to Reuchlin's model of vicariant processes (Reuchlin, 1978): the model proposes that every individual has a finite repertoire of cognitive processes at his disposal, and that certain situations tend to induce all participants to use the same process whereas others maximize individual differences. In reference to this model, it is possible that variability does exist in the use of proactive and reactive control, and that this variability is actually associated with individual differences in working memory capacity as per our thesis, but that young healthy adults express little variability in laboratory tasks, thus placing our studies in a situation where the same pattern of cognitive control emerged for all participants and no correlation with other constructs could be observed.

Although this hypothesis means that working memory capacity may be correlated with the tendency to use proactive control despite our inability to evidence this correlation in our samples, its logical corollary is that the classic association between working memory capacity and fluid intelligence is not due to the use of proactive control. Indeed, the vast majority of studies have tested this association in young healthy adults (Ackerman et al., 2005); if there is too little variability in the use of proactive control to create a correlation with working memory capacity in these samples, then this variability is presumably too small to drive individual differences in fluid intelligence. In other words, according to the interpretation that our samples contained too little variability in the use of proactive control, it might be the case that working memory capacity is related to proactive control, but proactive control cannot explain its relationship with fluid intelligence.

All in all, this interpretation suggests two possible research directions. The first would be to extend the test of the relationships between working memory capacity and proactive control in a more diverse sample selected to maximize individual differences in the use of proactive control. A developmental approach might be a solid choice, since natural changes in the use of proactive control seem to be reliably observed throughout the lifespan (see pp. 70-73). The second possibility would be to use other types of tasks to measure cognitive control mechanisms. According to Reuchlin's model of vicariant processes, there might exist situations that maximize

variability in the use of cognitive control mechanisms and where participants differ more markedly as a function of their working memory capacity than in the tasks used in the present work. For example, one possibility is that laboratory tasks, with the strong emphasis they place on performing well, incentivize all participants to use proactive control; more ecologic measures might be able to capture more variability in cognitive control (see also pp. 63-64).

### **3. A prediction problem?**

A second possible reason for our failure would be that a relationship does exist between working memory capacity and mechanisms of the DMC framework, but that this relationship is not adequately described in terms of a higher tendency to use proactive control for participants with high working memory capacity. There are two main ways to interpret a relationship between working memory capacity and cognitive control in the context of the DMC framework without referring to the tendency to use proactive control.

#### ***3.1. Individual differences in control efficiency***

Participants with high working memory capacity may perform differently, not because they use a different control mechanism, but because they do so more efficiently. In other words, all participants would tend to use the same control mechanism – presumably proactive control in the case of our samples, as proposed above – but participants with high working memory capacity would be more efficient at implementing this control mechanism in practice. This hypothesis is relatively congruent with our conclusion that participants with high working memory capacity tend to always perform better in all situations and do not demonstrate the more nuanced pattern of performance indicative of proactive control: indeed, participants with more efficient cognitive control should simply perform better in all possible situations. According to this interpretation, the correlation between working memory capacity and high-level cognition would be caused by the more efficient cognitive control of participants with high working memory capacity, which would lead them to be more efficient in general, including high-level cognitive tasks.

Individual differences in the efficiency of control mechanisms were not explicitly modeled in the original account of the DMC framework (Braver et al., 2007), but they are implied by the very nature of the cognitive control mechanisms: participants using reactive control to selectively retrieve contextual information when a critical event occurs may be expected to differ in their ability to accurately retrieve the information; participants using proactive control to prepare processing in advance may be expected to differ in their ability to

actively maintain contextual confirmation in a state of sustained activation. In practice, a few clues tend to suggest that participants with high working memory capacity may be more efficient at implementing both reactive and proactive control. For reactive control, one argument comes from Experiment 3 in Richmond et al. (2013) and from our own Experiment 5a: in both cases, an experimental manipulation was used to induce reactive control in all participants, and participants with high working memory capacity demonstrated higher performance on trials with an X probe (BX trials in Richmond et al. and AX trials in our own Experiment 5a). This result could indicate that participants with high working memory capacity were more efficient at retrieving the identity of the probe in secondary memory when using reactive control (Redick, 2014; Richmond et al., 2013). Interestingly, this interpretation converges with the finding that participants with high working memory capacity distinguish themselves by being more efficient at selectively retrieving information in secondary memory (Unsworth & Engle, 2007a). As for proactive control, maintaining a single piece of information in a state of high activation is one of the two abilities deemed to be more efficient in participants with high working memory capacity according to the controlled attention framework (Engle & Kane, 2004).

In short, this hypothesis seems relatively plausible; unfortunately, it would also be very difficult to test. The elegance of the DMC framework resides in its ability to predict different patterns of results as a function of control mechanism; a hypothesis based on the general efficiency of cognitive control would simply predict higher performance in all cases. Such a prediction would make it nearly impossible to disentangle cognitive control from its confounding variables, since there is generally no way to tell whether a high performance in a task is caused by an efficient cognitive control or by any other factor of performance. In fact, this prediction is exactly the type of siren song against which Underwood (1975) warns us: its appeal may well reside in the very fact that it is difficult to falsify. In other words, we do not believe this possibility to hold much promise for future research, despite its plausibility.

### ***3.2. The independence of proactive and reactive control***

A different possibility is that participants differ neither in their tendency to use one or the other control mechanism, nor in their efficiency at implementing these mechanisms, but in their ability to implement more than one mechanism. In other words, participants with high working memory capacity may differ from others in that they are able to implement both reactive control and proactive control at the same time, whereas participants with low working memory capacity would be limited at implementing a single control mechanism. This hypothesis is based on the idea that the two control mechanisms may actually be independent, which means participants

could implement only one mechanism, neither of the two, or both at the same time. The independency of the two control mechanisms was suggested in the original account of the DMC framework (Braver et al., 2007), but it has never been thoroughly tested. However, recent data tend to suggest that proactive and reactive control are actually dissociable and can appear simultaneously in the same participants (see Gonthier, Braver, & Bugg, 2014).

Although most – if not all – prior studies have described variability in cognitive control mechanisms in terms of a shift from one mechanism to the other (see pp. 70-73), this does not mean that the two mechanisms are necessarily contingent: the high cost of implementing cognitive control (Braver et al., 2007) may function as an incentive to use only one mechanism at a time, without preventing certain participants from implementing both mechanisms simultaneously. It is also the case that classic experimental paradigms such as the AX-CPT are geared towards observing shifts in control mechanisms; indeed, performance in the AX-CPT is often interpreted by computing a proactive behavioural index or by looking for a crossover interaction between experimental condition and performance on AY and BX trials. In both cases, a single performance index is used to assess which control mechanism is being implemented, which tends to convey an increase in the use of one mechanism as a decrease in the other. It is therefore possible that the two mechanisms are truly independent, but that this point has been overlooked because no dedicated study has tried to test this idea.

Most of the experiments presented here were designed to observe effects related specifically to proactive control, such as a difference in delay-related activity (Chapter 4 and Chapter 7) or in the use of contextual information (Chapter 5); it is not surprising that these experiments did not detect individual differences related to the use of multiple mechanisms. However, the hypothesis of independent control mechanisms offers a simple interpretation for two results observed in the present work. The first is the fact that participants with high working memory capacity tended to perform better on all trial types in the AX-CPT; this result can be interpreted with the idea that they used the two mechanisms concurrently, since one mechanism could always complement the other. The second and most important point is the result of Experiment 7b, where participants with high working memory capacity demonstrated more probe-related activity, congruent with a higher tendency to use reactive control, but no difference in delay-related activity, congruent with an equal tendency to use proactive control. These findings are best explained in terms of a higher tendency of participants with high working memory capacity to use reactive control in addition, rather than instead of, proactive control.

The hypothesis that the two control mechanisms can be implemented simultaneously would explain the higher performance of participants with high working memory capacity in

high-level cognitive tasks with the simple idea that these participants function more efficiently through the implementation of two control mechanisms instead of one. In some ways, this interpretation is close to the idea that participants with high working memory capacity have more efficient cognitive control overall, as suggested above; however, it differs critically in implying that the use of reactive control in addition to proactive control would improve performance on fluid intelligence tasks. There are a few pieces of data to support this idea. A high fluid intelligence seems associated with a pattern of high activity in the prefrontal cortex when confronted with high interference trials in the *n*-back task, which might reflect efficient reactive control (Gray, Chabris, & Braver, 2003); neural activity on high interference trials has also been reported to mediate part of the correlation between working memory capacity and fluid intelligence (G. C. Burgess et al., 2011). These results suggest that reactive control may in certain cases be associated with fluid intelligence, although the argument is only indirect. It is difficult to model exactly how using reactive control in addition to proactive control could improve performance in a fluid intelligence task. However, a recent study suggests that participants with high working memory capacity may perform better in the APM because they are more efficient at resisting the lure from incorrect responses with high salience (Jarosz & Wiley, 2012). This finding might reflect more reactive control for participants with high working memory capacity during the task, although many other interpretations are possible.

This interpretation is generally congruent with the DMC framework and offers a plausible interpretation of our results and the literature, but it seems rather difficult to test in practice. Doing so would require designing new paradigms allowing to independently assess the two mechanisms of the DMC framework with dissociable measures. The predicted result would be a difference in the use of one mechanism as a function of working memory capacity, but no difference in the use of the other; based on the arguments detailed above, the most likely pattern would be that all young healthy participants tend to use proactive control, but that participants with high working memory capacity also implement reactive control as an additional mechanism. There are few points of reference to test this hypothesis, which means a dedicated experimental endeavour would be required. On the other hand, we believe that this line of research has the potential to enrich both the cognitive control and the working memory literature.

## **4. A theory problem?**

### **4.1. *The fall from grace of cognitive control***

It seems doubtless that cognitive control and working memory task are related constructs, as extensively detailed in the introduction of this work. However, this does not mean that



individual differences in working memory capacity are necessarily related to individual differences in cognitive control; this idea is analogous to the position, defended by Engle and collaborators (e.g. Kane & Engle, 2003), that working memory involves short-term memory processes but that individual differences in working memory are not primarily determined by the efficiency of these processes. Therefore, the third possible reason for our failure to observe a relationship between working memory capacity and proactive control would be that individual differences in working memory capacity are actually unrelated to individual differences in cognitive control. In this view, the correlation between working memory and high-level cognition would be due to one or several factors other than the use of a particular cognitive control mechanism.

Even though this interpretation lies at the exact opposite of our thesis, it is surprisingly congruent with many aspects of the data. In particular, it offers a parsimonious interpretation for the fact that cognitive control measures are poor mediators of the relationship between cognitive control and fluid intelligence (see p. 61); it explains the lack of bivariate correlations between working memory capacity and cognitive control tasks observed in certain experiments, such as our own Experiment 6; and it explains why we failed to observe a specific relationship between working memory capacity and proactive control. There is also the fact that participants with high working memory capacity perform better in virtually all complex situations, even when proactive control should be inefficient – such as on AY trials in the AX-CPT. This finding is particularly difficult to interpret in the context of the DMC framework, but it could be caused by factors other than cognitive control. Lastly, this interpretation could explain the puzzling finding that working memory capacity correlates with tasks that seemingly require little cognitive control – such as the ball-catching task in Experiment 1a and Experiment 1b.

