ENS
ÉCOLE NORMALE SUPÉRIEURE

Thèse de Doctorat

En vue de l'obtention du grade de

DOCTEUR
DE L'ÉCOLE NORMALE SUPÉRIEURE

École Doctorale
Cerveau Cognition Comportement (ED3C, n°158) – UPMC

Discipline :
Sciences Cognitives

Présentée et soutenue par
Mikaël BASTIAN

le mardi 15 septembre 2015

Titre
Dynamics & monitoring of mind-wandering –
Dynamique et introspection de la rêverie éveillée

Unité de recherche : Laboratoire de Sciences Cognitives et Psycholinguistique, ENS

Thèse dirigée par : Jérôme SACKUR – École des Hautes Études en Sciences Sociales

Membres du jury

Jonathan	SMALLWOOD	– University of York	- rapporteur
Arnaud	DELORME	– CNRS, Univ. Toulouse (UPS)	- rapporteur
Catherine	TALLON-BAUDRY	– CNRS, École Normale Supérieure	- examinatrice
Birte	FORTSMANN	– Universiteit van Amsterdam	- examinatrice
Stanislas	DEHAENE	– INSERM, Collège de France	- examinateur

Numéro identifiant de la thèse ____________________

Consciousness is in constant change. (...)
Now we are seeing, now hearing; now reasoning, now willing;
now recollecting, now expecting; now loving, now hating;
and in a hundred other ways we know our minds to be alternately engaged.

William James (1892),
The Stream of Consciousness,
in *Psychology*, Chapter XI.

RÉSUMÉ

Les pensées humaines changent constamment: on regarde, on se souvient, on prévoit... Mais comment les gens accèdent-ils à cette succession de leur propres pensées ? Cette thèse a étudié l'introspection de la dynamique des pensées en capitalisant sur le phénomène saillant et surprenant de la rêverie éveillée (Chapitre 1).

Les rêveries sont ces pensées spontanées à propos de nos préoccupations personnelles. Je décris d'abord comment des fluctuations lentes permettent de prédire ces épisodes de rêverie (Ch. 2, 3). Mais ces dynamiques pourraient aussi déterminer le contenu et l'introspection des pensées. En effet, les patients avec des troubles de l'attention (TDAH) rapportent plus de pensées "vides": ce qui pourrait venir de troubles de la dynamique et/ou de l'introspection de leurs pensées (Ch. 4). Par ailleurs, deux expériences et une étude sur smartphone suggèrent que le langage intérieur facilite la conscience de la rêverie (Ch. 5). Le langage contribue aux capacités de contrôle : les pensées verbales pourraient donc être plus stables et plus vives. Finalement, je suggère que la détection des pensées n'est pas un accès direct à des éléments bien définis. Il s'agirait plutôt d'un mécanisme décisionnel ajustable, qui s'applique à des variables internes continues et dynamiques, comme dans la perception où une décision s'applique à des variables externes (Ch. 6).

En somme, ces études jettent une lumière nouvelle sur l'introspection humaine et retrouvent des intuitions anciennes (Ch. 7). En effet, nos données appuient une proposition philosophique faite il y a 125 ans par William James, un des pères fondateurs de la psychologie scientifique: nos pensées sont un flux continu, et détecter la rêverie dépend aussi des dynamiques de ce flux.

Mots clés: conscience, attention, pensées, rêverie éveillée, introspection, rythmes psycho-biologiques

ABSTRACT

Humans' conscious experience is always changing: now seeing, now remembering, now planning. Yet, how people notice the unfolding of their own thoughts remains unclear. The present thesis studied the dynamics and introspective monitoring of thoughts, by capitalizing on the salient and often unnoticed phenomenon of mind-wandering (Chapter 1).

Mind-wandering is the rise of thoughts about personal concerns. Against the idea that this rise is unpredictable, I first describe the characteristics of slow rhythms that predict mind-wandering occurrences during goal-directed tasks (Ch. 2, 3). Interestingly, these dynamics may determine thought content and introspection. Indeed, patients with Attention deficits (ADHD), who would likely experience alterations in both the dynamics and introspection of mind-wandering, report more "empty thoughts" (Ch. 4). Also, two experiments and a study using smartphones suggest that inner speech facilitates awareness of mind-wandering (Ch. 5). Inner speech contributes to monitoring capacities, thus verbal thoughts could be better sustained in time, increasing their vividness. Finally, I suggest that the detection of inner thoughts is not a direct access to clear-cut elements, but rather an adjustable decision mechanism applied to internal continuous and dynamic variables, similar to what happens in perception (Ch. 6).

In sum, these studies shed a new light on human's introspection and confirm old insights (Ch. 7). Indeed, they provide empirical support to a philosophical claim made 125 years ago by William James, one of the fathers of scientific psychology: we experience a continuous stream of thought, and detecting mind-wandering may depend on these dynamics.

Keywords: consciousness, attention, thought/thinking, mind-wandering, introspection, psycho-biological rhythms

TABLE OF CONTENTS

Table of Contents

REMERCIEMENTS / ACKNOWLEDGMENTS / DANK / AGRADECIMIENTO / 你致谢

(Full translation in English on the right)

Les pensées sont peut-être liées les unes aux autres, mais une première pensée reconnaissante se tient bien à l'écart et va à Jérôme Sackur. Directeur de cette thèse, il m'a enseigné, conseillé, encouragé et supporté tant et si bien qu'il explique plus de 51% de ma variance scientifique. Merci pour tout depuis cinq ans.

Les rôles de Valentin Wyart et de Jonathan W. Schooler ont été cruciaux: Jonathan, as he trusted me when I first came to his lab in Santa Barbara to discover mind-wandering studies four years ago, et Valentin, pour sa contribution décisive à ma maturation scientifique. I also wish to thank Eric Klinger, Valérie Pennequin et Laurie Tuller pour avoir su inspirer l'étudiant tourangeau que j'étais, et l'avoir orienté jusqu'ici.

Cette thèse fut grandement enrichie par mes collaborateurs et collaboratrices: Charlotte Van Den Driessche par son travail sur les troubles de l'attention, et Sébastien Lerique & Vincent Adam par leur courage et leur talent dans le développement de Daydreaming. *Merci aussi à Jacques Pesnot y Rodrigo Balp pour leur patience et confiance – por su paciencia y confidencia – en tant que premiers étudiants que j'ai eu à encadrer – porque fueron mi primeros estudiantes. Ik denk ook aan Marieke Van Vugt, met wie het een genoegen was om samen te werken, et je remercie mon ami Marc-Antoine Durand pour son aide dans le lancement de* Daydreaming.

Merci aux chercheuses et chercheurs du LSCP Sharon Peperkamp, Anne Christophe, Sid Kouider, Franck Ramus, Emmanuel Chemla, Emmanuel Dupoux, mais aussi Sylvain Charron & Romain Trachel, pour leurs sages commentaires sur mes projets. Isabelle Brunet, Vireack Ul, Michel Dutat et Radhia Accheb ont toujours fait un travail administratif et technique remarquable, et j'ai beaucoup de reconnaissance pour leur patience et bonne humeur. Quant à Isabelle Dautriche et Auréliane Pajani, mes voisines de bureau, elles ont su significativement diminuer mon stress et augmenter ma motivation (tout à $p < .01$*)* . 谢谢你给孙悦

Je remercie enfin les membres de mon jury d'avoir accepté de juger cette thèse :
Stanislas Dehaene, Arnaud Delorme, Birte Forstmann, Catherine Tallon-Baudry & Jonathan Smallwood.

La Direction Générale de l'Armement et la Fondation de l'École Normale Supérieure m'ont permis de travailler sur le sujet fascinant de la pensée humaine en me fournissant un soutien financier. Je suis grandement reconnaissant de cette confiance, et je suis honoré de rendre cette thèse comme le produit fini concret de leur investissement.

Ce flot de pensées reconnaissante s'achève finalement en remerciant mes parents et ma sœur, pour leur soutien constant, leur écoute et leur affection. En, natuurlijk, dank ik mijn geliefde Josefien Huijgen, voor haar dagelijkse steun gedurende mijn hele PhD.

Thoughts may be interdependent, but a first grateful thought is now standing aside and goes to the Director of the present thesis: Jérôme Sackur. He taught me, advised me, cheered me and supported me so much and so well, that he accounts for more than 51% of my scientific variance.

The role of Valentin Wyart and Jonathan W. Schooler were crucial: Jonathan, as he trusted me when I first came to his lab in Santa Barbara to discover mind-wandering studies four years ago, and Valentin, for his decisive contribution to my scientific maturation. I also wish to thank Eric Klinger, Valérie Pennequin and Laurie Tuller for inspiring the undergrad I was and orienting him to this present point.

This thesis was greatly enriched by my collaborators: Charlotte Van Den Driessche and her work on ADHD, Sébastien Lerique & Vincent Adam and their courage and talent in developing the Daydreaming app. I also thank Jacques Pesnot and Rodrigo Balp for their patience and trust as being the first students I supervised. I also think about Marieke Van Vugt, whom with it was a pleasure to collaborate, and I thank my friend Marc-Antoine Durand whose help was determining in promoting the Daydreaming app.

Thanks to the researchers of the Laboratoire de Sciences Cognitives et Psycholinguistique: Sharon Peperkamp, Anne Christophe, Sid Kouider, Franck Ramus, Emmanuel Chemla, Emmanuel Dupoux, and also Sylvain Charron & Romain Trachel, for their insightful comments on my work. Isabelle Brunet, Vireack Ul, Michel Dutat and Radhia Accheb did a remarkable administrative and technical job, and I thank their patience and cheerfulness. I am also grateful to Isabelle Dautriche, Yue Sun and Auréliane Pajani, my officemates, who significantly decreased my stress and increased my motivation (both at $p < .01$).

I also wish to thank the members of my jury for accepting to judge the present work:
Jonathan Smallwood, Arnaud Delorme, Birte Forstmann, Catherine Tallon-Baudry and Stanislas Dehaene.

The Direction Générale de l'Armement and the Fondation de l'Ecole Normale Supérieure allowed me to work on the fascinating topic of human thoughts by providing me with financial support. I am greatly grateful for this trust and I am honored to deliver this dissertation as a concrete end-product of their investment.

This stream of grateful thoughts will finally end by thanking my parents and my sister, for their constant support and affection. And, of course, I thank my beloved Josefien Huijgen, for every day she helped me go through during this whole PhD training.

CHAPTER 1: INTRODUCTION

1. How does science study human thought?

Human thought has always been fascinating, due to its unobservable and seemingly unpredictable nature. We often ask people "What are you thinking about?" and expect to hear about some self-generated mental content – "I was telling myself how much..." / "I was remembering when we..." – above and beyond pure perception. Answers such as "I'm looking at that rock" are disappointing if the other person was thinking about her job, while indeed staring at a rock. This privileged access to one's own thoughts inspired popular stories where characters had the extraordinary power to read other people's minds: series (*The twilight zone, 1961; Star Trek, 1966-69*), movies (*What women want,* 2000; *Thoughtcrimes,* 2003), books (*Harry Potter, 1997-2007*), and comics (*X-men, 1963-2014*). Interestingly, these stories evidence how unclear the nature of thought is: what would mind-readers read? Inner voices (e.g. *Star Trek*, *What women want*) and/or visuo-auditory mental images (*Harry Potter*, *X-men*)? In 2015, how do cognitive scientists tackle this problem? What do we know about how thoughts follow each other, or what it is to experience and report on one's own thoughts?

This introduction focuses on how science studies human thought. More specifically, how science studies the phenomenon of mind-wandering (Smallwood and Schooler, 2006, 2015): these personal thoughts unrelated to the task at hand that arise while reading, driving or listening to someone. People suddenly thinking about future plans (Baird et al., 2011), or having spontaneous intrusions about romantic relationships (Baird et al., 2013a), mind-wandering is both a salient and unpredictable phenomenon. As such, it is an ideal ground to identify the objective correlates of subjective experiences, as well as the mechanisms by which people assess their thoughts and by which thoughts follow each other. Thus, after an historical presentation of how mind-wandering studies became a respected field in neurocognitive sciences after a century-long defiance, I will identify key findings in the mind-wandering literature, and show that they do not account for the dynamics, nor the introspective monitoring of thought yet. I will then present five empirical series of studies I conducted, two that aimed at understanding the dynamics of mind-wandering, and three that aimed at understanding how people access their own thoughts.

2. *Thoughts' nature and dynamics in the 20th century: a brief history*

a) Thoughts according to Behaviorism (1913-1970)

What does Psychology study? Thinking? Surprisingly, the answer to this question determined the rise of modern Psychology as a science. And, a century ago, Psychology did become a respected science by dropping all studies on subjectivity. In 1890-1892, William James described with his sharpened introspection the flow of thought as a "stream of consciousness" (James, 1892). Twenty years after – and less than three years after his death in 1910 – Psychology was to be defined as the science whose goal was the "prediction and control of behavior" (Watson, 1913). Psychology should not be based on introspection, and be more similar to the study of animal behavior. Thus, when a response follows a stimulus, one must seek the regularities of this stimulus-response coupling. Whether the human (or animal) subject has any awareness of the stimulus, the response or their relation was not relevant. Such "behaviorist" views of human thought naturally led to the "elimination of states of consciousness as proper objects of investigation", as was called for by Watson (Watson, 1913), for most of the 20th century. This view was to be further enforced, even after the demise of behaviorism, by studies that showed that, in fact, human participants are rarely aware of any of the stimulus-response coupling elements (Nisbett and Wilson, 1977).