If cognitive control does not explain the predictive value of working memory capacity, then what does? A recent trend in the literature seems to be a return to a mnemonic approach to working memory capacity. Through reanalysis of key studies, Unsworth and Engle (2007b) have proposed that short-term memory tasks are as predictive of fluid intelligence as working memory tasks. The same authors have also argued that retrieval in secondary memory is a major basis of the correlation between working memory tasks and fluid high-level cognition (Unsworth and Engle, 2007a). Recent research has suggested that the relationship between working memory and fluid intelligence may be largely mediated by the efficiency of primary and/or secondary memory (e.g. Shipstead et al., 2014; Mogle, Lovett, Stawski, & Sliwinski, 2008; Unsworth et al., 2014). These studies are mostly based on latent variable analyses and may be confounding cognitive control with memory – since complex memory tasks necessarily involve cognitive

control – but there is no denying that a paradigm shift has been slowly taking place in recent years, with more emphasis being put on the mnemonic aspects of working memory.

What about other correlates of working memory capacity? As we have seen, the processing speed hypothesis is not extremely satisfying (see pp. 30-31), but it does have the merit of explaining why working memory capacity was consistently associated with faster response times in most of our studies and especially on the AX-CPT. Several prior studies have also reported results consistent with a general advantage in response speed for participants with a high working memory capacity in cognitive control tasks (see Keye et al., 2009; Wilhelm et al., 2013). However, we believe yet another factor to constitute the most promising and understudied alternative; this factor is motivation (or task engagement). As we have seen (p. 32), both working memory and fluid intelligence tasks are affected by motivation; cognitive control also has strong ties with task engagement (Matthews, Warm, Reinerman, Langheim, & Saxby, 2010).

Although the idea that motivation explains the relationship between working memory capacity and fluid intelligence is generally discarded (see p. 32), there are several reasons to believe that this hypothesis has been insufficiently considered in the literature: only a handful of studies have directly tested the role of motivation (mainly Heitz et al., 2008, and Unsworth & McMillan, 2013); past studies directly testing the role of motivation in the relationship between working memory capacity and high-level cognition have used rather crude questions such as "how motivated were you?" (Unsworth & McMillan, 2013); and participants with high working memory capacity seem to demonstrate a higher pupillometric dilation at baseline (Heitz et al., 2008), which could indicate a higher baseline level of investment in experimental tasks.

Another frequently overlooked finding is that working memory capacity correlates with the need for cognition, or the willingness to engage in complex and effortful cognitive processing, and that need for cognition actually mediates the relationship between working memory capacity and reasoning (Fletcher, Marks, & Hine, 2011). This finding suggests a plausible account for the relationship between working memory capacity and high-level cognition. Participants with high working memory capacity may be simply be those participants who are most inclined towards investing a great deal of effort in complex laboratory tasks such as working memory tasks, as evidenced by their higher need for cognition. In turn, these participants may be more motivated to engage a lot of effort in other complex tasks such as fluid intelligence tasks. Thus, working memory capacity would act as a good predictor of high-level cognition, not because it indexes a meaningful cognitive ability, but because it indexes the willingness of participants to engage in a complex task. This hypothesis has the merit of easily explaining virtually all results in the literature: after all, these results can be adequately

summarized by saying that a high working memory capacity is almost always predictive of a high performance as long as the task is sufficiently complex. If it is the case that highly motivated participants simultaneously obtain a high performance on working memory tasks and on high-level cognitive tasks, then there is no need to conjure up another construct such as cognitive control to explain the data. As a consequence, we believe that a promising direction for future research would be a more systematic assessment of the role of noncognitive constructs – such as motivation, task engagement, need for cognition and mental effort – in the relationship between working memory capacity and high-level cognition.

#### **4.2. A functional view of complex cognition**

The previous section proposed that another factor than cognitive control drives the correlation between working memory capacity and high-level cognition. Importantly, this proposition relies on a very specific premise: the correlation between working memory capacity and high-level cognition is thought to reflect the role of one psychological process in particular. This premise served as the basis for the present work, and also underlies many conceptualizations of the working memory construct (e.g. Engle & Kane, 2004). However, this core assumption may be erroneous, reflecting what de Ribaupierre and Pascual-Leone (1984) called a structuralist error: indeed, it is perfectly possible that the statistical relationship is not tied to one psychological process. This is not to say that the correlation would be due to a couple of stable and easily identifiable processes, either (such as primary memory, secondary and attention control, as defended by Shipstead et al., 2014 and Unsworth et al., 2014); instead, we argue that the correlation may be determined by a very large set of elementary processes which vary as a function of the specific tasks and the specific population being studied (for a similar argument, see Thomson, 1916).

The quest for the one process underlying the correlation between working memory capacity and high-level cognition overlooks one fundamental aspect of working memory tasks: their inherent complexity. Working memory is often reified as a unitary construct corresponding to a unique cognitive system, but this view is not accurate; instead, the maintenance of information in working memory results from the interaction of a large number of brain areas or elementary cognitive processes, prompting certain researchers to consider working memory as an emergent property of the mind (Postle, 2006; see also Conway, Moore, & Kane, 2009). This idea is not revolutionary: several models of working memory have insisted on the fact that it is constituted of a combination of processes rather than a unitary cognitive system (such as Cowan's embedded processes model in 1995), a couple of recent works have begun emphasizing

the multiplicity of determinants of working memory capacity (e.g. Unsworth et al., 2014), and most researchers are certainly conscious that the notion of working memory does not map onto a specific black box placed somewhere in the brain. In practice, however, this complexity is not well addressed by experimental studies. In fact, most experiments simply consider working memory as a well-delimited ability indifferently measured by any working memory task.

Since working memory emerges from the interaction of many component processes, it is actually more appropriate to think in terms of "performance in working memory tasks" than in terms of working memory capacity. In practice, the literature suggests that performance in working memory tasks results from a large number of factors, including (and this list is certainly not exhaustive) both primary and secondary memory (Unsworth & Engle, 2007a), cognitive control (Engle & Kane, 2004), strategy use (Dunlosky & Kane, 2007; for a review, see Thomassin, 2014), motivation (Brose et al., 2012), the level at which to-be-remembered stimuli are processed (Loaiza, McCabe, Youngblood, Rose, & Myerson, 2011), processing speed in the case of speeded tasks (Fry & Hale, 2000), at least two different mechanisms for refreshing information during the task (Camos, Lagner, & Barrouillet, 2009), binding or relational integration (Wilhelm et al., 2013), the ability to coordinate two tasks at once in the case of complex span tasks (Bühner, König, Pick, & Krumm, 2006), and presumably the efficiency of task-specific processes such as mathematical abilities in the case of the operation span. Importantly, all of these processes are liable to be associated with individual differences.

Of course, the same is true of the other constructs considered in the present work. The nature of *g* has been the focus of considerable debate, but most researchers agree that the general factor of intelligence simply represents the sum of a large set of functional processes. Spearman himself cautiously referred to *g* only as the sum of the determinants of shared variance among tests of intellectual ability (see Carpenter et al., 1990). Many of the aforementioned factors of working memory performance also apply to intelligence tests: this is the case, for example, for processing speed, motivation and strategy use; others factors seem more specific to reasoning tests, such as the use of perceptually-based heuristics in solving test items (Carpenter et al., 1990). As for cognitive control tasks, it is obvious from the very definition of cognitive control that they rely in large part on task-specific abilities (see pp. 62-63).

The critical point here is that all of the component processes of working memory tasks and fluid intelligence tasks may be correlated, alternately or simultaneously. For example, both a fluid intelligence task and a working memory task may require a high processing speed, mathematical knowledge, a high motivation and an efficient cognitive control; all these processes could be expected to create a correlation between the two constructs. Other tasks could

primarily require spatial abilities, secondary memory and the use of complex and demanding strategies, creating a different substrate for the correlation. In children, the correlation might be primarily driven by individual differences in mathematical knowledge, whereas in young adults it might depend more on motivation. In short, the source of the correlation between working memory capacity and high-level cognition may simply depend on the specific tasks being used as well as the sample being considered.

This functional view of complex cognition confers little relevance to the idea of embarking in a quest for the one process driving the relationship between working memory and high-level cognition: depending on the precise features of the tasks, one or several component processes of performance may be shared, and these component processes may or may not be related to individual differences in the sample. Although the same idea could apply to many areas of cognitive psychology, it is especially true for the correlational approach typically used in working memory and fluid intelligence research: since these constructs are among the most complex functions of the human mind, they can also be expected to involve the greatest diversity of component processes, whereas determining the correlates of visual perception would involve less candidates.

In concrete terms, what can we make of this? A first step would be to recognize the complexity of the constructs in play and to adopt a functional view of working memory capacity; we believe that such an approach could only be heuristically valuable and would spark new research lines. As an example, a functional approach of working memory capacity would place little emphasis on the gathering of large sets of correlational data – which constitute a very large share of all individual differences studies in the field of working memory research, but which do not tell us much if correlations involving working memory capacity are inherently multifactorial – and more emphasis on experimental studies attempting to isolate specific factors of performance in a task through direct manipulation. Sooner or later, adopting a functional view of complex cognition will be required if we are to attain a deep understanding of working memory and how it relates to the rest of human abilities.

#### **4. Conclusion**

A series of 15 experiments including a total of 957 participants and using a wide range of methods failed to provide evidence in favor of the thesis that individual differences in working memory capacity are related to the tendency to use proactive control. The previous section presented three main hypotheses to explain this surprising finding: our thesis may be valid, but variability in the use of proactive control may have been insufficient in our sample to adequately

test it; working memory capacity may actually be related to cognitive control, but to some aspect of control other than the tendency to use proactive control; or individual differences in cognitive control may not bear any special relationship with individual differences in working memory capacity. We do not defend one interpretation in particular: we believe all three explanations to be plausible, and all three are congruent with certain aspects of the literature and of our data.

It seems however that two reasonable statements can be made. One, the currently available data suggest that working memory capacity is not specifically related to the tendency to use proactive control, contrary to our thesis. And two, even if a relationship between the two constructs does exist, the mere fact that we have so consistently failed to observe it suggests that its heuristic value must be low, at least in our sample: a psychological law that does not allow one to predict the pattern of results in any one of 15 experiments would be of little practical interest to the researcher.

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# APPENDICES

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# APPENDIX A. THE COMPOSITE COMPLEX SPAN

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The Composite Complex Span:  
French Validation of a Short Working Memory Task

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Working memory capacity (WMC), defined as the ability to maintain and manipulate information at the same time, is a central construct in human cognition. In particular, WMC is thought to play a role in a range of complex behaviors (Engle & Kane, 2004). Interestingly, WMC is subject to individual differences that appear relatively stable in time (Klein & Fiss, 1999); these individual differences are strongly related to fluid intelligence (Ackerman, Beier & Boyle, 2005) and more generally to performance in high-level cognitive tasks (Engle & Kane, 2004). It is therefore of interest to accurately measure individual differences in WMC.