Yet, how did behaviorist researchers account for problem solving? When someone enters a room with a problem, does not exhibit any obvious behavior in the room, and exits with a solution, a few "thoughts processes" cannot be ignored. In line with the classical equation of thought as inner language (Rousseau, 1755), these "thought processes" were described as covert verbal behavior (Skinner, 1959). Interestingly, the fact that one can easily verbalize the steps of one's reasoning might have comforted the idea that such reasoning was already verbal, and that this covert verbal behavior was just made overt when verbalizing. Moreover, problem solving appearing as an action, speech was more easily conceived as an action too, requiring motor commands, than the active retrieval of visual details. The behaviorist period therefore saw progress in the study of inner speech, such as the measuring of (verbal) "thought processes" by tracking activity of the tongue and speech musculature (Sokolov, 1972), or by hypothesizing that inner speech is in fact external behavior that is progressively internalized (Vygotski, 1933).

b) Empirically navigating the stream of consciousness (1970-2000)

However, thought is not only a little voice in one's head. Influenced by the popular success of the "Transpersonal" and "Humanistic" psychology movements, led by Abraham Maslow in the 1940/60's (Strange, 1978), as well as by the recent research on LSD (Grof, 1972) and the rediscovery of eastern spiritual and psychological traditions (Taylor, 1978), Jerome Singer and his students and collaborators John Antrobus and Kenneth Pope started a research program on human consciousness. Notably, they edited the book *The Stream of Consciousness: Scientific Investigations into the Flow of Human Experience* (Pope and Singer, 1978) compiling work on various "normal" and "altered" states of consciousness: the stream of thought (Klinger, 1978; Pope, 1978), daydreaming (Singer, 1978), dreaming (Starker, 1978), optimal functioning (Csikszentmihalyi, 1978) and even meditation (Taylor, 1978). The goal of Pope and Singer was to give a scientific account of the otherwise "excessively mystical or "gimmicky" characteristics" of consciousness exploration (Singer, 1974, p.215 cited by Strange, 1978), by providing empirical and experimental evidence for William James' insights (James, 1892). This view of human thoughts therefore comes from very different traditions that the studies on inner speech: while "visual imagery", "inner experience", "waking fantasy" and even "no-thought-ness" are indexed in *The Stream of Consciousness* (Pope and Singer, 1978), neither is "inner speech" nor "verbal thoughts"; Vygotski and Sokolov are not even cited.

In their attempt to investigate human experience, Singer and his contemporary colleagues used psychophysics and physiological tools such as Electroencephalography (EEG) and pupillometry. Crucially, they also developed various techniques to measure thought contents, such as "think-aloud paradigms", where participants verbalize all their thoughts (Pope, 1978; Ericsson and Simon, 1980; Fox et al., 2011), or "experience sampling" where participants precisely describe their inner experience at a given moment or throughout a short period (Klinger, 1978; Csikszentmihalyi and Larson, 1987; Klinger and Cox, 1987; Hurlburt and Schwitzgebel, 2007). Used in the laboratory, these techniques helped uncovering that thoughts depend less on the environment when lying or sitting than when standing, and when alone than when in the presence of others (Pope, 1978). It was also shown that daydreaming reduces ocular activity (Singer, 1978). The incredible novelty was that science could now be done outside the laboratory, by sampling people thoughts in whatever context people happened to be. Note that these methods were the exact opposite of behaviorists' experiments that served as a framework for many experiments in cognitive psychology: instead of measuring participants' responses to a task, without asking for any introspection, experience sampling exclusively relied on introspection, and no specific task needed to be performed (Klinger and Cox, 1987). This approach evidenced contexts that determined happiness (Csikszentmihalyi and Hunter, 2003; Killingsworth and Gilbert, 2010), and ultimately provided empirical evidence that inner speech constituted only about 20% of inner experience (Heavey and Hurlburt, 2008).

As a continuation of transpersonal and humanistic psychology, these studies also served psychotherapy: alcoholic cravings, for example, could therefore be understood as dysfunctional fantasies triggered by environmental cues (Cox and Klinger, 1988). This put inter-individual differences at the heart of the field. Meticulous questionnaires were devised aiming at capturing the richness and determinants of thought contents, such as the Individual Differences Questionnaire (Paivio and Harshman, 1983), to study imagery versus verbal processes (Paivio, 1979), or the Imaginal Processes Inventory (Singer and Antrobus, 1966), to study individual differences in thought flow. Findings about inter-individual differences in thought therefore span throughout the last 30 years: we now know, for instance, that compared to younger persons, older adults experience less task-unrelated thoughts (Giambra, 1989); that people with lower working memory scores report more cognitive failures (Kane et al., 2007); that the amount of inner speech of a person negatively predicts her speech rate (Hurlburt et al., 2002); that people reporting more mind-wandering have better delay discounting capabilities (Smallwood et al., 2013), etc.

Finally, note that these various and productive lines of research on the stream of consciousness were not mainstream (Callard et al., 2013). Objective methodologies, inspired by behaviorism, predominated in prestigious cognitive journals. Thus daydreaming studies were published in specialized journals such as *Journal of (Abnormal/Clinical/Consulting) Psychology*, *Journal of Personality Assessment*, *Perceptual and Motor Skills*, making it harder to obtain research grants. Moreover, note that the absence of both controlled stimuli – self-generated thoughts are "inner stimuli" – and controlled responses – introspective reports are fragile because experimenters seemingly cannot control them – may have cast long-lasting doubt on the field, at least from the point of view of traditional neuroscience.

c) The era of the wandering mind (2000-today)

How can we thus explain the boost in mind-wandering research observed in the last decade? This might be due to technical and theoretical improvements, combined with the discovery of the ubiquitous Default Mode Network (Gusnard and Raichle, 2001, 2001; Raichle et al., 2001).

First, the spreading of neuro-imaging techniques such as Positron Emission Tomography (PET, for instance: Shulman et al., 1997), functional Magnetic Resonance Imagery (fMRI, Gusnard et al., 2001), Electro/MagnetoEncephaloGraphy (EEG / MEG, Scheeringa et al., 2008; Brookes et al., 2011), intracerebral EEG (Jerbi et al., 2010), functional Near Infra-Red Spectroscopy (fNIRS, Stevenson et al., 2011; Durantin et al., 2015) and the development of computers with enough power to process the resulting data allowed for a "confirmation" of subjective reports. For example, when two different images are presented to each eye, participants report experiencing only one image at a given moment, but in alternation with the other image, in a phenomenon called "binocular rivalry" (Levelt, 1967). Taking inspiration from a study with primates (Leopold and Logothetis, 1996), an fMRI study (Tong et al., 1998) first showed that presenting faces elicited greater activity in the so-called Fusiform Face Area (FFA), whereas presenting houses elicited greater activity in the so-called Parahippocampal Place Area (PPA). Crucially, they then showed that, under constant presentation of an ambiguous image where one eye saw the face and the other eye saw the house, binocular rivalry was evidenced by both subjective and neural alternations between reports of "face" and greater activity in FFA, and reports of "house" and greater activity in PPA. In sum, neural activity obtained using subjective reports in ambiguous cases matched remarkably well the neural activity of non-ambiguous cases, where the two images truly alternated. A second study (Owen et al., 2006) with locked-in syndrome patients, who appeared to be in coma but remained conscious, further evidenced that complex mental acts, such as directed mental imagery – e.g. imagining playing tennis – could be performed and elicited consistent brain activity. In contrast with skeptical views on introspection (Nisbett and Wilson, 1977), these two studies, among many others, demonstrated that participants' subjective reports can be reliable and thus valuable. In sum, these were technical improvements that allowed checking on subjective reports.

Second, theoretical improvement, notably through the development of theories of perceptual consciousness, paved the way to the study of subjectivity by controlling both stimuli and responses. For example, theoretical proposals, such as the Global Workspace Theory of consciousness of Bernard J. Baars (Baars, 1988), were bench-marked on psychophysical phenomena such as the attentional blink (Raymond et al., 1992), fostering the Global Neuronal Workspace theory of consciousness (Baars, 2002; Dehaene et al., 2006). The attentional blink is a perceptual phenomenon such that, when the delay between two visual stimuli is around 200/300 ms, participants tend to report the first stimulus only, being unable to report the second stimulus. Interestingly, however, when displayed in immediate succession, the two visual stimuli can be reported, as well as when the delay between them is greater than half a second. This phenomenon is called attentional blink because it seems that attention to the first stimulus prevents seeing the second for the duration of a “blink”. However, if one does not attend to the first stimulus, the attentional blink disappears. In behavioral terms, accuracy of any judgment on the second stimulus is close to chance around 200-300 ms. Yet, in cognitive terms, this phenomenon is truly associated with participants’ reports of whether they did see, or did not see, the stimulus. Crucially, at certain latencies, with equal physical stimulation, proportion of seen and not seen stimuli can be roughly equated. These situations are ideal to study consciousness, given that a controlled and constant stimulus elicits controlled accurate or inaccurate responses, that are mapped onto the presence or absence of conscious perception. Contrasting trials where participants claimed to have seen the second stimulus to those were they did not, an EEG study (Sergent et al., 2005) evidenced that unseen trials elicited intact early visual Event Related Potentials (ERP) components, but that later ERP components in these trials diverge from seen trials after 270 ms. Thus, there certainly was some early processing that participants were not aware of, but, differences in later processing were associated with differences in subjective reports. Moreover, source modeling of the EEG data suggested that the difference lay in the recruitment of a Fronto-Parietal Network (FPN) in the seen trials, but not in the unseen trials. Together with other studies contrasting seen with unseen stimuli, the FPN was proposed as a Global Neuronal Workspace (GNW) sub-serving consciousness (Dehaene et al., 2006).

Here, the improvement in the early 2000s was theoretical: beyond a neural implementation – the FPN as a key region for conscious reports – the mechanism by which representations become conscious was stressed (Dehaene and Naccache, 2001). Indeed, the GNW capitalizes on the view that consciousness is a (Cartesian) Theater where representations become reportable (Dehaene and Naccache, 2001; Baars, 2002). Typically, provided that there is enough stimulus strength and attention on the stimulus, a perceptual representation propagates to the GNW in an all or none fashion. This propagation allows for non-perceptual modules, such as language modules, or memory modules to take stock of the representation and report it (Baars, 2002; Cohen and Dennett, 2012). However, when a representation enters the GNW, other candidate representations are momentarily blocked. A similar phenomenon is at play during the attentional blink: a first stimulus enters the GNW and blocks entry in the workspace of second stimulus, for about 300 ms. However, if the first stimulus is not attended, the second stimulus can be processed. In sum, these studies provided a complete framework for perceptual representations to be either conscious, possibly conscious (“preconscious”) or not conscious (subliminal). Indeed, the *mechanisms* of perceptual consciousness were specified: all or none ignition, blocking of other representations ; as well as its plausible candidate *implementation*: the recruitment of long-range neurons of the FPN. Finally, the GNW theory even proposed a *function* for perceptual consciousness: the global broadcasting of representations, allowing memorization, report and planning.

Finally, a last element can account for a regain interest in mind-wandering studies. Concurrent to the development of neuro-imaging and theorizing on consciousness, a set of regions was found to ubiquitously "deactivate" during task completion, compared to rest (Gusnard et al., 2001; Raichle et al., 2001). This network was described as comprising two hubs: the medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC), and of a large part of the medial temporal lobe. It was discussed as a "Default Mode" Network (DMN), because of its activity when participants are in their "default" state: rest in the scanner. Interestingly, from its first formulations, the DMN was said to reflect:

> *… "a continuous "simulation of behaviour", "an inner rehearsal" and "an optimization of cognitive and behavioural serial programs" for the individual's future, which represents another feature of continuous activity in the baseline or resting state."*
>
> Gusnard and Raichle, 2001 p.692

This, perhaps unknowingly, was a clear call for studies on mind-wandering. Importantly, it was published in *Nature Reviews Neuroscience*, and certainly did play a role in the subsequent flourishing of mind-wandering as a more mainstream line of investigation in cognitive neuroscience. In fact, beyond a few alternative interpretations of DMN functional activity, such as reflecting vigilance to peripheral upcoming events (Gilbert et al., 2007), DMN activity was soon related to the subjective experience of mind-wandering, as measured both by the daydream frequency scale of the Imaginal Processes Inventory (Mason et al., 2007), and later by online experience sampling (Christoff et al., 2009; Stawarczyk et al., 2011b; Kucyi et al., 2013) inside the scanner. Since then, the functional as well as anatomic connectivity of the DMN have been better understood (Buckner et al., 2008), as well as the functions of two of its sub-networks in self-relatedness and in the temporal orientation of thought (Andrews-Hanna et al., 2010). Its relation to mind-wandering has also been explicitly discussed (Fox et al., 2015), given that even if DMN activity is consistently activated in mind-wandering, the reverse inference of DMN activity as implying mind-wandering does not hold. Indeed, on the one hand, DMN is also activated in goal-directed tasks such as perspective taking (Dumontheil et al., 2010) and autobiographical planning (Schacter et al., 2012), that are not spontaneous, contrary to mind-wandering. On the other hand, mind-wandering also involves regions outside the DMN, such as the FPN (Mason et al., 2007;

Christoff et al., 2009), as well as the mid-insulae, temporopolar and secondary somatosensory cortices (Fox et al., 2015). Finally, DMN connectivity also correlates with vigilance states where postulating conscious internal mentation is uncertain, as it differs between minimally conscious and unconscious patients (Vanhaudenhuyse et al., 2010).

In sum, at the end of the 20th century, studies on daydreaming and mind-wandering belonged in the specialized fields of clinical and social psychology. Progress in theorizing on perceptual consciousness, as well as the rise of neuro-imaging techniques, permitted the validation of subjective reports and closed the hundred years ban on consciousness in mainstream scientific psychology. At last, the ubiquitous, albeit many faceted DMN (which encompasses in fact more than a seventh of the brain, Yeo et al., 2011) was discovered along with its role regarding self-generated thought and mind-wandering. These three key elements are now combined, and form the basis of contemporary research on spontaneous, self-generated thoughts: mind-wandering is thought to emerge from episodic memories engaging the medial temporal lobe, that are associated with self-relevant, past or future information in the DMN, and buffered in the FPN giving rise to conscious assessment and reporting (Smallwood et al., 2012a; Fox et al., 2015).