The ubiquitous complex span tasks are certainly the most frequently used paradigm to assess working memory (for a review, see Conway et al., 2005; Redick et al., 2012). Complex spans are based on the model of simple span tasks, which require participants to memorize a series of stimuli presented in quick succession. Contrary to simple spans, however, complex spans interleave the presentation of to-be-remembered stimuli with a processing task – for example reading a sentence or solving a mathematical operation. This association of processing and storage requirements constitutes a direct operationalization of the definition of working memory. Complex spans typically demonstrate excellent psychometric properties (Conway et al., 2005; Redick et al., 2012): they have good internal consistency (Redick et al., 2012), stability over time (Klein & Fiss, 1999), convergent and criterion validity (Redick et al., 2012). By contrast, other tasks frequently used as working memory measures are not nearly as successful: for example, the backward span is more strongly associated with short-term memory than with working memory (e.g. Engle, Tuholski, Laughlin, & Conway, 1999) and the *n*-back task demonstrates limited reliability as well as limited correlations with other working memory measures (Jaeggi, Buschkuhl, Perrig, & Meier, 2010, Redick & Lindsey, 2013).

Many different complex spans have been developed over the years. The seminal complex span was the reading span (Daneman & Carpenter, 1980). In the original version of the task, participants were asked to read a series of sentences and decide whether they were correct; the last word of each sentence had to be memorized for serial recall at the end of a trial. Other classic complex span tasks are the operation span, in which participants have to decide whether mathematical operations are correct while memorizing unrelated stimuli presented after each operation (Turner & Engle, 1989; Unsworth, Heitz, Schrock, & Engle, 2005), and the symmetry span, in which participants have to decide whether spatial displays are vertically symmetrical while memorizing spatial locations (Kane et al., 2004). Yet other complex span tasks exist, such as the counting span, navigation span or rotation span (see Kane et al., 2004). Despite being based on a variety of materials, such as visual, spatial,



verbal and numeric stimuli, all these complex span tasks seem to assess the same underlying construct: latent variable analyses generally indicate that complex span tasks load on a common, domain-general factor, and that this domain-general factor has better predictive validity than domain-specific factors (e.g. Kane et al., 2004). For these reasons, individual differences studies often combine several complex span tasks to obtain a domain-general estimate of WMC (for recent examples, see Unsworth, Brewer & Spillers, 2011; Redick & Engle, 2011; McVay & Kane, 2012).

The present work was motivated by two issues related to the practical use of complex span tasks. Firstly, although many researchers choose to combine multiple complex span tasks in the same protocol, this solution makes for a long procedure that can be tedious for the participant. Most studies employing more than one multiple complex span tasks have used the reading span, symmetry span and operation span; having a participant complete the most common versions of all three tasks (Unsworth et al., 2005) yields a total of 42 trials, or 192 stimuli to remember and 192 processing demands to carry out, without even taking into account the training phases for each task. This large number of trials makes it difficult to include other tasks in the same experimental session. It may also pose experimental problems by decreasing participant engagement in the task and increasing fatigue; this is not a trivial issue since complex spans are sensitive to task sequence, both because performing a complex span may decrease performance in subsequent tasks (Schmeichel, 2007) and because performance in complex span tasks can be lowered if demanding tasks have been previously completed in the same testing session (Healey, Hasher, & Danilova, 2011). Importantly, the large number of trials included in common complex spans comes from the fact that they were designed as stand-alone tasks, sufficient to obtain a psychometrically sound measure of WMC by themselves. However, this constraint is not unavoidable: since the different complex spans are known to reflect a common underlying construct, we may consider the association of multiple complex spans as a single working memory test. If individual complex spans are viewed as subtests of a larger test, then they do not need to have individually sufficient psychometric properties and the number of trials per task can be reduced. In other words, it is possible to construct a working memory test including several complex span tasks serving as subtests, with only a small number of trials per subtest, as long as the total number of trials across all subtests is sufficient to obtain a reliable measure.

Secondly, the range of available complex span tasks is limited for French-speaking samples. Two versions of the reading span task exist in French, but they both differ significantly from the widely used English-speaking version of the task (Unsworth et al.,

2005). The first version (Desmette, Hupet, Schelstraete, & van der Linden, 1995) is not computerized and only includes correct sentences, which means the only processing requirement is to read the sentences. The second version (Delaloye, Ludwig, Borella, Chicherio, & de Ribaupierre, 2008) is computerized and includes incorrect sentences, but the sentences differ markedly in structure from English-speaking versions – their average length is 5.5 words (whereas the average length is 12.6 words in Unsworth et al., 2005), and half the sentences begin with the word *they*. Both versions of the task require participants to remember the last word of each sentence, rather than unrelated stimuli (as is the case in Unsworth et al., 2005); the words also have to be recalled orally, which precludes using the task in group sessions. As for other complex spans such as the symmetry span and operation span, they do not rely on verbal materials, which means they could be adapted by simply translating the instructions; however, there may be differences in normative data between French and English-speaking samples. In particular, Unsworth and colleagues (Unsworth et al., 2005) recommend that all participants with accuracy lower than 85% on the processing task be excluded from the sample; we have observed that a very large number of participants consistently fail to reach this level of performance in work from our own lab, especially on the operation span.

In order to address both these issues, we constructed the Composite Complex Span (CCS), a French-speaking composite working memory task. The CCS included three subtests: the reading span, symmetry span and operation span. These tasks were chosen because they are the most widespread complex span tasks, because they have been validated in very large samples (Redick et al., 2012), and because they represent a variety of materials: with these three subtests, the CCS includes numeric, visuo-spatial and verbal content. All three subtests were designed to mimic the widespread English-speaking versions of the tasks (Unsworth et al., 2005). Because the three subtests were not intended to be used in isolation, they were shortened relative to the original versions by halving the number of trials. The CCS was entirely computerized and did not require oral responses from the participants, thus allowing for group administration.

## **Method**

### **The Composite Complex Span**

The CCS includes three subtests: the reading span, symmetry span and operation span, presented in this order. The whole procedure takes approximately 25 minutes. All three subtests have the same structure: in each trial, participants have to solve a series of simple

processing problems while memorizing unrelated stimuli presented after each problem. At the end of a trial, a grid containing all possible to-be-remembered stimuli appears on the screen; participants have to click the cases of the grid corresponding to the stimuli they have seen, in the correct order. An illustration of the operation span subtest is presented in Figure A1.

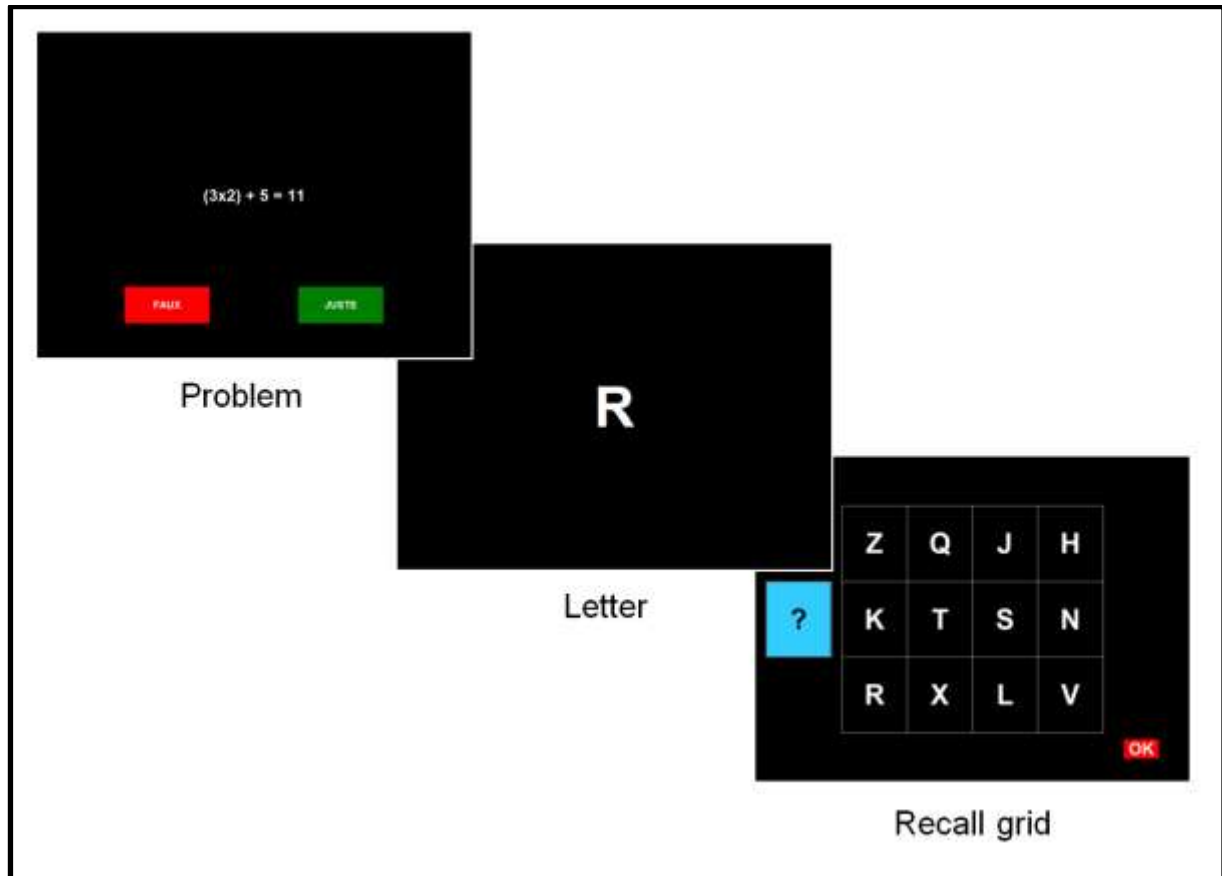


Figure A1. Illustration of the operation span subtest of the CCS. A series of problems and letters to memorize is followed by the recall grid.

The reading span subtest requires participants to tell whether sentences are correct while memorizing unrelated digits; the symmetry span requires participants to tell whether spatial displays are vertically symmetrical while memorizing spatial locations within a grid; and the operation span requires participants to tell whether mathematical operations are correct while memorizing consonants. The difficulty of the reading span and operation span ranges from a set size of 4 (four processing problems to solve interleaved with four stimuli to memorize) to a set size of 8. For the symmetry span, set sizes range from 3 to 6. These set sizes were used because they produced the most satisfying distribution of scores during pilot testing. A general notion in psychometrics is that less sensitivity is needed at the extremes of a scale because most participants fall in the middle of a normal distribution; as a consequence, each subtest includes a single trial for the lowest and highest set sizes and two trials for all

other set sizes. The trials are presented in pseudo-random order to ensure that participants cannot anticipate the set size of the current trial (Unsworth et al., 2005).

Each subtest is preceded by a training phase including three practice sessions, based on the procedure used by Unsworth and colleagues (Unsworth et al., 2005). Participants receive feedback on their performance after each trial in the practice sessions. The first practice session trains participants to memorize stimuli without a concurrent processing demand; for example in the reading span training, participants simply have to memorize and recall a series of digits. Participants complete three practice trials in this first session (one trial each of set sizes 2, 3 and 4). The second practice session trains participants to perform the processing task, without a memory requirement: for the reading span training, participants only have to tell whether sentences are correct. Participants initially complete fifteen practice trials in this session; if they fail to correctly answer at least 65% of trials, however, the practice session is repeated until they meet this criterion. There is no time constraint on this second practice session, but the participant's response times are registered and serve to calculate a time limit to complete the processing problems in the subsequent phases of the task. The time limit is calculated as the participant's mean response time plus 2.5 standard deviations (Unsworth et al., 2005). If the participant fails to answer the processing problem within this delay during the third practice session or the real block of trials, the program registers an error and moves on to the next stimulus. This time limit ensures that participants cannot freely rehearse the series of to-be-remembered stimuli while they are supposed to answer a processing problem. The third and final practice session trains participants to perform the memory and processing tasks simultaneously and is similar to the real block of trials. Prior to beginning the third session, participants are instructed that the memory and the processing tasks are equally important, and that they should strive to remain above 85% of accuracy on the processing task at all times. Participants again complete three practice trials in this session (one trial of set size 2 and two trials of set size 3).

### **Stimuli For The Complex Span Tasks**

#### **The reading span task.**

To-be-remembered stimuli are digits from 1 to 9, counterbalanced across trials. The same digit never appears twice in the same trial, and no trial includes a meaningful sequence of numbers. The sentences for the processing task are based on the stimuli used by Desmette and colleagues (Desmette et al., 1995). Half the sentences were made nonsensical by replacing one select word by another word incongruent with the meaning. All nonsensical sentences remained syntactically correct – e.g., *Un étranger apparut sur le seuil et tendit à la*

*fille un petit sac de fenêtres* [A stranger appeared on the doorstep and handed the girl a small bag of windows]. The position of the incongruent word was comprised between the middle point and the end of the sentence, counterbalanced across all trials. Each trial includes between 25% and 75% of incorrect sentences.

### **The symmetry span task.**

To-be-remembered stimuli are sequentially presented spatial locations in a 4x4 matrix; the stimuli are displayed to the participant as one square of the matrix coloured in red. Spatial locations are counterbalanced across trials; the same location never appears twice within the same trial; and the locations never form a meaningful spatial pattern. The spatial displays for the symmetry judgment task were re-used from the classic computerized version of the symmetry span (Unsworth et al., 2005) with permission from the authors. These spatial displays are constituted of black and white squares in a 8x8 matrix; half the displays are vertically symmetrical, and each trial includes between 25% and 75% of vertically symmetrical displays.

### **The operation span task.**

To-be-remembered stimuli are consonant letters chosen for their visual and phonological distinctivity (for example, the task includes the letter N but not the letter M), counterbalanced across trials. The same letter never appears twice within the same trial, and the letters never form a meaningful sequence. The mathematical operations for the processing task follow the same structure as the original operation span (Turner & Engle, 1989; Unsworth et al., 2005). Each operation string includes two simple operations and a stated result – e.g.,  $(2 \times 2) + 7 = 11$ . The operands include all digits from 1 to 9; the first operation in the string can be a multiplication or a division and the second operation can be an addition or a subtraction, counterbalanced across trials. The correct result of the operation string is always an integer comprised between 1 and 20. The stated result is incorrect in half the operation strings, and each trial includes between 25% and 75% of correct operations.

### **Scoring Method**

Performance in the CCS was scored with the partial credit load method (Conway et al., 2005); in other words, participants are awarded one point per correctly recalled stimulus in each trial. With this scoring method, a participant correctly recalling four out of five stimuli in a trial of set size 5 would get four points. The partial credit method is the preferred scoring method for complex span tasks (Conway et al., 2005; Redick et al., 2012); we adopted the load version after pilot testing because it produced slightly more normal distributions in our

sample. This scoring method yields one working memory score for each subtest. Working memory scores on each subtest are then transformed into  $z$ -scores and the three  $z$ -scores are averaged, yielding a single composite working memory score. Processing accuracy scores, calculated as the percentage of processing problems correctly answered by the participant, are also retrieved for each subtest. Participants with less than 85% accuracy on a processing task are typically excluded from the Sample (Conway et al., 2005; Unsworth et al., 2005); however, pilot testing suggested that this criterion is too strict in French student samples. For this reason, we instead elected to exclude participants who score in the bottom 5th percentile of the distribution of processing accuracy scores. When a participant scores below the exclusion criterion in a single subtest, his working memory score is calculated as the average of his scores on the two other subtests; when a participant scores below the criterion in two or all three subtests, his data is discarded entirely.

## **Validation Procedure**

### **Convergent validity tasks.**

Two tasks were used to assess the predictive validity of the CCS. The first task was set II of Raven's Advanced Progressive Matrices (APM; Raven, Raven & Court, 1998), a test of fluid intelligence. Set II of the APM is constituted of 36 items of ascending difficulty; each item comprises a matrix of nine geometric patterns that follow various logical rules. On each item, the bottom-right piece of the matrix is missing, and the participant has to select the correct piece to complete the matrix among eight alternatives. Working memory demonstrates consistent correlations with fluid intelligence, and the APM are frequently used to test convergent validity when validating complex span tasks (e.g. Unsworth et al., 2005; Redick et al., 2012).

Because we wanted to ensure that the CCS correlates with working memory tasks other than complex spans, we choose the alpha span as a second convergent validity measure (Oberauer, Süß, Schulze, Wilhelm, & Wittmann, 2000). This working memory task requires participants to read a series of words and to recall the first letter of each word in alphabetical order. The alpha span is not a complex span with interleaved presentation of processing problems and to-be-remembered stimuli; instead, the processing requirement in the task is to rearrange the first letters of each word in alphabetical order. We constructed a French version of the alpha span for this validation study. The alpha span included five practice trials with set sizes ranging from 2 to 8, and eight target trials with set sizes ranging from 4 to 8, similar to the reading span and operation span subtests.

### **Validation sample.**

A total of 1093 participants completed the CCS (mean age = 20.79 years,  $SD = 4.61$ ; 142 male). These data were collected over the course of three years, in the context of several different experiments not reported here. All participants were university students participating for course credit; they were recruited at the University of Savoy or at the University of Grenoble, France. The following inclusion criteria were observed: having French as a first language, having no history of neurological disorders, and taking no psychoactive drugs. All participants provided written informed consent prior to the experimental session. A subset of these 1093 participants ( $N = 303$ ) performed the task on two separate occasions, allowing for the examination of test-retest reliability. Two other subsets additionally completed either the APM ( $N = 184$ ) or an alpha span ( $N = 249$ ) in the same session as the CCS, allowing for the examination of convergent validity.

## **Results**

### **Descriptive statistics**

Among the total Sample of 1093 participants, 20 participants (1.8%) were excluded because they failed to reach the accuracy criterion on the processing tasks in two or all three subtests. Another 99 participants (9.1%) failed to reach the accuracy criterion in a single subtest, and their working memory scores were calculated on the basis of the two other subtests. The remaining 974 participants (89.1%) performed adequately in all three subtests. Most participants needed a single practice session on the processing task to reach the accuracy criterion in each subtest; more than one practice session was required for 12 participants in the reading span (1.1%), 6 participants in the symmetry span (0.5%), and 33 participants in the operation span (3.0%).

Descriptive statistics for working memory scores and processing accuracy scores are presented in Table A1. Overall, the working memory scores for each subtest were normally distributed. For the reading span and symmetry span subtests, processing accuracy scores showed high kurtosis coefficients, indicating a floor effect (similar to Redick et al., 2012); this floor effect on processing scores is a desirable feature of complex spans since the processing task is only intended as a distraction rather than a sensitive psychometric measure (Redick et al., 2012). For the operation span, processing accuracy scores were approximately normally distributed, indicating the absence of a floor effect.

Table A1

*Descriptive statistics for working memory and processing accuracy scores*

Measure	Mean	SD	Skewness	Kurtosis
Composite working memory score	-0.01	0.80	-0.60	0.57
Reading span				
Working memory score	32.12	8.71	-0.22	-0.39
Processing accuracy score	88.09	9.81	-2.10	6.06
Symmetry span				
Working memory score	18.37	5.38	-0.55	-0.23
Processing accuracy score	89.55	8.89	-1.79	5.37
Operation span				
Working memory score	28.88	7.48	-0.87	0.68
Processing accuracy score	80.93	12.32	-1.02	1.00

Working memory and processing accuracy scores as a function of percentile in the Sample are presented in Table A2. These data confirm the presence of a floor effect for processing accuracy on the reading span and symmetry span and the absence of this floor effect for processing accuracy on the operation span. In the latter case, most participants demonstrated adequate performance on the processing task except for participants in the bottom 5<sup>th</sup> percentile who scored barely above chance level. No floor or ceiling effect appeared for working memory scores on any subtest.

### **Reliability**

Internal consistency of the working memory scores was computed for each subtest with the Kane et al. (2004) method: the proportion of correctly recalled stimuli was calculated for each trial and a Cronbach's  $\alpha$  was calculated across all trials. Cronbach's  $\alpha$  were satisfying, with values above .70 for the reading span ( $\alpha = .72$ ), the symmetry span ( $\alpha = .72$ ) and the operation span ( $\alpha = .76$ ). These values are comparable to the coefficients reported by Redick et al. (2012), indicating that the decrease in the number of trials did not critically affect the reliability of the subtests. The internal consistency was even higher for the composite working memory score ( $\alpha = .84$ ).

Test-retest reliability of the working memory scores was calculated as the correlation between scores on the first session and scores on the second session. Correlation coefficients were moderate for the reading span,  $r(286) = .61$ , the symmetry span,  $r(287) = .69$ , and the



operation span,  $r(284) = .66$ . These values are lower than the test-retest reliability coefficients reported by Redick et al. (2012). However, test-retest reliability was higher and above .70 for the composite working memory score,  $r(298) = .77$ ; this value is similar to the results reported in Redick et al. (2012) and indicates satisfying test-retest reliability.

Table A2

*Percentiles for working memory and processing accuracy scores*

Measure	5 <sup>th</sup>	25 <sup>th</sup>	33.3 <sup>th</sup>	50 <sup>th</sup>	66.6 <sup>th</sup>	75 <sup>th</sup>	95 <sup>th</sup>
Composite working memory score	-1.41	-0.52	-0.33	0.04	0.37	0.61	1.14
Reading span							
Working memory score	18	26	28	32	37	39	46
Processing accuracy score	71	85.5	87.5	89.5	93.75	95	98
Symmetry span							
Working memory score	9	14	16	19	22	23	26
Processing accuracy score	74	85.25	89	92.5	92.5	96.5	100
Operation span							
Working memory score	15	23	27	30	33	34	39
Processing accuracy score	57.5	75	77.5	82.5	87.5	90	97.5

*Note.* The possible range of working memory scores is 0-48 for the reading span and the operation span and 0-27 for the symmetry span.