We just briefly reviewed the emergence of a cognitive neuroscience of mind-wandering. But, to what extent do mind-wandering studies explain its dynamics and introspective monitoring from a psychological standpoint?

3. *State of the art*

Four main lines of research, each associated with at least one theory, exist in the mind-wandering literature: studies 1) on thoughts contents, 2) on the causes and consequences of mind-wandering, 3) on the phenomenon of perceptual decoupling and 4) on the problem of mind-wandering awareness.

a) Thoughts contents and the Current Concerns theory.

The pioneering work of Eric Klinger aimed at understanding why participants in a given context start thinking about particular things. The Current Concerns theory (Klinger, 1978, 2013) therefore proposed that participants had “current concerns” - goals to which they were committed to, either long-terms goals, such as being a lawyer, or short-term goals such as booking a reservation – and that participants were likely to think about these concerns. Interestingly, a person's current concerns are active at a pre-attentive level to facilitate the processing of cues they are related to: walking by a garment shop, a person whose current concern was to buy jeans would notice the shop more than a person without this concern. In turn, the cues would trigger thoughts about the concern, and thought content is therefore predictable provided the combination of a current concern and a cue. Support for this theory came from a dichotic listening study (Klinger, 1978): two stories were presented in each ear of the participant, and the participants had to continuously indicate with a switch which story he/she was listening to. At critical moments, passages of one story related to the current concerns the participants had described in a previous session, while the other story did not. Results evidenced that participants switched more to the "current concerns" related passages, showing the pre-attentive effect. Moreover, sampling participants' thoughts ten seconds after critical passages revealed that about 20% of the concern-related passages reflected participants thoughts. This work was recently replicated in a simpler, non-dichotic setting (McVay and Kane, 2013).

Although people sometimes think about past concerns, current concerns likely facilitate a "prospective bias" in the orientation of people thoughts: indeed, people think more about the future than about the past (Smallwood et al., 2009b), and consistent with a motivational theory of thought contents, this bias decreases when people's mood is depressed (Smallwood and O'Connor, 2011). This sense of mental travel in mind-wandering is consistent with the role of the DMN and specifically medial temporal lobe in memory (Huijgen and Samson, 2015) and future thinking (Schacter et al., 2012). Also, in line with both the current concerns theory, and the involvement of the DMN in self-related processing and perspective taking (Andrews-Hanna et al., 2010), most mind-wandering thoughts seem to be about the self rather than about other people (Ruby et al., 2013). Finally, mind-wandering is also mostly about positive events (Ruby et al., 2013). Note that most of these characteristics have been replicated in many countries (Canada, United States, United Kingdom, Germany, Belgium, China, Japan) and thus across very different cultures (Song and Wang, 2012).

b) Causes and consequences of MW: the controversial role of executive functions.

The emergence of mind-wandering can be explained by other theories than the somewhat teleological account of the Current Concerns theory, that posits that mind-wandering is for problem solving and agenda monitoring. Indeed, the finding that mind-wandering is associated with cognitive and memory failures (Carriere et al., 2013), and with poor performance on working memory tests (Kane et al., 2007) suggests that mind-wandering arises after executive failures in sustaining task-related attention (McVay and Kane, 2010). However, whether mind-wandering reflects executive failure is still highly debated. Indeed, participants with *greater* executive resources report *more* mind-wandering in easy task (Levinson et al., 2012). Similarly, aging decreases both executive resources and mind-wandering amounts (Giambra, 1989; Jackson and Balota, 2012; McVay et al., 2013). Finally, note that the correlation between mind-wandering and low working memory scores does not lead to any clear causal prediction: if a person mind-wanders while taking the working memory test, she or he will naturally have poor performance (Mrazek et al., 2012a). In fact, an alternative theory even suggests that mind-wandering requires executive resources, as evidenced by lower mind-wandering in hard than in easy tasks (Teasdale et al., 1995; Ruby et al., 2013).

Some evidence can be interpreted as either executive failure or executive recruitment: for example, time spent on task increases mind-wandering (Thomson et al., 2014). This could reflect greater automation of task demands, that would thus free executive resources (Mason et al., 2007), or, in full contradistinction, this could reflect resource exhaustion due to fatigue. Similarly, feelings of anxiety, stress or boredom increase mind-wandering (Kane et al., 2007). This can either be seen as a consequence of executive failures (anxiety and stress also decrease working memory scores) or as a strategic change in one's allocation of executive resources to more important inner thoughts than the task at hand (Baars, 2010). Finally, mind-wandering and ruminations appear to both occupy executive resources and also arise from dysfunctional monitoring of one's mental contents: mind-wandering is greater among depressive patients (Hertel, 1998; Smallwood et al., 2007b) or when negative mood was induced (Smallwood et al., 2009a), and can be relieved by externalizing thoughts in expressive writing (Gortner et al., 2006). The practice of mindfulness (Mrazek et al., 2013), known to improve self-regulation (Brown and Ryan, 2003), or even short mindful breathing exercises (Mrazek et al., 2012b), also decrease mind-wandering.

Obviously, understanding the causes of mind-wandering would help understand what its evolutionary advantage is, if any, provided that we mind-wander from 30% to about half of our waking time (Kane et al., 2007; Killingsworth and Gilbert, 2010). Researchers that followed proposals of the Current Concerns theory found that mind-wandering indeed improved creativity (Baird et al., 2012), problem solving (Ruby et al., 2013), autobiographical planning (Baird et al., 2011), agenda monitoring (Klinger, 2009) and delay discounting (Smallwood et al., 2013). Mind-wandering would also alleviate boredom (McMillan et al., 2013), by offering pleasant fantasies (Mason et al., 2013) and contracting time (Terhune et al., 2014).

However, escaping the here and now also has important costs (Mooneyham and Schooler, 2013): mind-wandering is involved in car accidents (He et al., 2011; Galéra et al., 2012; Berthié et al., 2015), plane crashes (Casner and Schooler, 2014), medical errors (Smallwood et al., 2011b). It predicts poor grades (Smallwood et al., 2007a; Mrazek et al., 2013; Risko et al., 2013; Szpunar et al., 2013) and unhappiness (Killingsworth and Gilbert, 2010), and even cell aging (Epel et al., 2013). Most of these detrimental consequences arise because mind-wandering is associated with a state where attention is decoupled from the task at hand. The following section presents studies about the extent of this decoupling.

c) The perceptual decoupling phenomenon.

We all experience that, as we attend to our stream of thoughts, the meaning of sentences we hear or read is not accessible anymore (Smallwood et al., 2008b; Smallwood, 2011a). Indeed, mind-wandering impairs our ability to detect gibberish sentences, where words would have been scrambled in a syntactically correct way (Schad et al., 2012). In fact, mind-wandering also seems to alter more elementary processes, such as the processing of words meaning, as indexed by inabilities to detect non-existing words (Schad et al., 2012). Such profound decoupling from the environment questions whether only attentional resources are lacking to process external information, or whether there is also a true "perceptual decoupling" (Smallwood et al., 2011a; Smallwood, 2013a), that is impoverished representation of the external world. Supporting low perceptual failures, it was found that early visual and auditory ERP components (P1, N1) amplitudes decreased during mind-wandering (Kam et al., 2011). Moreover, these decrements were not only found on task-related stimuli, but also on distracting (Barron et al., 2011), background oddball (Braboszcz and Delorme, 2011) and irrelevant stimuli (Kam et al., 2011), suggesting that mind-wandering also affects stimuli that are not at the center of attention.

Yet, how perceptual decoupling relates to mind-wandering is still debated: it could be an active inhibition of external inputs in order to avoid the disruption of the inner train of thoughts (Smallwood, 2013a, 2013b), in which case one would expect perceptual decoupling to start before, or co-occur with the subjective experience of task-unrelated thoughts. An alternative hypothesis is that perceptual decoupling results from a passive mechanism, as a by-product of the re-allocation of attention away from the senses and towards memory and self-related processing (Smallwood et al., 2012a; Franklin et al., 2013b).

d) The meta-awareness problem.

If mind-wandering is so detrimental to performance, it is also because mind-wandering episodes are not only deliberate, but also sometimes spontaneous (Shaw and Giambra, 1993; Seli et al., 2014), and even unwanted (Baird et al., 2013a). Mind-wandering thus cast doubts on human introspection, as people often simply lack reflexive awareness, or meta-awareness (Schooler, 2002) of their state of mind-wandering. A paradigmatic example is mindless reading: we sometimes experience mind-wandering without noticing it, and our eyes keep skimming the text mindlessly, only to realize after some time that we did not understand anything because of these thoughts. This subjective surprise at such a discrepancy between our goal and our thoughts was studied in experimental settings by requiring participants to report their mind-wandering episodes spontaneously, by catching them themselves. These self-caught episodes of mind-wandering were assumed to reflect how much one realizes that one was mind-wandering. If all mind-wandering episodes were aware, then random sampling of participants' attentional state outside self-reports should only lead to reports of focused attention: mind-wandering episodes should have been exhausted in self-caught reports. Various experiments show that this is not the case: although instructed to self-catch all mind-wandering episodes, participants still reported mind-wandering in about 20% of the random experimentally triggered external thought-probes (Schooler et al., 2004; Sayette et al., 2009, 2010; Baird et al., 2013a). Such a dissociation is consistent with the notion of meta-awareness (Schooler, 2002; Schooler and Schreiber, 2004; Winkielman and Schooler, 2011): while self-caught episodes of mind-wandering would have reached a form of reflexive awareness, and be re-represented so that the participant could explicitly acknowledge mind-wandering, probe-caught episodes of mind-wandering would precisely have been forced by external means into such a re-representation. This lack of meta-awareness does not mean that the mind-wandering episode was unconscious the same way subliminal stimuli are unconscious: report being the criterion for consciousness (Cohen and Dennett, 2012), people could still *retrospectively* report the presence of mind-wandering. In a sense, they may represent a "pre-conscious" (Dehaene et al., 2006) form of mind-wandering. The meta-awareness hypothesis therefore states that mind-wandering episodes would likely arise because of a failure to re-represent the stream of thoughts, and thus people would be mind-wandering until they eventually notice it (Hasenkamp et al., 2012; Broadway et al., 2015; Fox and Christoff, 2015).

Interestingly, a few studies show that meta-awareness can be manipulated: alcohol intoxication (Sayette et al., 2009) and cigarette craving (Sayette et al., 2010) increase the amount of probe-caught mind-wandering without increasing the amount of self-caught mind-wandering, and thus presumably decrease the capacity to notice a greater amount of mind-wandering. Similarly, the memory of past romantic relations was more intrusive – and also less aware – when participants still experienced feelings ("hot flames") than when they did not experience any feeling anymore ("cold flames", Baird et al., 2013a). Finally, adults with Attention Deficit / Hyperactivity Disorder (ADHD) profiles reported more unaware mind-wandering (Franklin et al., 2014). Overall, this pattern of findings suggests that noticing mind-wandering might be related to executive functions, given that disturbances in these executive functions by alcohol, cigarette craving, ADHD, or intrusive thoughts, decrease awareness of mind-wandering.

In sum, the mind-wandering literature revolves around four main theories. Three of them account of *why* the mind would wander (Smallwood, 2013a): because of the activation of current concerns (Klinger, 1978, 2013), because of executive failures (Kane et al., 2007; McVay and Kane, 2010), or because of meta-awareness failures (Schooler, 2002; Winkielman and Schooler, 2011). The fourth theory accounts for *how* the mind wanders: by eliciting a state of perceptual decoupling, presumably so as to insulate the stream of thought from external disruptions (Smallwood et al., 2012a; Smallwood, 2013b). This contemporary synthesis provides a good basis for a mechanistic account of mind-wandering and more broadly thought generation, maintenance and introspection. The many central questions that remain to be answered are discussed in the next section.

4. Dynamics and introspective monitoring of mind-wandering

a) Predicting thoughts spontaneous occurrence: the dynamics of subjectivity

How does mind-wandering start? Answering this question is critical if one wishes to predict mind-wandering occurrence, and more generally how thoughts follow each other. As reviewed above, the Current Concern theory (Klinger, 1978, 2013) inspired attempts at cuing mind-wandering content by presenting stimuli that were related to participants current concerns (Klinger, 1978; McVay and Kane, 2013). Other cues, such as visual illusion of going forward or backward have been used to change the temporal orientation of mind-wandering (Miles et al., 2010). Although significant, the modest impact of these methods confirms how unpredictable mind-wandering episodes are. A complementary approach could explore the existence of regular patterns: slow fluctuations could lie behind seemingly unpredictable phenomenon.

A similar approach was found in studies of vigilance (Richard, 1980). Vigilance, in this sense is the ability to attend for long periods of time to tedious tasks with few critical stimuli. Operational studies and applied psychology during the World War II period certainly stressed the need to understand how agents perform in such tasks, where simple actions must be taken quickly in a mostly dim and monotonous environment: controlling gauges, radars, video recordings, etc. In a seminal paper, participants were required to detect rare events – the hand of a clock moving in a double, instead of a single increment – in a two hours long experiment (Mackworth, 1948; Richard, 1980), and significant decrements in performance were evidenced after the first 30 minutes. Further findings across the day and through different sessions, also evidenced fluctuations in performance with a 60-120 minutes period (Okawa et al., 1984), correlated with fluctuations of body temperature (Ramautar et al., 2013). Daytime fluctuations in performance have also been described among children in educational settings, with similar peaks of performance before noon and then in the late afternoon (Testu, 1994). Interestingly, mind-wandering research has used similar vigilance tasks with simple detection of rare events (Cheyne et al., 2009; Smallwood et al., 2011a). In fact, circadian fluctuations were also found in mind-wandering (Giambra et al., 1989), with a peak of spontaneous mind-wandering in the late morning and early afternoon, compared to early morning and evening.