On average, working memory scores were higher on the second session for the symmetry span, the operation span, and the composite working memory score (all  $ps < .001$ ), indicating a practice effect. However, the effect was relatively small; on average, participants recalled 1.6 more stimuli on the second session of the symmetry span (out of a total of 27) and 1.7 more stimuli on the second session of the operation span (out of a total of 48). The practice effect did not reach significance for the reading span,  $F(1, 285) = 2.44$ ,  $p = .12$ ,  $\eta^2_p = .01$ ; on average, participants recalled 0.8 more stimuli on the second session of this subtest (out of a total of 48).

### Validity

Convergent validity was assessed by examining the correlations between the three subtests. For reference, Redick et al. reported the following median correlation coefficients between the reading span, symmetry span and operation span in four different samples:  $r = .46$  for the reading span and symmetry span,  $r = .62$  for the reading span and operation

span, and  $r = .46$  for the symmetry span and operation span. In the CCS, working memory scores were moderately correlated across the three subtests (see Table A3). As can be seen, these correlation coefficients are lower than those reported by Redick et al. (2012), but not disproportionately so, suggesting that the short versions of the subtests retained satisfying validity.

Table A3

*Cross-task correlations for the working memory scores*

Measure	Reading span	Symmetry span
Reading span	-	
Symmetry span	.33	-
Operation span	.53	.38

Concurrent validity was assessed as the correlation between the composite working memory score and performance on the APM and the alpha span task. As expected, the working memory composite score correlated with Raven's APM,  $r(184) = .39$ ,  $p < .001$ . This correlation is close to usually observed values: Redick et al. (2012) reported a median coefficient of  $r = .32$  for the correlation between complex span tasks and Raven's matrices in 11 different samples. The working memory composite score also correlated with the alpha span,  $r(249) = .54$ ,  $p < .001$ . Again, this correlation is close to the expected value: for example, Oberauer et al. (2000) reported a .49 correlation between a similar alpha span task and a version of the reading span.

### Discussion

This article presented the CCS, a composite working memory task including short versions of three complex spans, the reading span, symmetry span and operation span. The CCS demonstrated satisfying reliability and validity. Observed values for internal consistency, test-retest stability, and concurrent validity were quite close to the values reported for English-speaking versions of the subtests (Redick et al., 2012). Performance on the CCS appeared relatively stable in time, and the task showed the expected correlations with Raven's APM and with an alpha span task. Overall, the CCS seems to constitute an adequate task to measure domain-general working memory capacity in French-speaking samples.

Despite including only half as many trials in total as the three classic computerized versions of the subtests (Unsworth et al., 2005), the CCS shows similar psychometric

properties. The satisfying qualities of the CCS demonstrate that short versions of complex span tasks may be used to provide an accurate measure of working memory; in other words, it is not necessary to have participants complete full versions of multiple complex spans to obtain a valid measure of their working memory capacity. While the CCS has been validated in French, it is straightforward to generalize this conclusion to other languages. However, it should be noted that the composite working memory score is more reliable than scores on the individual subtests; this reflects the fact that the CCS should be viewed as a unitary task assessing domain-general working memory, rather than as a task battery assessing working memory for different types of materials.

The only major difference between the CCS and original versions of the three complex spans resides in performance on the processing tasks. Published versions of English-speaking complex spans typically recommend to exclude participants who score lower than 85% on the processing task (Conway et al., 2005; Unsworth et al., 2005), which results for example in about 15% of exclusions for the operation span in American samples (Unsworth et al., 2005). As can be seen in Table A3, applying the same criterion in our Sample would result in excluding approximately 25% of participants on the reading span and symmetry span and more than 50% of participants on the operation span subtest. Why such a discrepancy? The instructions, the practice phases and the difficulty of the processing tasks are all identical in the CCS and in the original versions of the complex spans. The most likely explanation is a true difference between the samples; for the operation span subtest in particular, a significant portion of French psychology students come from Arts divisions and are ill-at-ease with mathematical operations. The fact that complex spans have reduced validity when the processing task is too difficult for participants (Turner & Engle, 1989) may be a cause for concern. However, most participants in our Sample appeared to adequately carry out the processing tasks, and the global CCS score demonstrated satisfying validity. For these reasons, the best solution is probably to retain the same processing task difficulty as the original versions of the tasks for the sake of comparability, but to adopt less stringent exclusion criteria. In this sense, discarding the data of a subtest for participants who score in the bottom 5<sup>th</sup> percentile in the processing task seems to be an adequate choice.

The CCS relies on the idea that combining working memory tasks related to different types of materials is a great way to eliminate content-specific variance and to obtain a valid, domain-general measure of working memory capacity (Kane et al., 2004). However, all three subtests in the CCS use the same complex span structure; as a consequence, it is likely that performance in the CCS still includes method-specific variance. Complex span tasks are not

the only valid working memory measures: a wide variety of very different tasks can also yield useful estimates of working memory capacity, even tasks without clear processing and storage requirements (Oberauer, 2005). To obtain a truly general measure of working memory capacity, it may be desirable to combine complex span tasks with other working memory tasks (Redick et al., 2012). Since the alpha span is not a complex span task and demonstrates a significant correlation with the CCS, replacing the reading span subtest with the alpha span may partially solve this problem in studies where limiting method-specific variance is important.

In summary, the CCS constitutes a short working memory task suitable to obtain a domain-general estimate of working memory capacity. Despite being shorter than classic complex span tasks, the CCS demonstrated satisfying psychometric properties in a large French sample.

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## APPENDIX B. DETAILS FOR STUDY 2

Table B1

*List of irrelevant words in Experiment 2a*

Order of presentation	Words	Time of presentation
1	carnaval	Target
2	pharmacie	Target
3	bicyclette	Delay
4	trafiquant	Delay
5	galaxie	Delay
6	oxygène	Target
7	barbecue	Target
8	réacteur	Delay
9	vagabond	Target
10	labyrinthe	Delay
11	sanglier	Delay
12	aviation	Target
13	continent	Target
14	perroquet	Delay
15	prophétie	Target
16	incendie	Target
17	ministère	Target
18	casino	Delay
19	forteresse	Delay
20	pellicule	Delay
21	embuscade	Target
22	magicien	Delay
23	tremblement	Delay
24	réservoir	Target
25	crépuscule	Target
26	éléphant	Delay
27	araignée	Delay
28	autopsie	Target
29	satellite	Delay
30	japonais	Delay
31	opéra	Target
32	champignon	Target
33	esclavage	Target
34	oreiller	Delay
35	signature	Target

36	marionnette	Target
37	minimum	Delay
38	géomètre	Delay
39	crocodile	Target
40	cocaïne	Target
41	héritage	Delay
42	technicien	Target
43	caporal	Target
44	somnifère	Delay
45	agenda	Delay

*Note.* "Delay" indicates that the word was heard during the delay period of the mental rotation task, whereas "Target" indicates that the word was heard when the target of the mental rotation task appeared.

Table B2

*List of distractors in Experiments 2a and 2b*

haricot	étagère	épicerie
canapé	cicatrice	télégramme
sorcellerie	confiture	caravane
spaghetti	pyramide	amoureux
reportage	autoroute	horizon
étalon	manuscrit	météo
ouragan	étincelle	réfugié
parasite	cuisinier	cavalier
papillon	traumatisme	serveur
portefeuille	internet	maquillage
alibi	conducteur	escargot
comédien	pyjama	bouclier
écureuil	résidence	architecte
messenger	étiquette	allumette
pâtisserie	explosif	jardinier

Table B3

*List of irrelevant words in Experiment 2a*

Order of presentation	Words	Time of presentation
1	pellicule	Delay
2	syndicat	Delay
3	sanglier	Target
4	protocole	Delay



5	vagabond	Target
6	perroquet	Target
7	privilège	Delay
8	aviation	Target
9	forteresse	Delay
10	sympathie	Delay
11	incendie	Target
12	continent	Delay
13	galaxie	Target
14	japonais	Delay
15	technicien	Target
16	caporal	Delay
17	agenda	Target
18	crépuscule	Delay
19	crocodile	Delay
20	pharmacie	Target
21	araignée	Delay
22	solitude	Delay
23	innocence	Target
24	locataire	Target
25	oreiller	Delay
26	prophétie	Target
27	satellite	Delay
28	domestique	Delay
29	signature	Delay
30	catastrophe	Target
31	champignon	Target
32	labyrinthe	Delay
33	embuscade	Delay
34	réservoir	Target
35	somnifère	Target
36	éléphant	Delay
37	librairie	Target
38	entrepôt	Target
39	géomètre	Target
40	ministère	Target
41	héritage	Delay
42	oxygène	Target
43	carnaval	Delay
44	trafiquant	Target
45	marionnette	Target

*Note.* "Delay" indicates that the word was heard during the delay period of the mental rotation task, whereas "Target" indicates that the word was heard when the target of the mental rotation task appeared.

## APPENDIX C. DIFFERENCES BETWEEN SAMPLES IN THE AX-CPT

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### **Data collection for each sample**

One sample of French participants (Sample F) and two samples of American participants (samples A1 and A2) completed similar versions of the AX-CPT 40. Sample F included all participants who completed Experiment 5a (this manuscript); the data collection was performed at the University of Savoy, Chambéry, France. Sample A1 included all participants who completed the study of Richmond and colleagues (2013; Experiment 1); the data collection was performed at Temple University, Philadelphia, Pennsylvania, US. Sample A2 comprised participants who completed another unpublished study (Gonthier, Chow, Macnamara, Conway, & Braver, 2014); the data collection was performed at Princeton University, Princeton, New Jersey, US. Sample sizes were approximately equivalent for Sample F ( $N = 95$ ), Sample A1 ( $N = 104$ ) and Sample A2 ( $N = 92$ ).

All participants completed the AX-CPT 40 with 40% of AX trials, 10% of AY trials, 10% of BX trials and 40% of BX trials. Sample F included 100 trials, Sample A1 included 144 trials and Sample A2 included 200 trials in total. Presentation times were approximately equivalent for Sample F (cue = 500ms, delay = 3000ms, probe = 500ms, ITI = 1000ms), Sample A1 (cue = 1000ms, delay = 5000ms, probe = 500ms, ITI = 1000ms) and Sample A2 (cue = 1000ms, delay = 4000ms, probe = 500ms, ITI = undisclosed). Participants were required to respond to each stimulus (including both cues and probes) in all samples. The details of the task were comparable across samples with one exception: participants received an audio feedback after each response in Sample F and Sample A1, but not in Sample A2.

The raw data for each Sample were re-analyzed so that the data management methods were identical. The same dependent variables as in Experiment 2b and Study 5 were collected: error rates, median response times,  $d'$ -context and PBI calculated on errors after log-linear correction, PBI calculated on RTs, and the combination of the two PBIs after standardization. The standardization of the two PBIs was performed by subtracting the average and dividing by the standard deviation calculated across the three samples to allow for comparison between the samples. We also computed an additional measure, the within-subject standard deviation in response times for each trial type; this measure provided an index of intra-individual variability. Lastly, reliability coefficients were computed with the split-half method (see Experiment 2b, p. 134).