However, mind-wandering also appears to follow smaller dynamics, at the order of a few minutes or even few seconds. For example, a resting state study evidenced that attention to the environment and to one's thoughts slowly alternate at around .1 - .01 Hz (10-100 s) (Vanhaudenhuyse et al., 2011), and correlate with the fluctuations of DMN activity at the same pace. This suggests that tens of seconds should be an appropriate timescale for subjective unfolding. This shall be the timescale that we will investigate in the experiments where we attempt to describe the rhythms of mind-wandering.

b) Understanding introspection as a mechanism

How is mind-wandering introspected? The debate over the notion of meta-awareness clearly shows that we lack, and are in need of, a clear functional account of how participants reports their internal states of attention, be they focused or mind-wandering. The main problem of introspection is that it has been used both as a *method*, and as an *object*. As a method to build a psychological science, introspection was responsible for the downfall of studies on subjectivity, and was the unredeemed victim of the sacrificial rituals at the hands of the behaviorists. Indeed, studies on the limits of introspection – as an object – retrospectively justified this attitude: most psychological processes occur outside awareness (Nisbett and Wilson, 1977; Baumeister and Masicampo, 2010), therefore how could one build psychology based on introspection only? The same thing seems to happen in mind-wandering studies, where the limits of introspection are evidenced by a discrepancy between spontaneous and externally-triggered reports of mind-wandering (Schooler et al., 2004), while at the same time retrospective reports ask complex questions about detailed features of thoughts, such as... one's awareness of mind-wandering (Christoff et al., 2009)! Understanding introspection as a mechanism with a domain of application therefore constitute a first step towards being able to use it properly as a method. Two lines of research in the perceptual domain exemplify similar ambitions.

First, the Signal Detection Theory (SDT, Green and Swets, 1966a) framework has recently been applied to second order – meta-cognitive – behavior: while first order SDT defines false alarms as "detection" in the absence of the signal (Green and Swets, 1966a), second order SDT defines false alarms as a "high confidence judgment" in the absence of correct response (see for instance Fleming et al., 2010). Adapting the SDT framework to study meta-cognition as an object therefore allowed to study over- or under-confidence biases and meta-cognitive accuracy independently.

Second, studies on time estimation uncovered both the rich (multidimensional) content but limited capacity of introspection. Using a task where a visual discrimination task followed an auditory discrimination task with varying delays – from 0 (simultaneous presentation) to 1 second – two studies (Corallo et al., 2008; Marti et al., 2010) evidenced the classical Psychological Refractory Period (PRP, Pashler, 1994): with inter-tasks delay below 200ms, delays were inversely proportional to responses times: as the two task were closer to each other, response times on the second task were slower. This finding is consistent with the view that decisions engage a strictly serial mechanism and thus require an incompressible time. This bottleneck effect being reminiscent of the attentional blink, participants subjective experience was further explored. Notably, how accurate were participants' estimation of the "free time", the delay above 200ms that allows few milliseconds to separate the two decisions, and of the "slack time", the delay under 200ms, when the second decision could (but does not) start before the first is over? The richness of introspection was evidenced by the correlation between increasing delay above 200ms to 1000ms and subjective estimation. Yet, the limits of introspection were that, under 200ms, time estimations were constant. Crucially, this limit reveals introspective mechanisms: the estimation of slack time was constant around 0, meaning that below a 200ms delay, the second task subjectively seemed to start immediately after finishing the first task. These results are predicted by a Global Workspace Theory: the successful propagation of conscious representations would block other preconscious representations for about 200ms / 300ms, as in the attentional blink. Thus, such studies on the limits of introspection in fact provide a valid account of the mechanisms of perceptual consciousness, as well as an account of the dynamics of subjectivity.

Similarly, the slower dynamics of mind-wandering may also be linked to its introspection. In fact, mind-wandering and daydreams share the same problem nocturnal dreams once had: what if, instead of being truly generated by current concerns, and then explored, dreams were rather a second order reconstruction to give meaning to more or less random neural activation (Hobson and McCarley, 1977) [1]? Similarly, daydreams could be generated by current concerns, and be explored by the mind's eye between its beginning and end. But an alternative hypothesis would be that the subjective experience of mind-wandering is *constructed* at the very moment the participant assesses it. In such a case, when would the episode have started? On the one hand, the median estimation of the duration of their thoughts given by participants is around 5 seconds (Klinger, 1978). On the other hand, indirect markers of mind-wandering are evidenced by contrasting periods before on- and off-task reports. Yet, the length of these periods varies between studies: the last 3 seconds before reports (Hasenkamp et al., 2012), the last 10 seconds (Christoff et al., 2009; Braboszcz and Delorme, 2011), etc. Furthermore, eye movements during reading predict overlooking of a nonsense word about 5 seconds before the word (Schad et al., 2012), and activity in the Alpha band predicts missing targets about 20s before target presentation (O'Connell et al., 2009). Does this mean that mind-wandering is experienced during 3, 5, 10 or even 20s before the probe? These various findings and methodologies stress that the question of mind-wandering objective duration remains unknown, as well as the extent to which participants, when asked to report, take into account past information about attentional states. The present studies therefore aimed at studying the question of the dynamics of mind-wandering (Chapter 2, 3), and suggest that this dynamics is intrinsically related to the mechanisms leading participants to report on their subjective states (Chapter 3-6).

---

1 "According to this view, we are not so much scanning dream imagery with our (...) eye movements as we are synthesizing the visual imagery appropriate to them." (Hobson and McCarley, 1977 p.1338)

c) Rationale and overview of the studies

The studies that will be presented in the following chapters aimed at bridging the gap between the hour-long dynamics of vigilance studies and the faster-than-second dynamics of perceptual consciousness. We viewed mind-wandering as the best available paradigm to study consciousness and thought processes at the tens of seconds timescale. However, the study of mind-wandering runs into a few difficulties. First, studying self-generated activity allows for less control on the (inner) stimulus compared to perceptual activity. Second, compared to memory or perspective taking tasks, that also involve self-generated activity, mind-wandering is a spontaneous phenomenon whose occurrence seems unpredictable. Finally, understanding of the subjective aspect of mind-wandering is threatened by its dubious introspective reports. We propose to overcome these problems by 1) capitalizing on perceptual decoupling to understand and predict how participants report mind-wandering, and 2) studying the factors that allow for better awareness of mind-wandering.

First, we studied the macro-dynamics of mind-wandering throughout a simple go/no-go task (Chapter 2). We found that the variability of response times (RT) predicted both spontaneous (self-caught) and externally-triggered (probe-caught) reports of mind-wandering, compared to on-task reports. This difference inspired a Hidden Markov model where RT of each trial belonged to either an on-task RT distribution, or to a more variable off-task RT distribution. Interestingly, the model provided estimates of both the probability to start mind-wandering when on-task ("on-task inertia", 20s on average), and the probability to stop mind-wandering and switch back on-task ("off-task inertia, 10s on average).

Similar fluctuations around 30-s between on- and off-task thoughts were also suggested using a different approach that aimed at studying the first moments of mind-wandering (Chapter 3). We asked participants to perform a delayed match-to-sample task, so that we could study when and under which conditions aware and unaware mind-wandering occurred from a reference moment where we controlled that participants were on-task. We found that the likelihood to report mind-wandering peaked after 18 seconds, and then decreased. Yet, this pattern only occurred for aware mind-wandering: the probability to report unaware mind-wandering was comparatively constant. Finally, auditory noise affected the dynamics of aware, but not unaware mind-wandering. In sum, this second study evidenced that the typical dynamics of mind-wandering, and presumably of DMN activation, mostly reflected aware mind-wandering, sensitive to executive resources depletion.

The role of executive resources in mind-wandering was further explored with Attention Deficit / Hyperactivity Disorder (ADHD) patients (Chapter 4). Notably, both a study with children and with adults evidenced that mind-blanking, the absence of mental content, was a marker of ADHD compared to control groups. Ironically, if any ADHD subject reported more mind-wandering than control groups, it was the group treated with methylphenidate *against* ADHD symptoms. High levels of mind-blanking could be due to deteriorated on- and off-task thoughts, and/or to inabilities to access one's thoughts. The two last chapters sought to better understand how people become aware of their mind-wandering.

Taking inspiration from the salience of language and its role in executive function and self-awareness, inner speech was hypothesized to facilitate awareness of mind-wandering (Chapter 5). A first study evidenced that articulatory suppression decreased the amount of self-caught episodes of mind-wandering, which were more verbal than comparatively less aware probe-caught episodes. Using a go / no-go task, a second study confirmed that induction of verbal representations through higher words:picture ratio in the stimulus increased awareness of mind-wandering. Finally, an ecological study based on a smart-phone application that we designed (*Daydreaming*, for Android phones), evidence that inner speech vividness significantly predicted mind-wandering in natural contexts. Visual and auditory vividness did not have the same link to awareness.

A final series of studies provided a comprehensive framework to account for the introspective mechanisms at play in mind-wandering reports, and for how they may involve the dynamics of mind-wandering (Chapter 6). We hypothesized that detecting one's own mind-wandering is a decision process, with an internal noisy signal compared to an adjustable criterion. Using a continuous orientation tracking task, to obtain fine-grained performance at the hundredth second time scale, we showed that we could induce participants towards reporting more or less mind-wandering, and that these corresponding liberal or conservative attitudes were reflected in the amount of mind-wandering prior to the report. Indeed, compared to liberal reports, conservative reports of mind-wandering were preceded by greater amounts of indirect markers of mind-wandering. What were these markers? Interestingly, the amount of sensory processing, as well as the processing speed were affected. Moreover, we found evidence of integration of information up to 30 seconds prior to the reports, and the more conservative, the greater this information integration. In sum, this series of studies supports the view that introspective monitoring of mind-wandering is a decision mechanism that takes the dynamics of thought into account.

CHAPTER 2: MIND-WANDERING AT THE FINGERTIPS: AUTOMATIC PARSING OF SUBJECTIVE STATES BASED ON RESPONSE TIME VARIABILITY

This chapter is based on a research article published in *Frontiers in Psychology* in 2013 (Bastian and Sackur, 2013): Bastian M and Sackur J (2013) Mind wandering at the fingertips: automatic parsing of subjective states based on response time variability. *Front. Psychol*. **4**:573. doi: 10.3389/fpsyg.2013.00573

In this chapter, we showed that mind-wandering, regardless of being measured by probes or spontaneous reports, was associated in the Sustained Attention to Response Task (SART) with greater response times variability (RTCV). We thus sought to infer participants' mental states on the basis of this variability of response times. We did so by showing that not only was the absolute value of RTCV important, but also the distance of the report to a RTCV peak or trough. We also designed a Hidden Markov Model that could assign response times in each trial to either a distribution of response times elicited during on-task thought or to – a more variable – distribution of response times elicited during off-task thought. This model resulted in estimation of both on- and off-task thoughts durations, as we could compute, with a historical perspective, whether for each trial, the next trial was likely to be performed in the same mental state or not.

Abstract. *Research from the last decade has successfully used two kinds of thought reports in order to probe whether the mind is wandering: random thought-probes and spontaneous reports. However, none of these two methods allows any assessment of the subjective state of the participant between two reports. In this paper, we present a step by step elaboration and testing of a continuous index, based on response time variability within Sustained Attention to Response Tasks (N=106, for a total of 10 conditions). We first show that increased response time variability predicts mind-wandering. We then compute a continuous index of response time variability throughout full experiments and show that the temporal position of a probe relative to the nearest local peak of the continuous index is predictive of mind-wandering. This suggests that our index carries information about the subjective state of the subject even when he or she is not probed, and opens the way for on-line tracking of mind-wandering. Finally we proceed a step further and infer the internal attentional states on the basis of the variability of response times. To this end we use the Hidden Markov Model framework, which allows us to estimate the durations of on-task and off-task episodes.*

Keywords: *mind wandering, subjective report, response times variability, Hidden Markov Models, time-course analysis*

Introduction

Mind-wandering refers to the occurrence of task-unrelated and stimulus-independent thoughts (Stawarczyk et al., 2011a). In daily life, this spontaneous tendency of the mind to drift away from the here-and-now occurs about 30% to 50% of the time, with surprisingly few differences regarding the task at hand (Killingsworth and Gilbert, 2010).

The literature has successfully identified general factors that modulate the amount of mind-wandering, be they context-dependent or more persistent. However, the overall amount of mind-wandering may depend on both the frequency and the duration of episodes (Smallwood, 2013a). For example, mindfulness training might lead to *shorter* episodes of mind-wandering through enhanced awareness of their occurrence (Schooler et al., 2011), whereas global time spent mind-wandering might be reduced in a demanding task due to a reduction of the *frequency* of the episodes.

To our knowledge no extant methodology enables us to disentangle frequency from duration of mind-wandering episodes. Up to now, mind-wandering has been mainly accessed through discrete thought sampling: participants are randomly probed about their subjective states. This method only assesses mind-wandering at the moment of the probe, but that tells us nothing about the time-course of the alternating states.

As an attempt to overcome this issue, participants could be asked to estimate the time spent mind-wandering. Time estimation of conscious thoughts have already been reported (Klinger, 1978; Klinger and Cox, 1987), but lack secondary measures that would validate their reliability. This is critical, as one may be wary of any retrospective estimation of the time spent mind-wandering on account of the dangers of complex introspection (Nisbett and Wilson, 1977; Johansson et al., 2006), and on account of the conclusive evidence that introspection is only faithful when retrospection – looking back to what has been done – and generalization – describing the mechanism instead of the occurrence – are kept to a minimum (Ericsson and Simon, 1980). Moreover, little is known about time estimation of mental events (but see (Miller et al., 2010). Furthermore, among mental events, mind-wandering is most often characterized by a lack of introspective awareness: participants often find out they have been mind-wandering for some time without any previous acknowledgment of it (Schooler et al., 2011). It may thus be difficult for participants to estimate the duration of their mind-wanderings when precisely they do not notice that they were mind-wandering.

Similarly, we have no means of assessing participant's subjective states after a thought-probe. It has been suggested that spontaneous episodes of mind-wandering might cease due to the interruption by a probe (Schooler et al., 2011), but there is in fact little evidence to this effect. It is even conceivable that the episode might start again right after the probe – to "terminate the thought". In fact, reactive mind-wandering (mind-wandering about the fact that one has been caught mind-wandering), has also been suggested (Cheyne et al., 2009). Hence, after a probe, participants could either continue their thought, restart their thought, have an other thought, or get back to focus. There is just no method that would help disentangling the different options.

Spontaneous "self-caught" reports of mind-wandering may constitute an alternative to random thought sampling (Smallwood and Schooler, 2006). In this method, participant are requested to spontaneously report episodes of mind-wandering as soon as they notice them. Unlike random thought probes, this method allows continuous tracking of mind-wandering from the subject's perspective. However this tracking crucially depends on awareness. Further, it can even be argued that monitoring one's own mind-wandering is a task, and that as such, it is fallible, precisely because it is liable to mind-wandering. Finally participants may set higher thresholds to spontaneously stop and report than to respond "yes, I was mind-wandering" if probed (see Chapter 5). Hence, the absence of spontaneous report of mind-wandering is not sufficient to claim that the participant is not mind-wandering: she might not judge her off-task experience salient enough, she might not be aware of it, or she might have forgotten to make the report. Therefore, even the self-catching procedure does not ensures a fully continuous assessment of the wandering mind.

To summarize, there is currently a deep methodological limit in the assessment of mind-wandering: participants only tell us that they are mind-wandering when we ask them to do so, or when they are themselves aware of doing so. Therefore, they report mind-wandering at discrete time points that do not allow continuous tracking of their subjective state as they are experiencing it.

A crucial step to overcome this methodological issue may rely on the elaboration of a continuous index that would covertly track mind-wandering. Behavioral (response time variability (Cheyne et al., 2009; Seli et al., 2013), increased error rate (McVay and Kane, 2012), decreased comprehension (Smallwood et al., 2008b)), electro-physiological (increased heart rate and galvanic skin response (Smallwood et al., 2007b), pupil dilation (Smallwood et al., 2011a)) and neural variables (increased activity in the default mode and executive networks (Christoff et al., 2009), increased energy in theta and delta bands and decreased energy in the alpha and beta bands (Braboszcz and Delorme, 2011), decreased amplitude of sensory-triggered ERP (Kam et al., 2011) have been suggested to be such indicators of mind-wandering. However, crucially, all of these studies relied on contrasts between off-task and on-task periods, time-locked to discrete probes. Studies using random thought-probes (Christoff et al., 2009; Seli et al., 2013) opposed the few seconds preceding off-task reports to the few seconds preceding on-task reports. As for studies using spontaneous reports (Braboszcz and Delorme, 2011; Hasenkamp et al., 2012), they opposed seconds preceding and seconds following the spontaneous report, with the assumption that participants would be able to refocus immediately after the report.

While this approach seems a necessary step in the elaboration of an index of mind-wandering, we suggest that a global analysis taking into account the full length of the experiment is now critical. But how can we extrapolate subjective states away from discrete moments when subjects report them? Here, we propose the following strategy: first, we design a candidate index of mind wandering: this index should both correlate with subjective states when these are available, and it should be based on objective measures that are available even when participants do not report on their subjective states. Next, we compute the index at every time-point in the experiment and identify regular patterns (namely peaks and troughs) in its time-course. We then test whether the temporal position of reports relative to these patterns is predictive of the content of mind-wandering. We take the finding that temporal proximity to peaks of the index is predictive of mind-wandering, *above and beyond its absolute value*, as an indication that the index carries information about the subjective state of the participant throughout the entire duration of the experiment.

In this paper, we applied this strategy to a re-analysis of data of three experiments (N = 106, see Chapter 5) based on the Sustained Attention to Response Task (Robertson et al., 1997).

So as to theoretically validate the analyses, we go one step further and propose a model of the fluctuations of mind-wandering in our data. We conceptualize our participants experience during the experiment as a Markov chain of two attentional states: on-task and mind-wandering. We show that, based on the assumption that variability of response times is heightened in the mind-wandering state, we can parse the full time series of response times and reveal episodes of mind-wandering. We show that this latent classification is both internally consistent and correlates with participants subjective reports.

Methods

Data & Designs

All three experiments (N = 106) experiments were based on the Sustained Attention to Response Task (SART), a go/no-go paradigm with rare (< 12%) no-go trials. A digit between 0 and 9 was presented for 500ms every 2000ms on a computer screen and participants were required to press the space bar as fast and accurately as possible for each digit, but to withhold their response when the number was "3".

Experiments 1 (N = 25, see Chapter 5) and 2 (N = 34) had a within-participants design (respectively 3 conditions – SART single task, SART with articulatory suppression, SART with foot tapping – and 4 conditions – a standard visual SART with reversed speech or white noise and an auditory SART where numbers were displayed through earphones with static or moving random dots on screen). Experiment 3 had a between-participants design: a stereotype threat group (N = 15) a no-threat group (N = 17), and a public speaking threat group (N = 15).

All experiments assessed mind-wandering using random thought-probes. Moreover, Experiment 1 and the second part of Experiment 3 also required spontaneous reports of mind-wandering as soon as participants were realizing that were mind-wandering.

Contrastive Approach

Data Trimming

We focused on (random) reports of on-task thoughts (Nobs = 1302), and on random (Nobs = 902) and spontaneous (Nobs = 564) reports of mind-wandering. In two of the three experiments, participants could report that they were experiencing distraction or that they had task-related interferences, but for the present analysis, these reports were discarded.

Our analysis was conducted on the eight trials preceding on-task and off-task thought-reports. Thought-reports were discarded if these eight trials were not all correct go trials, for example if they contained a no-go trial or an omission (incorrect go trial). Thought-reports were also discarded if the eight trials included the first or the second trial of a block, or were interspersed with or immediately preceded by another thought-report (notably when participants where spontaneously reporting mind-wandering many times in a row). Indeed the trials immediately following thought-reports were significantly slower (640 ms, SD = 189) than those immediately preceding thought-reports (500ms, SD = 174, $F(1, 105) = 241$, $p < .001$) or in second position after them (490ms, SD = 170, $F(1, 105) = 390$, $p < .001$), making them unsuitable for an analysis based on response times variability.

A number of 562 on-task thoughts, 384 random reports of mind-wandering and 73 spontaneous reports of mind-wandering survived data trimming.

Results & Discussion

All data was analyzed using R (R Core Team, 2014) with the lme4 (Bates et al., 2014) package for mixed models analyses. All regressions are mixed models with participants, conditions (always 10 conditions), and experiments (always 3 experiments) as nested random factors, and we present *p*-values that are considered significant at the $\alpha = 0.05$ level.

Contrasting the trials preceding thought-reports. First, based on previous evidence that, in the SART, response time variability is higher in trials before no-go errors than in trials before successful withholding of the response (Cheyne et al., 2009), we wanted to assess whether response time variability was similarly higher preceding mind-wandering reports compared to on-task reports. We computed the Response Time Coefficient of Variability (RTCV: standard deviation / mean) of the eight trials preceding each probes. RTCV was higher in the eight trials preceding mind-wandering reports (0.204, SD = 0.108) than in the trials preceding on-task reports (0.171, SD = 0.082). We tested this difference in a logistic regression with RTCV as predictor (Nobs = 1019, Nsubj = 106, Ncond = 10, Nexpe = 3). We found that increasing RTCV significantly predicted reports of mind-wandering ($\beta = 2.65$, SE = 0.63, $z = 4.20$, $p < .001$). More precise contrasts between on-task reports and random reports of mind-wandering (Nobs = 946, Nsubj = 106) and between on-task reports and spontaneous reports of mind-wandering (Nobs = 635, Nsubj = 103) showed that RTCV increased both for randomly probed mind-wandering reports and spontaneous reports of mind-wandering (respectively $\beta = 2.60$, SE = 0.68, $z = 3.82$, $p < .001$ and $\beta = 3.39$, SE = 1.07, $z = 3.16$, $p < .01$). Moreover, the contrast between random and spontaneous reports of mind-wandering (Nobs = 457, Nsubj = 95) was not significantly predicted by the RTCV of the eight preceding trials ($p > .9$). ***Table 1*** shows that these effects already exist for the four trials preceding the reports and are robust regardless of whether we look at the 5, 6 or 7 trials preceding thought-reports.

Second, previous literature showed that specific patterns of response times could predict errors and/or mind wandering reports (Smallwood et al., 2008a; Smallwood, 2011b; McVay and Kane, 2012). We thus tested whether the increased variability we found before mind wandering could be accounted for by either linear or quadratic trends. To do so, we normalized response times by condition and by participant using z-scores. Linear trends were computed as the mean of the first differences of the eight trials before a probe (mean of (Rt_n - RT_{n-1}) where 8 < n < 2) and quadratic trends were computed as the mean of the second differences (mean of ((RT_n – RT_{n-1}) - (RT_{n-1} - RT_{n-2})) where 8 < n < 3). In a logistic regression with both the first and second differences as predictors, we found that the second difference was not a significant predictor (p > .6), but that the first difference marginally predicted mind-wandering reports (β = 0.62, SE = 0.33, z = 1.89, p = .059), to the effect that participants tended to slow down before a report of mind wandering.

If anything, this tendency goes against the literature that has shown a linear decrease in response times preceding mind-wandering episodes (Smallwood et al., 2008a). However, these previous results were obtained with random thought-probes, and not with a conjunction of random and spontaneous reports. To further evaluate this surprising tendency, we separately contrasted random mind-wandering reports with on-task reports in a logistic regression with the first difference as predictor, and found no significant effect (p > .5). As opposed to that, when we separately contrasted on-task reports and *spontaneous* reports of mind-wandering, we found that the first difference was highly predictive of mind-wandering (β = 2.49, SE = 0.66, z = 3.76, p < .001): participants slowed down before a spontaneous report of mind-wandering. To test whether this deceleration was specific to imminent spontaneous report, we also contrasted spontaneous with random reports of mind-wandering in a logistic regression with the first difference as predictor. We found indeed that a linear deceleration was highly predictive of spontaneous compared to random reports of mind-wandering (β = 1.75, SE = 0.68, z = 2.58, p < .01). ***Table 1*** shows the robustness of this analysis from the 4 trials preceding thoughts-reports.

Thus, a linear decrease of response times seems specific to impending spontaneous reports of mind wandering. Interestingly, this linear trend is partly dissociated from the general variability of response times as captured by the RTCV. Indeed, in a logistic regression with both RTCV and first difference as predictors, and on-task vs. spontaneous report as outcomes, we found both main effects of linear deceleration (β = 2.22, SE = 0.62, z = 3.55, p < .001) and of the RTCV (β = 3.29, SE = 1.12, z = 2.93, p < .01). The increase in RTCV preceding spontaneous reports is therefore not totally captured by the linear deceleration.

To summarize, we first found that high response time variability in the eight trials preceding a thought report was predictive of mind-wandering compared to on-task thought. This phenomenon was observed regardless of the method (random or spontaneous reports) used to assess mind-wandering. Second, we found that the eight trials preceding spontaneous reports of mind-wandering presented a specific pattern of linear deceleration compared to thought-reports collected via random thought-probes, regardless of their content (on-task or mind-wandering). Hence, although the linear slowing down of response times may be related to consciousness of an episode of mind-wandering, it does not appear to be a ubiquitous index of mind-wandering. On the contrary, RTCV predicted mind-wandering regardless of the method used to assess it. Therefore, RTCV seems a suitable candidate for a continuous index of mind-wandering.

Table 1 | Contrasting the 4–8 trials preceding mind wandering and on-task reports.