All participants also completed a symmetry span task and an operation span task. Participants in Sample A1 and Sample A2 completed the Unsworth et al. (2005) versions of the tasks; participants in Sample F completed the CCS. A composite working memory score was computed for each participant by standardizing the scores on the symmetry span and operation span (using the parameters calculated within the sample) and averaging the two values.

## **Results**

The first analysis tested the differences in performance on the four trial types as a function of the sample, for both error rates and RTs. The statistical significance of the differences between samples was assessed in ANOVAs, with the sample entered as an independent variable. When an omnibus ANOVA was significant, a follow-up test using Tukey's honestly significant difference (HSD) was performed to determine which samples were significantly different. The alpha level was set at .05 for all analyses. Descriptive statistics and statistical tests of the differences between samples are presented in Table C1. Overall, error rates were fairly comparable across the three samples; participants tended to make less errors in Sample F than in Sample A1. Response times were significantly faster and more stable in Sample F than in the two other samples.

The second analysis tested the differences on complex performance indices as a function of sample. Statistical significance was assessed with the same method as in the first analysis. Descriptive statistics and statistical tests of the differences between samples are presented in Table C2; overall, participants in Sample F were more proactive than participants in Sample A1 but less proactive than participants in Sample A2.

The third analysis tested the dispersion of the various measures presented in Table C1 and Table C2; the objective was to determine whether there was more inter-individual variability in some samples than others. This analysis used a Levene test, equivalent to an ANOVA on variances; when the Levene test was significant, a follow-up Tukey's HSD test was used to determine which samples were significantly different. The alpha level was set at .05 for all analyses. The results are presented in Table C3. Overall, inter-individual variability was fairly comparable across Sample F and the two American samples, except for intra-individual standard deviations in response times where there was less variability in Sample F. Importantly, the inter-individual variability in Sample F was equivalent to at least one of Sample A1 and Sample A2 for all complex indices of the tendency to use proactive control.

Table C1

*Performance on each trial type as a function of the sample*

Dependent variable	Trial type	Sample F	Sample A1	Sample A2	Differences between samples
Average error rate	AX	.048 (.066)	.139 (.131)	.060 (.061)	F = A2 < A1
	AY	.102 (.118)	.099 (.097)	.144 (.107)	A1 = F < A2
	BX	.068 (.105)	.122 (.163)	.051 (.073)	A2 = F < A1
	BY	.009 (.017)	.018 (.036)	.024 (.041)	F = A2 < A1
Median RT	AX	385 (45)	479 (73)	408 (73)	F < A2 < A1
	AY	454 (53)	554 (58)	514 (84)	F < A2 < A1
	BX	381 (87)	481 (106)	385 (110)	F = A2 < A1
	BY	351 (60)	440 (63)	381 (90)	F < A2 < A1
Intra-individual variability in RTs	AX	78 (23.8)	101 (46.7)	115 (37.6)	F < A2 < A1
	AY	65 (27.2)	108 (59.2)	87 (36.7)	F < A1 < A2
	BX	104 (52.8)	130 (73.0)	137 (59.9)	F < A2 = A1
	BY	87 (27.5)	127 (59.2)	94 (29.5)	F = A2 < A1

*Note.* Standard deviations in parentheses. "=" indicates that two samples were not significantly different; "<" (or ">") indicates that the average value of the DV was significantly lower (or higher) in a sample.

Table C2

*Average value of the proactive indices as a function of the sample*

Dependent variable	Sample F	Sample A1	Sample A2	Differences between samples
PBI-errors	0.096 (0.450)	-0.003 (0.431)	0.301 (0.289)	A1 = F < A2
PBI-RTs	0.117 (0.087)	0.078 (0.086)	0.153 (0.078)	A1 < F < A2
PBI-composite	-0.043 (1.602)	-0.715 (1.702)	0.853 (1.290)	A1 < F < A2
<i>d'</i> -context	2.79 (0.51)	2.17 (0.84)	2.74 (0.51)	A1 < A2 = F

*Note.* Standard deviations in parentheses. PBI-errors = PBI calculated on errors; PBI-RTs = PBI calculated on RTs; PBI-composite = combination of the two other PBIs after standardization; "=" indicates that two samples were not significantly different; "<" (or ">") indicates that the average value of the DV was significantly lower (or higher) in a sample.

Table C3

*Inter-individual variability for each dependent variable as a function of the sample*

Dependent variable	Trial type	Differences between samples
Average error rate	AX	F = A2 < A1
	AY	F = A1 = A2
	BX	A2 < F < A1
	BY	F < A1 = A2
Median RT	AX	F < A1 = A2
	AY	F = A1 < A2
	BX	F = A1 = A2
	BY	F = A1 < A2
Intra-individual variability in RTs	AX	F < A1 < A2
	AY	F < A1 < A2
	BX	F < A1 < A2
	BY	F = A1 < A2
PBI-errors		A2 < F = A1
PBI-RTs		F = A1 = A2
PBI-composite		A2 < F = A1
d'-context		F = A2 < A1

*Note.* PBI-errors = PBI calculated on errors; PBI-RTs = PBI calculated on RTs; PBI-composite = combination of the two other PBIs after standardization; "=" indicates that two samples were not significantly different; "<" (or ">") indicates that the inter-individual variability was significantly lower (or higher) in a sample.

The fourth analysis examined reliability coefficients for each measure as a function of the sample. This analysis treated reliability coefficients as correlation coefficients and used Fisher's  $z$ -transformation to test the difference between the values. The alpha level was set at .05 for all analyses. The results are presented in Table C4; overall, reliability coefficients were descriptively lower in Sample F for most dependent variables, but their values were not statistically different from Sample A2 in most cases. Importantly, reliability in Sample F was

not statistically different from at least one of the two other samples for all complex indices of the tendency to use proactive control.

Table C4

*Reliability coefficient for each dependent variable as function of the sample*

Dependent variable	Trial type	Sample F	Sample A1	Sample A2	Differences between
					samples
Average error rate	AX	.63	.81	.70	F = A2 < A1
	AY	.14	.11	.32	A1 = F = A2
	BX	.27	.69	.48	F < A2 < A1
	BY	.14	.66	.80	F < A1 < A2
Median RT	AX	.81	.89	.93	F = A1 = A2
	AY	.71	.69	.83	A1 = F < A2
	BX	.50	.74	.79	F < A1 = A2
	BY	.89	.92	.96	F = A1 < A2
Intra-individual variability in RTs	AX	.40	.67	.78	F < A1 = A2
	AY	.24	.35	.41	F = A1 = A2
	BX	.24	.30	.46	F = A1 = A2
	BY	.36	.46	.79	F = A1 < A2
PBI-errors		.21	.30	-.05	A2 < F = A1
PBI-RTs		.35	.56	.48	F = A2 = A1
PBI-composite		.37	.59	.40	F = A2 < A1
d'-context		.40	.77	.58	F = A2 < A1

*Note.* PBI-errors = PBI calculated on errors; PBI-RTs = PBI calculated on RTs; PBI-composite = combination of the two other PBIs after standardization; "=" indicates that two samples were not significantly different; "<" (or ">") indicates that the reliability coefficient was significantly lower (or higher) in a sample.

The fifth and final analysis examined the bivariate correlations between working memory capacity and the various dependent variables as a function of the sample. This analysis used the general linear model, with working memory capacity and sample entered as

independent variables. Differences between samples were assessed as the statistical significance of the interaction between working memory capacity and sample; when the interaction was significant, Fisher's  $z$ -transformation was used to determine which samples were significantly different. The alpha level was set at .05 for all analyses. The results are presented in Table C5. Overall, the correlations between working memory capacity and the various measures of performance were lower in Sample A2 and Sample F than in Sample A1; correlations were never statistically different across Sample F and Sample A2.

Table C5

*Bivariate correlation of each dependent variable with working memory capacity as a function of the sample*

Dependent variable	Trial type	Sample F	Sample A1	Sample A2	Differences between samples
Average error rate	AX	.03	-.36*	-.18	F < A1
	AY	-.05	-.01	-.15	A1 = F = A2
	BX	-.24*	-.39*	.04	A2 < A1
	BY	.05	-.28*	.00	A2 = F < A1
Median RT	AX	-.22*	-.24*	-.19	A2 = F = A1
	AY	-.31*	-.06	-.19	A1 < F
	BX	-.20	-.22*	-.14	A2 = F = A1
	BY	-.25*	-.36*	-.22*	A2 = F = A1
Intra-individual variability in RTs	AX	-.26	-.19	-.12	A2 = A1 = F
	AY	-.01	.02	.04	F = A1 = A2
	BX	-.06	-.09	-.23*	F = A1 = A2
	BY	.03	-.16	-.10	F = A2 = A1
PBI-errors		.12	.26*	-.09	A2 < A1
PBI-RTs		.12	.32*	.20	F = A2 = A1
PBI-composite		.15	.34*	.09	A2 < A1
$d'$ -context		.18	.43*	.16	A2 = F < A1

*Note.* PBI-errors = PBI calculated on errors; PBI-RTs = PBI calculated on RTs; PBI-composite = combination of the two other PBIs after standardization; "=" indicates that two

samples were not significantly different; "<" (or ">") indicates that the absolute value of the correlation coefficient was significantly lower (or higher) in a sample. \*  $p < .05$ .

### **Summary and conclusion**

The only systematic difference between French and American samples emerged on raw performance indices: French participants were slightly more accurate, and their response times were faster and more stable. In terms of indices of the tendency to use proactive control, French participants were always at the midpoint between the two American samples. The dispersion of scores was slightly less in French participants, but it was always statistically equivalent to at least one of the American samples. Thus, there were no systematic differences in performance between French and American samples – such as a higher tendency to use proactive control in American students or a lower range of ability in French students – that could explain the absence of relationships between working memory capacity and the tendency to use proactive control in Chapter 6.

Reliability coefficients were lower in the French sample; this is certainly attributable to the lower number of trials in the version of the task used in this sample (about half as many trials as in Richmond et al., 2013). However, most reliability coefficients were not statistically different between the French Sample and at least one of the American samples; this was especially the case for the PBIs and the  $d'$ -context, which were the primary measures of interest in Chapter 6. Thus, differences in reliability are not likely to explain the lack of significant relationships in Chapter 6.

Lastly, correlations between working memory capacity and the various measures of performance in the AX-CPT were identical in the French sample and in Sample A2, although they tended to be lower than in Richmond et al. (2013). In other words, the weak relationships between working memory capacity and the AX-CPT reported in Chapter 6 were not systematically higher in American samples.



## APPENDIX D. DETAILS FOR EXPERIMENT 5b

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The strategy training used the following instructions, detailed screen by screen.

### **Screen 1:**

In the task, when the first letter is an A, and it is followed by another letter, what % of the time do you think that second letter is an X?

Please type your answer in the box.

### **Screen 2:**

Actually, when the A is followed by another letter, 80% of the time it is an X. That's a lot!