	4	5	6	7	8
On vs. Off Nobs = (on/off)	**2017 (1082/935)**	**1761 (946/815)**	**1494 (813/681)**	**1247 (692/555)**	**1019 (562/457)**
RTCV	1.44 (3.85)***	1.05 (2.73)**	1.85 (3.79)***	1.91 (3.81)***	2.65 (4.20)***
Linear trend	0.21 (1.90)	0.05 (0.32)	0.38 (1.88)	0.72 (2.80)**	0.62 (1.89)
Quadr. trend	−0.04 (− 0.80)	0.04 (0.37)	−0.13 (− 0.98)	−0.08 (− 0.44)	0.10 (0.41)
On vs. Random Off	**1815 (1082/733)**	**1594 (946/648)**	**1362 (813/549)**	**1146 (692/454)**	**946 (562/384)**
RTCV	1.22 (3.12)**	0.94 (2.43)*	1.72 (3.40)***	1.81 (3.47)***	2.60 (3.82)***
Linear trend	−0.01 (− 0.04)	−0.17 (− 1.08)	0.07 (0.30)	0.29 (1.02)	0.24 (0.66)
On vs. Spont. Off	**1284 (1082/202)**	**1113 (946/167)**	**945 (813/132)**	**793 (692/101)**	**635 (562/73)**
RTCV	2.01 (3.62)***	1.10 (1.93)	1.74 (2.30)*	2.12 (2.93)**	3.39 (3.16)**
Linear trend	1.01 (4.86)***	0.98 (3.57)***	1.73 (4.32)***	3.07 (5.35)***	2.49 (3.76)***
Rand. Off vs. Spont. Off	**935 (733/202)**	**815 (648/167)**	**681 (549/132)**	**555 (454/101)**	**457 (384/73)**
RTCV	0.82 (1.41)	0.17 (0.27)	0.40 (0.58)	0.08 (0.10)	0.09 (0.09)
Linear trend	0.93 (4.27)***	1.07 (3.67)***	1.42 (3.41)***	1.71 (3.62)***	1.75 (2.58)**

$*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

Contrasting the trials preceding and following thought-reports. Next, we wanted to assess the potential effect of interruptions (spontaneous reports of mind wandering or random external probes) on the RTCV of immediately following trials. As the very first trial after an interruption is significantly slower than the other trials (see § "Data Trimming"), we excluded it and computed the RTCV on the second to fifth trial after an interruption. In order to avoid a null effect exclusively due to excessive data-trimming, we selected reports preceded by four or followed by five correct no-go trials, that were not interspersed with or preceded by an other thought-report nor included the first two trials of a block. After trimming, 2508 thought reports were included, 1286 (on-task: 746, off-task: 540) of which had both their 4 preceding trials and their 5 following trials as correct go trials. We then ran a logistic regression contrasting mind-wandering and on-task reports, with RTCV and the position of the trials (before vs after) as predictors. We added the thought-report identity as random variable to the other random variables (participant, condition and experiment) since some differences are paired. We found a main effect of RTCV, indicating that higher RTCV was predictive of mind-wandering ($\beta = 3.85$, SE = 1.08, $z = 3.55$, $p < .001$), no main effect of position (before / after, $p > .2$), and crucially no interaction ($p > .8$, ***Figure 1***). This shows that trials *after* a report of mind-wandering are still more variable than trials after an on-task report, which may be indicative that the internal state of participants is not drastically modified by the interruption. Of course we cannot conclude from this null result that participants do not refocus after a report of mind-wandering, as we do not have secondary assessment of subjective states after each probe. Perhaps surprisingly however, this null result indicates that, in our tasks, no-go trials and probes are unobtrusive, so that variability of response times can be used as a *continuous* index of mind-wandering.

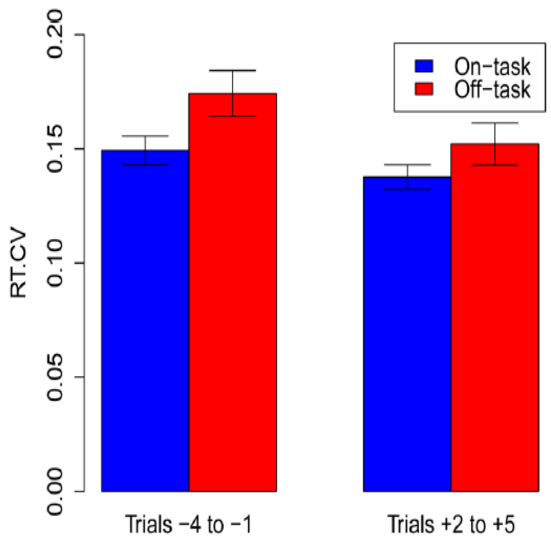


Figure 1: RTCV (Response time coefficient of variability) as a function of whether participants are on-task or mind-wandering ("off-task"), for both the trials preceding and following a report. *Error bars are standard errors of the mean.*

Global Analysis

Methods, results and discussion

Now, we set out to use the RTCV as a continuous index of variability in participants response times. To do so, we removed the first two trials of each experimental block and the first trial after an interruption (random probe or spontaneous report) from the series of correct go responses. On this series, we computed the RTCV within running windows of eight trials, time-stamped to occurrence of the last trial in the window. We then smoothed this index using locally weighted polynomials (LOESS, Cleveland, 1979), to allow interpolations at the moment of reports[2], yielding a Continuous Variability Index (CVI) that we shall study hereafter. We illustrate the time course of the CVI on ***Figure 2***, for an arbitrary participant.

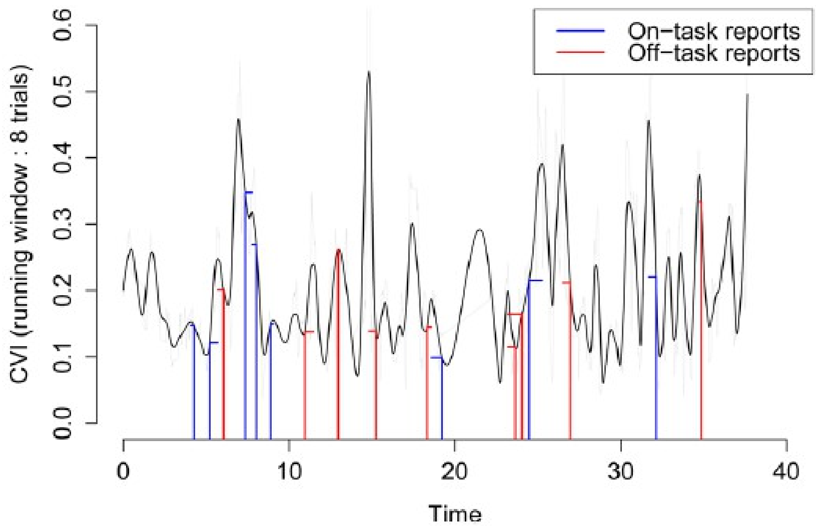


Figure 2: Distribution of the Continuous Variability Index (CVI) across the experimental session of an arbitrary participant (time in minutes). *Vertical lines represent the CVI value (in RTCV units) at the moment of the report, horizontal lines represent temporal distance from the report to the closest peak in the CVI. We predict that On-task reports (blue) have a lower CVI (shorter vertical lines), and a higher temporal distance to their closest peak (longer horizontal lines) than Off-task reports (red).*

2 To ensure robustness of the results, we tested a wide range of smoothing parameters. The results presented bellow use a smoothing kernel of 1 minute 30 seconds, but the pattern of results is identical across a wide range of kernels.

First, we checked whether the interpolated values of the CVI at the moment of the probes could predict their content. Note that this analysis does not strictly replicate the contrastive analyses presented above, as the dataset here is not trimmed. Notably, running windows on which the computation of the index is done can span across correct no-go trials, incorrect go trials (omissions) and interruptions. We then ran a logistic regression with the content of the report as outcome (on-task: 1302, mind-wandering: 1466) with the CVI at the moment of the report as predictor (Nsuj = 106). We found that CVI significantly predicted the content of the report, with higher values being predictive of mind-wandering (β = 2.30, SE = 0.42, z = 5.55, p < .001).

This result extends the contrastive approach used so far, but does not modify its logic. Now we reasoned that if the CVI does reflect the time-course of subjective states, its critical moments, namely its local extrema (troughs and peaks), might correspond to a different probabilities of being in a mind-wandering state. More precisely, we predicted that local peaks of CVI might correspond to increased likelihood of an occurrence of a mind-wandering episodes. Hence, the temporally closer to peaks, the more likely to report mind-wandering. To test this hypothesis, we measured the temporal distance of thought-reports to the closest peak in the CVI. We ran a logistic regression with the content of the report as outcome and temporal distance as predictor. We found that temporal distance significantly predicted the content of the report, with lower values (closer to peaks) being predictive of mind-wandering (β = -0.43, SE = 0.17, z = -2.61, p < .01).

However, on average, by construction, local peaks have higher CVI values than troughs. Thus the effect of temporal distance just presented may be simply an obfuscated replication of the effect of the CVI *value*. To control for that, we ran a logistic regression on the content of the report with the interaction between CVI at the time of the probe and the temporal distance to the closest peak as predictor. We crucially found that this interaction was negative and highly significant (β = 3.37, SE = 0.54, z = 6.21, p < .001). When the temporal distance was null (the probe was on the peak), the CVI was not a significant predictor of mental content (p > .5), but became so as the probe is farther from the peak. Conversely, when the CVI was null, the temporal distance to the closest peak predicted mental content (β = -1.17, SE = 0.29, z = -4.03, p < .001). However, the negative interaction indicates that this temporal effect decreased with increasing CVI. To summarize, both effects were in opposition: the predictive power of temporal distance decreased with increasing CVI, and the predictive power of CVI decreased with increasing closeness to a peak.

Our results build on and extends previous findings: errors are typically preceded by higher response time variability (Cheyne et al., 2009), and higher rate of mind-wandering correlate with higher RTCV at the participant level (Hu et al., 2012). Indeed, we show that the prediction of mind-wandering through values of RTCV is local (preceding the reports), robust and valid throughout the experiment: we found that *all* the trials of a given SART experiment contain information about mind-wandering since the temporal distance to a peaks of variability was indeed a significant predictor of mind-wandering. Furthermore that local fluctuations in variability should be predictive of mind-wandering opens the way for on-line detection of mind-wandering.

Hidden Markov Model of mind-wandering fluctuations

Methods

The reasoning behind the Continuous Variability Index (CVI) can be followed-up. We found that mind-wandering is characterized by increased response times variability. If we hypothesize that participants are at each time point in one of two distinct states, on-task (OT) or mind-wandering (MW), the previous findings suggest that when in each of these states, participants will produce responses according to distinct response generation processes. Based on the previous observations and assumptions, we model the alternation of on-task and mind-wandering states. We assume further that OT and MW states have transition probabilities to themselves and the other state, yielding a Markov chain (***Figure 3***). The notion of a Markov chain is the formal, quantitative counterpart to the intuition that on-task and mind-wandering states are organized in runs, so that if at one time point the participant is in one of the two states, it is more probable that he or she should be in the same state at the next time point. The transition probabilities give us a precise estimate of the volatility of each state. Observe two critical points: first, these volatilities are independent from each other, so that for instance OT might be stable (the probability to transition to MW is low), while MW might be more volatile (probability to transition from MW to OT is high). Second, the notion of a Markov chain of attentional states is based on a discretization of time in successive steps. Of course, this is a crude simplification, but it does correspond to the logic of our experiments, which are organized in discrete trials.

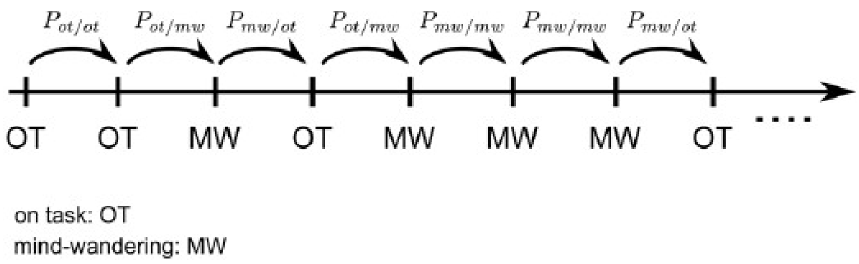


Figure 3: Markov Chain of attentional states: *Illustrative time series of on-task (OT) and mind-wandering (MW) states, with two pairs of complementary probability transitions to stay (ex. $P_{ot/ot}$: stay focused) in the same state or transition (ex. $P_{ot/mw}$ = 1-$P_{ot/ot}$: start mind-wandering) to the other.*

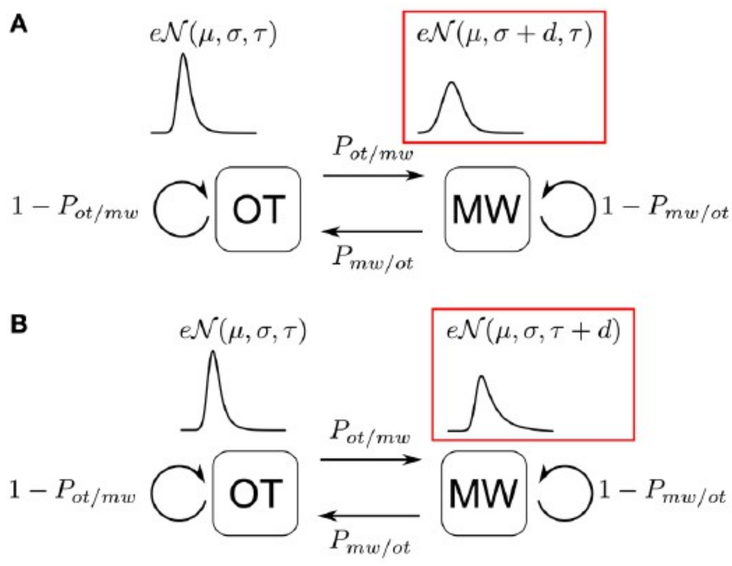


Figure 4: Six-Parameters Models accounting for increased variability during mind-wandering. *$P_{ot/mw}$: transition probability to start mind-wandering when on-task, $P_{mw/ot}$: transition probability to come back on task when mind-wandering, μ: mean of the distribution, σ: variance of the distribution, τ: skewness of the distribution. The critical parameter is d, "difference parameter", applied either to σ ("variance model") if variance increases during mind-wandering, or to τ ("exponential model") if skewness increases during mind-wandering. A) Variance Model B) Exponential Model.*

Now, we do not observe directly this Markov chain, but only the response times. However, the preceding sections suggest that in MW, participants generate more variable response times than in OT. Thus, if we can make plausible assumptions about the two distinct response generation processes, we could try to infer the underlying Markov states. This is precisely the logic of Hidden Markov Models: to an unobserved Markov chain of two internal states corresponds at each trial an observed output (the response time), which is emitted according to two different probability laws---that here differ according to their variability (***Figure 4***).

Thus, one critical step in this model is to characterize the variability of response times. On a descriptive level (Luce, 1986), response times are distributed according to skewed normal laws, meaning that to a bulk of responses that are roughly normally distributed must be added a long "right" tail of slow responses. These properties are nicely captured with the exponentially modified gaussian distribution (ex-gaussian), which is the sum of a gaussian distribution and of an exponential distribution. The parameters of an ex-gaussian are standardly known as the mean (μ) and variance (σ) of the gaussian component, and the rate of its exponential component (τ, which yields the weight of the right hand tail). With this in mind, it is clear that what appears in the CVI as an increase of variability can come from two changes in the ex-gaussian: First, the variance of the gaussian component (σ) could increase, spreading response times around the peak of the distribution. Second, the exponential rate parameter of the distribution (τ) could increase, adding slow response times (see red frames in ***Figure 4***).