This means that most of the time you can predict which button you have to press in response to the second letter, depending on the nature of the first letter.

### **Screen 3:**

Because you can predict your response on the second letter beforehand, a useful strategy to optimize your performance in the task is to actively prepare your response after the first letter, so that you are ready to make the response when you see the next letter.

The objective of this final session of the task is all about using this strategy.

### **Screen 4:**

It is very likely that an X will follow an A. Therefore, whenever you see an A as the first letter, you should use the delay between the first and the second letter to prepare for a "yellow" response.

Whenever the first letter is not an A, you should use the delay between the first and the second letter to instead prepare for a "blue" response.

During the rest of the task, we would like you to implement this strategy by actively preparing your response in advance.

### **Screen 5:**

The normal rules of the task still apply:

- In the rare instances when the A is followed by another letter other than X, you should try to make a “blue” instead of a “yellow” response.

- In the rare instances when the first letter is followed by a digit, you should try to withhold your response altogether.

Because of the advance preparation strategy, you may find yourself having trouble in these rare cases, and you will probably make more errors.

That is OK. Unlike when you did this task previously, there are no penalties for errors. Just do the best you can!

### **Screen 6:**

In this session we are interested in the effect of using the advance preparation strategy in the task, so please try to keep using the strategy, even if you find yourself making some errors.

Of course, you should still try your best not to make errors, but it is less important than using the strategy.

### **Screen 7:**

You are now going to train on using this advance preparation strategy. You may find the following training repetitive, but it is designed to help you deeply encode the strategy.

The experimenter is going to perform the next trials.

After you see the first letter on a trial, please say out loud “yellow” if the first letter is an A, or “blue” if the first letter is not an A.

You should say this during the delay, while the + is visible on the screen.

### **Screen 8:**

Here are two examples of what you should do during a trial.

First trial :

You see an A. You say nothing.

You see the +. During the delay you say "yellow".

You see an X. You say nothing.

Second trial :

You see an F. You say nothing.

You see the +. During the delay you say "blue".

You see an H. You say nothing.

Before the final phase of the training:

**Screen 9:**

You are now going to perform the next trials yourself.

You should still say out loud "yellow" during the delay after you see an A, and "blue" during the delay after you see any other letter.

Now you should also use the response buttons to respond to the letters, exactly like in the two previous sessions of this task.

## APPENDIX E. DETAILS FOR STUDY 8

Table E1

*List of trials in the short-term memory task*

Series	Length	Word1	Word2	Word3	Word4	Word5	Word6	Word7
1	5	tendance	culture	grenouille	bonté	cassette		
2	5	registre	violon	instinct	boisson	accueil		
3	7	dégât	tribu	civil	peinture	ressource	insulte	dragon
4	6	rituel	pompier	enfance	province	accès	serpent	
5	5	impact	complot	adulte	permis	tournée		
6	6	coupable	délaï	finance	bâton	richesse	organe	
7	7	courrier	désordre	pêcheur	section	essence	légende	cristal
8	5	canard	pasteur	info	récit	orchestre		
9	6	triomphe	mineur	frangin	langage	empire	anneau	
10	7	défaite	tonnerre	altesse	parler	rupture	immeuble	poignet
11	6	vieillard	requête	avril	coupure	archive	bourreau	
12	5	modèle	aîné	routine	piano	chagrin		
13	5	vendeur	bougie	tiroir	réserve	curé		
14	6	psychiatre	serviette	séjour	rançon	sergent	merveille	
15	5	tennis	rocher	tissu	chaos	rabbin		
16	5	pognon	moustache	dialogue	maillot	décor		
17	5	magie	avant	bataille	bandit	ménage		
18	5	carnet	coiffeur	écrit	migraine	chariot		
19	7	rumeur	barrage	menu	cité	dessert	guerrier	plafond
20	7	ensemble	récolte	transfert	tambour	approche	massacre	habit
21	5	chameau	regret	racine	circuit	rasoir		
22	5	fourmi	épaule	zéro	coutume	cortex		
23	7	comte	gentil	salade	dispute	tapis	bouquet	promesse
24	7	dépêche	aveugle	progrès	allié	rivière	fierté	station
25	6	grenade	dehors	promenade	poumon	chantier	mamie	
26	7	mémé	piscine	colonne	janvier	soupçon	aller	couronne
27	5	fumier	verdict	poignard	tendresse	éclair		
28	5	revue	ambiance	liquide	rideau	mobile		
29	7	poème	agence	centaine	écran	autel	pigeon	adjoint
30	7	orage	parrain	coucou	sommet	accent	bonhomme	chanteur
31	6	plateau	délires	auberge	longueur	ordure	direct	
32	5	prénom	hauteur	vivant	fusée	balcon		
33	6	pilule	obstacle	domaine	motif	tigre	volant	
34	5	déesse	saison	otage	escroc	prochain		
35	6	biscuit	casier	diplôme	coton	principe	chrétien	
36	7	promis	marchand	alarme	querelle	surface	wagon	heureux
37	6	tomate	mardi	espion	privé	printemps	métal	
38	6	humour	expert	citron	renfort	crevette	armoire	
39	7	aura	limite	gendarme	concierge	poignée	méchant	concours
40	7	liaison	lecture	vainqueur	vertige	frisson	foyer	casquette
41	6	villa	maudit	engin	chaussette	alerte	crédit	
42	7	ballon	auteur	comté	symptôme	touriste	sirène	balai

Appendix E: Details for Study 8

43	5	cafard	séance	panique	jeton	baraque		
44	5	mouchoir	médaille	décembre	briquet	placard		
45	7	congrès	patrouille	monnaie	novembre	terreur	soulier	victoire
46	7	berger	serveur	diamant	vertu	puissance	remords	poubelle
47	5	échelle	voyou	stylo	coiffure	défi		
48	5	média	album	possible	tunnel	conflit		
49	6	assiette	secteur	remise	désastre	aveu	humeur	
50	7	fatigue	emploi	garage	savon	commande	tenue	saucisse
51	7	lessive	pourboire	juré	septembre	bonnet	étape	taureau
52	6	panier	ballet	centrale	talon	issue	distance	
53	7	substance	palais	fiston	complice	terrasse	réplique	drapeau
54	5	crayon	angoisse	transport	tonton	usage		
55	6	donnée	degré	ivrogne	commun	budget	caution	
56	7	bagarre	record	semblant	poète	orbite	femelle	horaire
57	6	dessin	patate	divorce	humain	serment	brouillard	
58	7	frontière	crapaud	vedette	épée	achat	piqûre	fortune
59	6	pirate	formule	affiche	milliard	ancien	cachette	
60	7	passport	mouton	serrure	fauteuil	plastique	trafic	moral
61	7	échec	fillette	perruque	bagnole	souffrance	tournage	fumée
62	6	nation	bouquin	copie	pari	portée	délit	
63	5	raté	souris	technique	moteur	version		
64	6	coma	ruban	barrière	alliance	écoute	salaire	
65	7	chômage	calcul	bisou	sérieux	venue	insecte	remarque
66	6	jury	allée	abeille	miroir	guitare	crochet	
67	5	trottoir	chinois	marteau	juillet	vampire		
68	6	potion	banane	antenne	sagesse	canal	lunette	
69	6	acide	prophète	baleine	musée	royaume	robot	
70	5	virus	tension	matière	collier	égard		
71	5	union	parfum	danseur	mérite	outil		
72	6	absence	géant	échange	marquis	mandat	compagnon	
73	5	période	forêt	scandale	grenier	attente		
74	7	option	orteil	troisième	désert	réveil	tuyau	balance
75	5	boutique	conduite	patrie	oignon	moins		
76	6	produit	suisant	navire	mallette	dépôt	rebelle	
77	6	fonction	clinique	rayon	débat	champagne	légume	
78	5	pétrole	hôtesse	raisin	chasseur	figure		
79	7	bagage	soutien	baaignoire	éclat	massage	boxeur	second
80	5	jeunesse	audience	cachet	malin	trompette		
81	6	cinglé	futur	recette	oubli	prière	fermier	
82	6	métro	troupeau	marin	cervelle	indien	pension	
83	6	tempête	mélange	roman	cheville	asile	région	
84	5	assaut	refus	tabac	tailleur	profil		
85	7	abri	octobre	navette	superbe	congé	mystère	jumeau
86	7	horloge	appui	écart	demeure	aspect	radar	gardien
87	6	descente	prétexte	carton	blessé	méthode	poursuite	
88	5	mignon	hommage	acier	défaut	couvent		
89	7	ticket	dentiste	jeudi	vaurien	couloir	indice	revanche
90	6	brigade	bijou	patience	automne	comptoir	sauvage	
91	5	panneau	commerce	vapeur	tatouage	cabine		
92	7	canon	agneau	facture	cabane	moto	baron	suspect
93	6	valet	détresse	gagnant	cognac	requin	fromage	
94	7	menace	poupée	pareil	filet	portail	cigare	loyer
95	7	facteur	critique	passion	médecine	marrant	essai	cravate
96	6	tristesse	rencard	épreuve	caserne	douceur	carreau	

## APPENDIX F. DETAILS FOR STUDY 9

Table F1

*List of items in our version of the APM, with corresponding item in the original APM (Raven et al., 1998), rule types, and number of rules*

Item number in our version of the APM	Item number in the original APM	Rule types	Number of rules
Item 1	Item 2	Pairwise	2
Item 2	Item 3	Pairwise, Constant*	2*
Item 3	Item 5	Pairwise, Constant*	2*
Item 4	Item 7	Addition*	1*
Item 5	Item 9	Addition, Constant*	2*
Item 6	Item 11	Addition	2
Item 7	Item 14	Pairwise, Constant*	2*
Item 8	Item 15	Addition	2
Item 9	Item 18	Unclassified*	N/A*
Item 10	Item 19	Unclassified*	N/A*
Item 11	Item 20	Addition, Constant	3
Item 12	Item 21	Pairwise, Constant	3
Item 13	Item 22	Addition, Subtraction**	3*
Item 14	Item 24	Pairwise, Constant	3
Item 15	Item 23	Addition, Subtraction**	4*
Item 16	Item 25	Pairwise, Constant	2
Item 17	Item 33	Addition, Subtraction*	2*
Item 18	Item 32	Pairwise, Constant**	4*
Item 19	Item 35	Addition, Subtraction, Constant**	4*
Item 20	Item 36	Addition, Subtraction, Constant**	4*

*Note.* \* Items whose rule types were classified by Carpenter et al. (1990). \*\* Items where our classification differs from that of Carpenter et al.