Thus, if we are correct in assuming that *variability* is diagnostic of mind-wandering, we can conceive of each response time at each trial as a sample from one of two ex-gaussian distributions that differ in their variance or rate parameters. We observe the response times and would like to infer the underlying states that generated them. In a sense, what we are looking for is a partitioning of the trials in latent classes with respect to the distributions of observed response times (see (Vandekerckhove et al., 2008) for an example of latent class analysis based on response times). Here, crucially, this partitioning is further constrained by the assumption that the underlying states are organized as a Markov chain.

As a first foray into this kind of analysis of response time series, we tried the simplest and most straightforward models: we assumed that the two emission probability distributions were ex-gaussians with the same mean, and only differed in either the variance of their gaussian component or in the rate of their exponential component. This yielded six free parameters: the transition probabilities of the underlying unobserved Markov chain ($P_{MW \rightarrow OT}$ and $P_{OT \rightarrow MW}$), the three parameters of the base (which we arbitrarily chose as OT) ex-gaussian distribution (μ, σ, τ), and the critical difference parameter *d* that was added either to the variance or the rate of the base distribution, and thus yielded the higher variability MW emission law. If we succeed in so doing, for each trial, the model should yield the posterior probability that the participant should be in OT or MW. In order to account for the fact that trials are not equally distributed in time, and so as to remain within the markovian paradigm, we discretized time in steps of 2 seconds (equal to the offset of two successive correct go trials). Therefore, most trials would be one Markov transition from each other, but trials farther apart in time (because of correct no go trials, incorrect go trials, or thought probe interruptions) would be separated by a sequence of more than one Markov transitions. We estimated such models for one experiment with 47 participants (Experiment 3 in Bastian, Franklin, Schooler & Sackur, submitted).

Our goal was threefold: first, it should yield an independent, principled and confirmatory evidence that variability in response times crucially distinguishes MW from OT states. Second it might help us tease apart the components of variability described and observed in the previous sections: we systematically contrasted a model where the only source of increased variability for the MW state comes from the variance of the gaussian component (hereafter "variance model") with a model where the increase in variability comes from the rate of the exponential component ("exponential model", see ***Figure 4***). Finally, and most importantly, we should get an estimate of the volatility of each of the states, through the estimates of the transition probabilities $P_{MW \rightarrow OT}$ and $P_{OT \rightarrow MW}$.

Such models are intractable analytically, but can be implemented as graphical bayesian models (see (Lee and Wagenmakers, 2014), for an introduction to bayesian graphical models in cognitive science), and can be estimated using Markov Chain Monte-Carlo methods (MCMC). To do so, we used the JAGS software (Plummer, 2003) and the rjags package for *R*. We used uniform priors for all six parameters. We ran two separate models (variance and exponential) for each of the 47 participants, using four MCMC chains of 30000 samples each, with a thinning of 2, and after a burn-in period of 2000 samples.

Results and discussion

First, we compared the variance and the exponential models using the Deviance Information Criterion (DIC) for each model, for each participant: we computed the difference of DIC for the exponential and variance models, knowing that lower DIC indicates better convergence. The mean DIC difference across participants was -90.2, favoring the exponential model and this difference was significant as shown by a paired Wilcoxon signed rank test (V = 247, $p < .001$). In other words, the "exponential model" provides a better fit to the data than the "variance model". Therefore, hereafter we focus on the exponential model.[3]

Visual inspection of the sample chains and Gelman diagnostic (Gelman and Rubin, 1992) showed that convergence was attained, therefore it makes sense to interpret the posterior distributions of the parameters. First, as a sanity check, we compared the mean posterior μ and σ with observed participants' mean and variance of response times. The correlations were highly significant ($\beta = 1.2$, $t(45) = 19.44$, $p < 10^{-15}$, $R^2 = .89$ for the μs / means correlation and $\beta = 0.93$, $t(45) = 4.7$ $p < 10^{-4}$, $R^2 = 0.32$ for the σs / variance correlation). Note that the intercept was significant and positive only for the correlation of σs and variances (41.4, $t(45) = 4.6$, $p < 10^{-4}$), which is to be expected because in the model, the exponential parameter adds a further contribution to the observed variance---thus the empirical variance over-estimates the variance component of an ex-gaussian model. These facts suggest that the models did converge on the basic properties of individual response times. Next, we investigated the exponential rate τ and the critical difference parameter *d*. For all participants the model was able to estimate a positive *d*, with a mean of .51, and a base τ for the OT state of .02. This suggests that the model partitioned the trials in two classes: a class of less variable, quasi-normally distributed response times, and a class of highly variable, heavily skewed response times (see ***Figure 5A*** for the overall posterior distribution of *d*).

Now we come to the crucial hidden Markov chain transition probabilities, that we obtained for each participant. The grand mean across all participants of the mean estimates were respectively .11 and .18 for $P_{OT \rightarrow MW}$ and $P_{MW \rightarrow OT}$. Critically, this difference was significant as revealed by a paired Wilcoxon test (V = 246, $p < .001$, see ***Figure 5B*** for a plot of the overall posterior distributions of $P_{MW \rightarrow OT}$ and $P_{OT \rightarrow MW}$). Two remarks are in order here. First, these transition probabilities are well below .5, meaning that neighboring trials are more likely to belong to the same state than to the

3 Furthermore, none of the properties reported below for the exponential model were found significant with the variance model. Thus the variance model also lacked internal consistency. As a consequence it did not correlate with subjective reports of participants.

opposite state, in agreement with the intuition that mind-wandering and on-task states come in stretches longer than our time step of two seconds. Second, and most interestingly, the fact that $P_{OT \rightarrow MW}$ is lower than $P_{MW \rightarrow OT}$ shows that OT is more stable than MW. From this we can estimate the predicted duration of the episodes: in the OT state, if the probability of a transition is .11, it means that a transition will occur on average every 1/.11 = 9.09 steps, that is, every 18.2 seconds, because of the 2 seconds time step we used. Similarly, the predicted duration of MW episodes will be (1/.18) * 2 seconds = 11.1 seconds.

We can now come to the posterior estimates of the underlying Markov states. Recall that for each participant and for each trial, the model computes the posterior probability that the particular response time comes from one or the other (MW or OT) ex-gaussian distribution. We illustrate the time course of these underlying hidden states on ***Figure 6A***, for an arbitrary participant. As is visible on the plot, and as was already clear from the posteriors of $P_{MW \rightarrow OT}$ and $P_{OT \rightarrow MW}$, the model distinguishes runs of OT and MW states. This was confirmed by the fact that the overall (across all participants) distribution of posterior probabilities for the hidden states was bimodal (***Figure 6B***): this means that for a clear majority of trials, the model unambiguously assigns each trial to one or the other latent class. It is thus now possible to test whether the states identified by the model correspond to subjective states as experienced by participants. To this end, we applied the same logic as in the previous descriptive sections: first we contrasted the value of the state at the moment of a thought probe when the report is "on-task" to its value when the report is "off-task". Again, remember that states are only estimated at the moment of correct go trials. Therefore, we needed to interpolate its value at the moment of the probes, which we did by using LOESS smoothing (Cleveland, 1979). Then, we coded OT states as 1 and MW as 2, and computed the median values for each participant separately for mind-wandering and on-task reports. This median value was higher (1.44 as opposed to 1.38) when participants reported "off-task", and this difference was significant according to a two-tailed paired Wilcoxon signed rank test ($V = 54$, $p < .05$). This result replicates, in a principled way, the results of the "global analysis" section, where we found that the CVI at the moment of "mind-wandering" reports was higher than at the moment of an "on-task" report. In other words, MW states, as identified by the model, correspond to mind-wandering in the subjective reports of participants. Thus not only does the model have internal consistency, in that it succeeds in partitioning trials in two latent classes of differing variability, it also parallels subjective reports of participants.

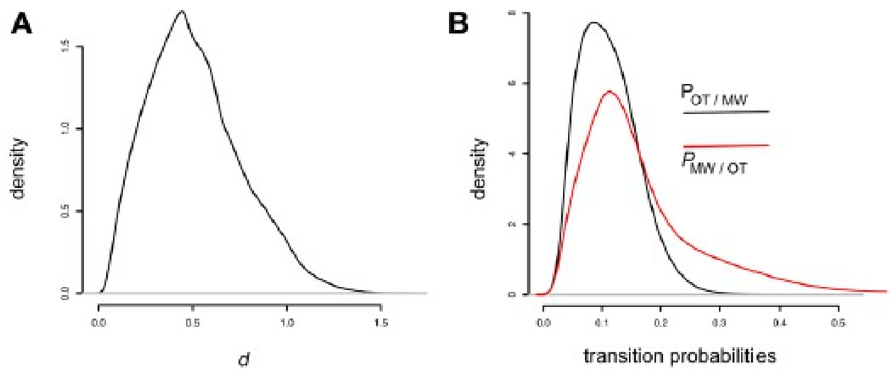


Figure 5: *A) Overall posterior distribution of the parameter d in the exponential model, pooled across all 47 participants (60000 samples per participant). Note that the prior was uniform over [0, 2]. B) Overall posterior distribution of the two transition probabilities in the exponential model. The prior was uniform over [0, 1] (60000 samples per participant).*

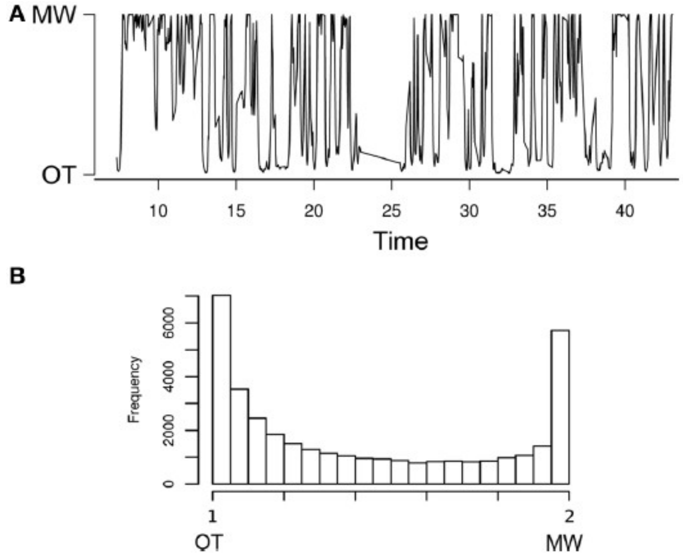


Figure 6: *A) Posterior distribution of hidden state across the experimental session of an arbitrary participant (time in minutes). B) Posterior distribution of the hidden states across all participants and trials. This distribution seems bimodal, meaning that the model categorically distinguishes between the two hidden states.*

General Discussion

In this paper, we showed that in a very simple cognitive task, variability of response times is intimately linked to mind-wandering. Our paper has both practical and theoretical implications. On the practical side, we contribute to the elaboration and test of a continuous and covert index of mind-wandering, that could be used on-line. On the theoretical side, through our model of the fluctuations of variability, we contribute first to the parsing of the components of variability that reflect mind-wandering, and second to the distinction of frequency and duration of mind-wandering episodes. We will now review the main results we obtained and their implications. We first found that, in the few trials preceding a report, the Response Time Coefficient of Variability (SD/Mean) was highly predictive of the nature of the subsequent thought-report. This direct evidence of a relation between RTCV and mind-wandering is consistent with previous suggestions on the basis of retrospective reports of mind-wandering (Cheyne et al., 2009). Moreover, RTCV was equally predictive of both random and spontaneous reports of mind-wandering.

However, we did find a specific pattern of response times before spontaneous reports: our participants systematically slowed down before such reports. Further research is needed to determine the causes of this deceleration. We suggest that it might be due to a) a dual task cost coming from an upcoming infrequent response; b) the progressive rise to consciousness of an unconscious mind-wandering episode; c) the start of an episode of conscious mind-wandering. Further research is also needed to determine whether this deceleration is the cause of the spontaneous report, as would be the case if for example participants used this information as their decision variable to stop and report their subjective state.

Note that this deceleration before spontaneous reports was the only linear or quadratic trend that we identified as a predictor of mind-wandering. Previous findings (Smallwood et al., 2008a; Smallwood, 2011b; McVay and Kane, 2012) evidenced that an *acceleration* predicted a subsequent error, but intriguingly this trend was not predictive of a subsequent report of mind-wandering our data. Notice however that we simply tested the presence of linear or quadratic trends, whereas the descriptive nature of Principal Components Analysis (PCA), the methodology employed notably by Smallwood and colleagues, may help detect more complex patterns. In fact, the PCA factor that is mainly associated with mind-wandering ("Factor 2", Figure 1 in Smallwood et al., 2008a) could not easily be described as either simply an "acceleration", a "deceleration", or any linear combination of linear and quadratic trends of response times. It seems rather a fluctuation, ending with a deceleration in the three last trials. Thus it may be that we traded sensitivity for simplicity. As the results obtained by means of PCA and ours are thus not incompatible, further research is clearly needed in order to check whether both generalize to other contexts and tasks.

Next, we found that the Continuous Variability Index, a continuous version of RTCV, was a robust and local predictor of mind-wandering: regardless of whether a participant had just gone through a peak of CVI, or was about to reach one, she or he was more likely to report mind-wandering as the report (random or spontaneous) was closer to the peak. One may find it surprising that the effect of closeness to a peak of CVI does not depend on whether it is a past peak or whether it is yet to come. It may even seem to run counter to basic principles of metaphysics, as future events are generally not considered as having causal effects back in time (but see Bem, 2011). However, first, in our view, maxima of variability are only points in time when episodes of mind-wandering are most likely to occur. Thus mind-wandering could have started before variability in response times reaches its maximum. Second, rhythmic fluctuations have been shown in human vigilance, with periods ranging from 10 seconds (Fox and Raichle, 2007) to 5 or 30 min (Conte et al., 1995) and even 60 to 110 min (Okawa et al., 1984). As a consequence, the future of human vigilance seems predictable, and participants need not to be aware of these fluctuations to be anticipating them.