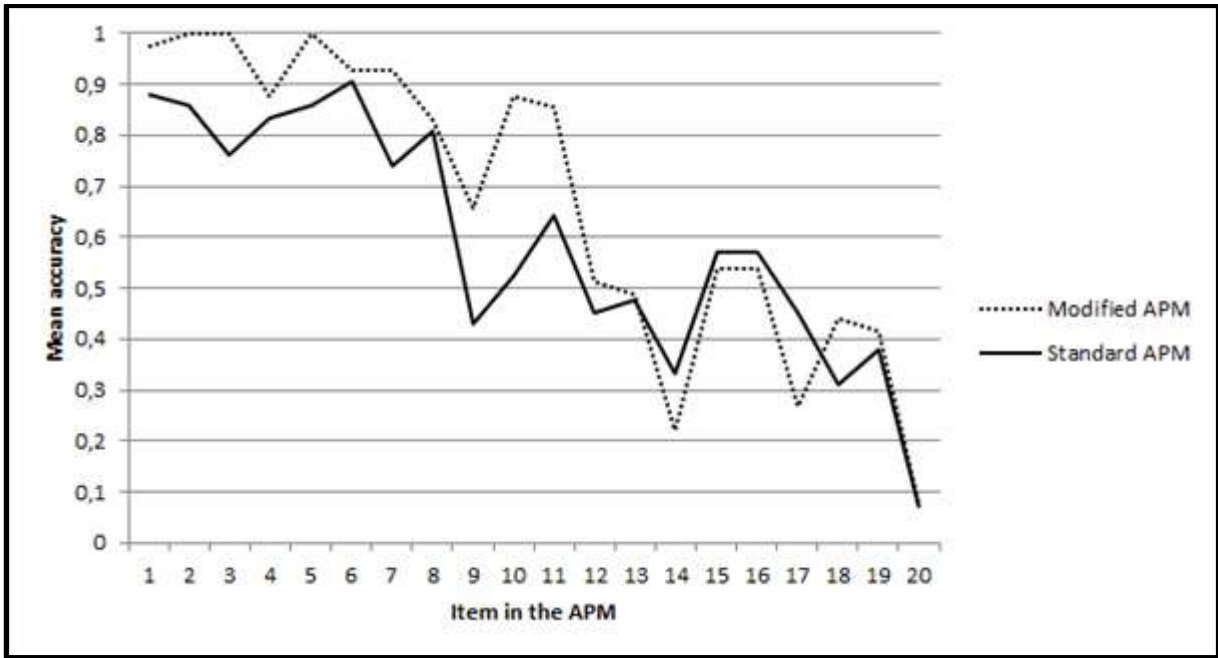


Figure F1. Mean accuracy for all items in the APM in Experiment 9a as a function of task version

## APPENDIX G. DETAILS FOR STUDY 10

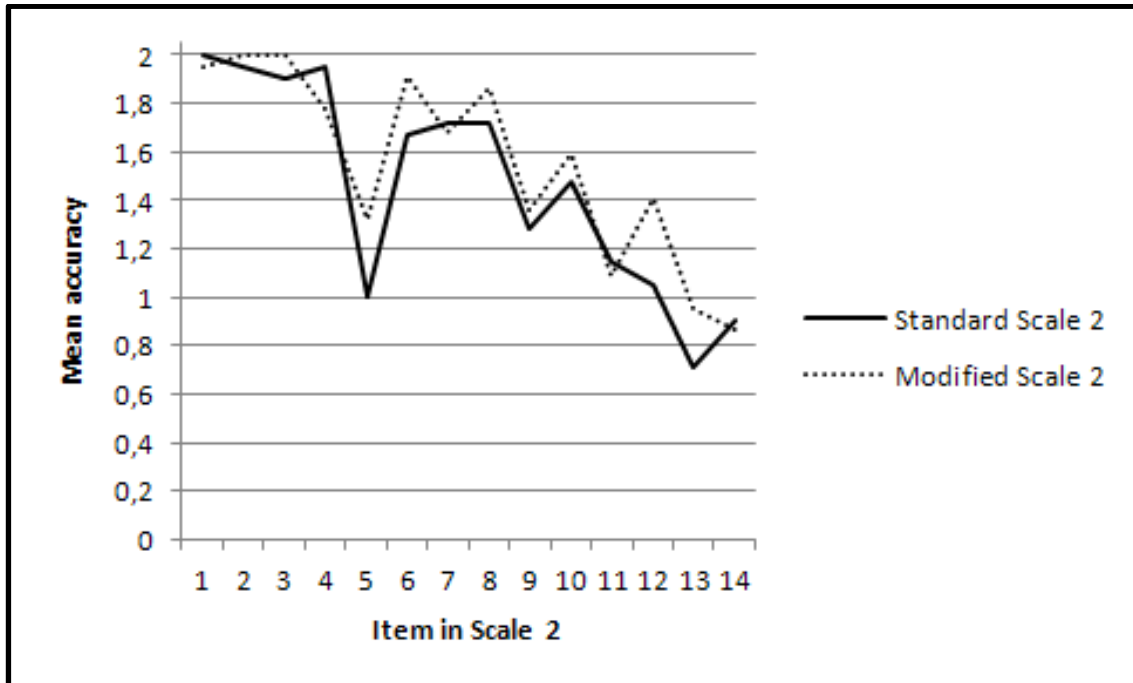


Figure G1. Mean accuracy for all items in Scale 2 of the CFT as a function of task version

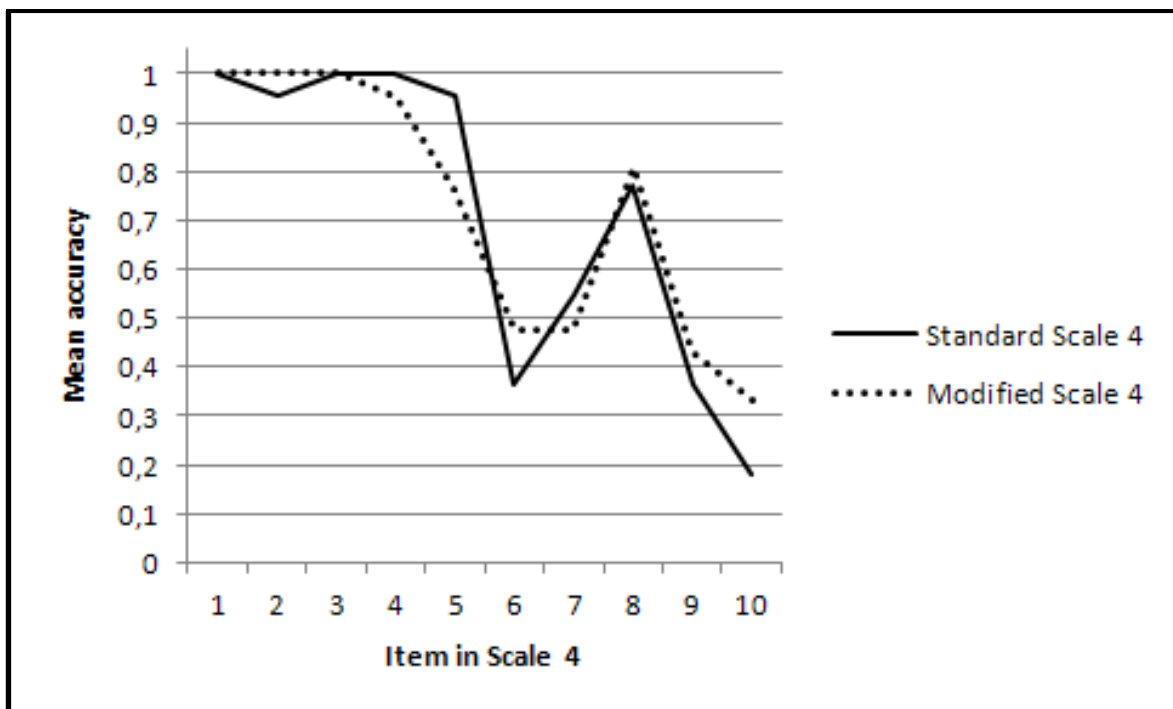


Figure G2. Mean accuracy for all items in Scale 4 of the CFT as a function of task version



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## ABSTRACT

The constructs of working memory and cognitive control are conceptually close; a high working memory capacity is hypothesized to be associated with an efficient cognitive control. This hypothetical association has large implications for human cognition and provides an elegant explanation for the frequently reported relationship between working memory capacity and fluid intelligence. However, the difficulty in operationalizing and measuring cognitive control makes this hypothesis hard to test. One model of cognitive control, the Dual Mechanisms of Control (DMC) framework, constitutes a possible solution to this problem: the model proposes two distinct mechanisms of cognitive control which can be efficiently operationalized and studied. There is reason to believe that one of these two mechanisms, proactive control, is specifically related to working memory capacity. The objective of the present research work was to assess the relationship between individual differences in working memory capacity and the tendency to use proactive control. This relationship was tested in four steps: 1) by using innovative measures of the tendency to use proactive control, based on newly developed paradigms; 2) with classic cognitive control tasks sensitive to proactive control; 3) with a neuroimaging approach using electroencephalography and functional magnetic resonance imaging; and 4) by testing whether the use of proactive control explains the relationship between working memory and fluid intelligence. Overall, our results do not support the idea that working memory capacity is uniquely related to the tendency to use proactive control; the data tend to indicate a general advantage of participants with a high working memory capacity in all situations.

**KEYWORDS:** working memory; cognitive control; fluid intelligence; dual mechanisms of control (DMC); individual differences; neuroimaging

## RÉSUMÉ

La mémoire de travail et le contrôle cognitif sont des construits proches ; on suppose généralement qu'une forte capacité en mémoire de travail est associée à un contrôle cognitif efficace. Cette hypothèse a des implications importantes pour la cognition humaine et apporte une explication élégante à la corrélation fréquemment reportée entre mémoire de travail et intelligence fluide. En revanche, les difficultés d'opérationnalisation et de mesure du contrôle cognitif rendent l'hypothèse difficile à tester. Un modèle récent du contrôle cognitif, le modèle à Deux Mécanismes de Contrôle (DMC), offre une solution à ce problème : ce modèle propose l'existence de deux mécanismes de contrôle cognitif distincts et permet de les opérationnaliser de façon efficace. La littérature prédit que l'un de ces deux mécanismes, le contrôle proactif, devrait être lié à la mémoire de travail. L'objectif de ce travail de recherche était de tester l'existence d'une relation entre les différences inter-individuelles en mémoire de travail et la tendance à mettre en place un mécanisme de contrôle proactif. Cette relation a été testée sous quatre axes de travail : 1) en utilisant de nouveaux paradigmes expérimentaux pour mesurer la tendance à utiliser le contrôle proactif, 2) grâce à des tâches classiques de contrôle cognitif choisies pour leur sensibilité au contrôle proactif, 3) à travers une approche par imagerie cérébrale incluant électro-encéphalographie et imagerie par résonance magnétique fonctionnelle, et 4) en tant que facteur explicatif de la relation entre mémoire de travail et intelligence fluide. Dans l'ensemble, nos résultats ne soutiennent pas l'idée selon laquelle la capacité en mémoire de travail est spécifiquement liée à la tendance à utiliser un mécanisme de contrôle proactif ; les données suggèrent plutôt un avantage général en faveur des participants à forte capacité en mémoire de travail dans toutes les situations.

**MOTS-CLEFS :** mémoire de travail ; contrôle cognitif ; intelligence fluide ; dual mechanisms of control (DMC) ; différences inter-individuelles ; imagerie cérébrale