Now, in fact, it is unclear whether participants are in any sense aware of the variability in their response times that we uncovered, and thus whether it has any causal role in their introspection. Perhaps peaks of CVI have a subjective counterpart, hence establishing a graded relation between CVI and mind-wandering. High CVI could for example be associated with highly vivid mind-wandering, or episodes that would be very likely to reach meta-awareness. However these are open questions and we do not know whether, in particular, participants use the variability of their response times as a decision variable to spontaneously stop the experiment and report mind-wandering. Nevertheless, our results show that continuous tracking of response times variability should be a very simple yet efficient way to detect mind-wandering as it unfolds in an experiment. Most importantly, our demonstration that local maxima of response time variability are good indicators of mind-wandering shows that the CVI could be used on-line: we do not need to know the grand average of variability in order to decide when it is “high” or “low”: proximity to local maxima is sufficient. Of course, since we showed that future peaks (which would be inaccessible on-line) are also indicative of mind-wandering, on-line detection would not be perfect. Yet, our results open the way for the detection of mind-wandering in the very first minutes of an experiment, just by tracking the fluctuations in response times variability. We acknowledge that the negative interaction between CVI value and temporal proximity to peaks should be taken into account in an on-line detector of mind-wandering: when the absolute variability is “low”, one should rely more on the temporal distance to a peak, but one should neglect the latter when absolute variability is high.

With this in mind, we vindicate a third method for mind-wandering studies, in addition to the random probe and the spontaneous reports techniques. Our results show that it is now possible to trigger probes at moments when mind-wandering probability is high. This detection technique would share properties with extant techniques: it would be external (as random thought-probes), but it would be unlimited (as spontaneous reports). With detection, one could test hypotheses about mind-wandering micro-dynamics with more precision. These dynamics may concern the very occurrence of mind-wandering, but also occurrence of its awareness or perception of external stimuli, or perception of time during mind-wandering. It would also be critical to study, how mind-wandering reacts to systematic detection, with a view to perhaps modify awareness of ones' thoughts or fluctuations in attention. We thus believe that the development of such a method might contribute to the application of mind-wandering studies to educational, applied and clinical psychology---as it might help limit the consequence of attentional lapses in industrial settings and offer new avenues for rehabilitation of some attention deficits.

On the theoretical side, we modeled the time series of response times for each participant as a Hidden Markov Model (HMM), where the critical variable that distinguishes the hidden states is the variability in the emission law. Of course, intertrial dependencies and sequential effects have been studied for a long time (see for instance Schvaneveldt and Chase, 1969; Gratton et al., 1992), but to our knowledge, our model is the first to extend the logic of intertrial dependence to full time series in psychological experiments (but see Craigmile et al., 2010, see also Killeen, 2013 for the suggestion of applying Hidden Markov Models *within* trials). We thus moved from the logic where each trial in an experiment is considered as independent, reflecting only the processing triggered by the experimental condition, to a logic where we adopt a *historical* perspective to each experimental run. The model reveals substantive information about response times in general and their relationship with mind-wandering.

First, the most surprising discovery is perhaps the fact that the “variance model” provides a far worse fit to the data than the “exponential model”. This suggests that, in our experiments, response time distribution is a mixture of two underlying distributions, a quasi-normal one and a heavily skewed one which, as we seem to see here, corresponds to periods of mind-wandering. This nicely fits previous suggestions (McVay and Kane, 2012) that mind-wandering is associated with "slow start" trials, during which participants produce abnormally slow responses due to being absent-minded. This also echoes to the finding that ADHD teenagers, who report more mind-wandering than control subjects (Shaw and Giambra, 1993), also present more skewed (higher τ) response times distributions than control subjects (Leth-Steensen et al., 2000).

The second important element is more directly related to mind-wandering studies. We were indeed able to reproduce in a principled way the association of high variability of response times with subjective reports of mind-wandering. This yield a highly interesting perspective on the asymmetry between the two transition probabilities and the associated runs length in the Markov chain of inner states. Remember that we found that OT was more stable than MW, and that as a consequence OT runs were on average longer (18.2 s) than MW runs (11.1 s). This mean duration of mind-wandering episodes echoes to previous suggestions based on subjective estimations (Klinger, 1978) and on slow fluctuations in the activation of the default mode network (Fox and Raichle, 2007; Vanhaudenhuyse et al., 2011). However, if our modeling and reasoning are correct, this might the first principled "objective" estimate of the duration and frequency of mind-wandering episodes as psychological states. Further researches are needed to test whether specific experimental variables or subjective conditions would separately impact each of the two transition probabilities, leading to various combinations of durations and frequencies for each of the two states.

In conclusion, we acknowledge that all our results are based on the same SART task. Further research is clearly needed to see whether this pattern is specific to this task or whether it generalizes to others. Our entire data set is constituted of *simple* response times, with very limited cognitive processing. The strong relation between response times variability might disappear when more complex cognitive processes are involved during response generation. One may in particular think that, if the variability due to cognitive processing is intrinsically high, it might easily mask differences in variability due to attentional states. In other words, the variability of response times might not be a diagnostic feature of mind-wandering with more complex tasks. If this were the case, one should try to determine whether this is due to the fact that, in more complex situations, the component of variability that originates in mind-wandering is more difficult to track, or whether it is simply absent.

Acknowledgments. *We thank Gabriel Synnaeve, Joachim Vandekerckhove, Isabelle Dautriche, Jonathan W. Schooler and Josefien Huijgen for insightful discussions. This research was funded by the Agence Nationale de la Recherche (France) "Dynamind" ANR-10-BLAN-1902-01, and by a grant from the DGA to MB.*

CHAPTER 3: THE INVOLVEMENT OF EXECUTIVE FUNCTIONS IN THE FIRST SECONDS OF MIND-WANDERING

This chapter is based on a research article by Bastian & Sackur (submitted). We sought to explore the first moments of mind-wandering generation by asking participants to perform a demanding delayed match to sample task. Participants had to hold in mind a mental image for as long as they could during each trial, and eventually (after 200ms - 26s) perform a task on the mental image, or assess their mental state. Thus, at the beginning of each trial, participants were focused, and we could observe when and under which conditions mind-wandering would occur. We found that aware mind-wandering increased with delay and peaked around 18 seconds. This finding is reminiscent of the slow (30-s) fluctuations of the Default Mode Network (DMN). However, this increase and peak disappeared with increased level of distracting noise, suggesting that they reflect a resource demanding mechanism. Finally, this increase and peak were not observed for unaware mind-wandering, which was unaffected by the level of noise, suggesting that unaware mind-wandering may come first, and may not require executive resources.

Abstract. *Why does the train of thoughts derail? Is it because of executive functions failures or because executive functions actively redirect focus to personal thoughts? We hypothesized that both mechanisms occur, creating two different kinds of mind-wandering: unaware mind-wandering results from executive failure while aware mind-wandering recruits executive resources. We evidenced this dual role of executive functions in a novel paradigm that targets the first 30s of mind-wandering. Participants had to hold a mental image in mind for an unpredictable delay before being probed about their mental content, while two levels of auditory noise controlled for executive resources depletion. Results indicated that the likelihood of aware thoughts increased with delay whereas it remained constant for unaware thoughts, suggesting constant failure rate in the latter but not in the former. Furthermore, only aware thoughts decreased under high noise, showing that aware thoughts require executive functions.*

Keywords: *attention ; mind-wandering; executive functions; dynamics; awareness*

Introduction

Mind-wandering, defined as spontaneous task-unrelated thoughts about personal concerns, is modulated by various task related and subject dependent factors (Smallwood and Schooler, 2015). However, the cognitive mechanisms causing the transition from focused to off-task thoughts are unknown. One first line of theorizing suggests that mind-wandering is the consequence of failures of executive control (Kane et al., 2007; Kane and McVay, 2012). Indeed, in demanding tasks, participants with lower executive resources report more mind-wandering (Levinson et al., 2012). Moreover, individual propensity for mind-wandering strongly correlate with mindlessness and cognitive failures (Carriere et al., 2013). Yet, a second line of theorizing claims that mind wandering *requires* executive resources. This executive-recruitment view explains why mind-wandering decreases in cognitively demanding tasks (Ruby et al., 2013), as well as in tasks with high visual load (Forster and Lavie, 2009) and why, in easy tasks, mind-wandering is more frequent in people with greater executive resources (Levinson et al., 2012).

Thus, it may seem that mind-wandering is both caused and mitigated by executive control. We hypothesized that this apparent paradox arises from the confusion between aware and unaware mind-wandering. Indeed, while participants are often conscious of their mind-wandering, some other episodes go unnoticed (Smallwood and Schooler, 2015). Previous findings suggest that this difference may be related to executive functions: Alcohol and cigarette craving, both known to disrupt executive functions (Heatherton and Wagner, 2011), increase the likelihood of unaware mind-wandering (Sayette et al., 2009, 2010). Similarly, young adults with an attention deficit, and thus, presumably executive dysfunction, report more unaware mind-wandering (Franklin et al., 2014). Reciprocally, we suggest that executive recruitment has an active role in the generation and maintenance of aware mind wandering. We followed two lines of reasoning to test this hypothesis.

First, if executive dysfunction and recruitment impact unaware and aware mind wandering separately, the temporal signatures of aware and unaware mind-wandering should diverge: the likelihood of aware mind-wandering should increase with time, reflecting the progressive recruitment of executive functions. Contrariwise, the likelihood of unaware mind-wandering, as a failure rate, should be constant. Thus the micro-dynamics of mind-wandering can be used as a window into the causal role of executive functions. Second, it has been shown that executive resources can be depleted with perceptual load (Forster and Lavie, 2009) and with verbal working memory interference (Tullett and Inzlicht, 2010). Thus, we predicted that a high auditory load should reduce aware episodes of mind-wandering, because it should deplete executive resources, while having no impact on unaware mind-wandering.

These hypotheses were tested with a novel mind-wandering protocol: participants were required to hold a mental image in mind for an unpredictable delay, up to 27 seconds. At the end of the delay, participants either performed an objective match-to-sample task, or were probed about their immediate mental content, so as to gauge mind-wandering. We considered each trial in isolation, with the assumption (confirmed in the data) that every trial started with participants re-focusing on the task.

Methods

Participants. 26 female participants (mean age: 22.6 y.o., SD = 3.2, range = [18, 32]) were recruited from the listings of our laboratory. Technical problems prevented full completion of the 60 probes for three participants that completed only 48, 53 and 59 probes out of the intended 60. All participants are included in the following analyses.

Materials & Methods

Stimuli. Polygons were randomly generated to have either 5, 7 or 9 sides, and had an area of 120 px^2. If different from the rotated sample polygon, the test polygon had the same number of sides, and a comparable area (difference < 10 px^2).

Task. Trials started with a central fixation cross (1 *s*), followed by a central random polygon (***Figure 1***). Participants were asked to mentally rotate this polygon by 180°. After 1.5 seconds, the polygon disappeared and the screen remained blank for an unpredictable delay, during which participants had to keep the mental image of the rotated polygon at the focus of their attention for as long as possible.

Delays. To ensure the unpredictability of the delay, 30 delay durations were sampled from an exponential distribution (half-life: 15s) truncated between 0.2 and 30s. Each of the 30 delays was presented once within each of four blocks, that alternated two noise conditions (counterbalanced across participants). In each block, half of the durations were randomly assigned to be match-to-sample (test) trials and half to be mind-wandering (probe) trials, thus creating 60 test trials (15 trials x 4 blocks) and 60 probe trials (15 trials x 4 blocks).

Test trials. At the end of the delay, test trials presented for half of the time the correctly rotated polygon or a different polygon that participant had never seen. Participants were required to respond same / different as quickly and accurately as possible.

Probe trials. A question mark signaled a probe trial. Participants then were asked to press the space bar that triggered a question about the content of their thought: "What were you just thinking about?". Seven exclusive answers, the meaning of which was explained in the instruction phase, were proposed: 1) "Polygon" (focused thought), 2) "Experiment" (Task-Related Interference – TRI), 3) "Sound" (Auditory-Noise-Related Distraction, SRD), 4) "Environment" (External-Distractions, ED), 5) "Personal things" (Mind-Wandering – MW), 6) "Other", 7) "I don't know". Then, a second question about thought awareness was asked: "Were you surprised to find yourself having this thought?", with two possible answers: "Yes" (unawareness) and "No" (awareness). For both test and probe trials, inter-trial interval lasted 2s before a new fixation cross was displayed.

Noise. Two conditions of noise, both to be ignored by participants, alternated in four blocks. In the low noise condition, participants were played white noise. In the high noise condition, they were played reversed speech: the audiobook of the first three chapters of Bergson's *The Creative Mind* was edited using the software *Audacity*. Speech was played backwards, silences longer than 1 second were truncated and the result was then vocoded in order to make it sound less natural and more robotic (see Supplementary Audio). Both sounds were played at an average volume of -10dB.

Results

All data was analyzed using R (R Core Team, 2014) and the R package lme4 for mixed models analyses (Bates et al., 2014). Analyses are model comparisons between General Linear Mixed models (GLMM) with participants as a random factor. Therefore we will present *chi* squares and their associated p-values for each model featuring a condition that increased the goodness of fit, and thus proved to be significant at the $\alpha = 0.05$ level (Levy, 2014). Only thought reports that were not made too quickly (< 150 ms) or too slowly (> 12.5 seconds) were further analyzed (> 98.5% of all reports). Response times in the match-to-sample task were similarly truncated under 8 seconds (1.5% removed).

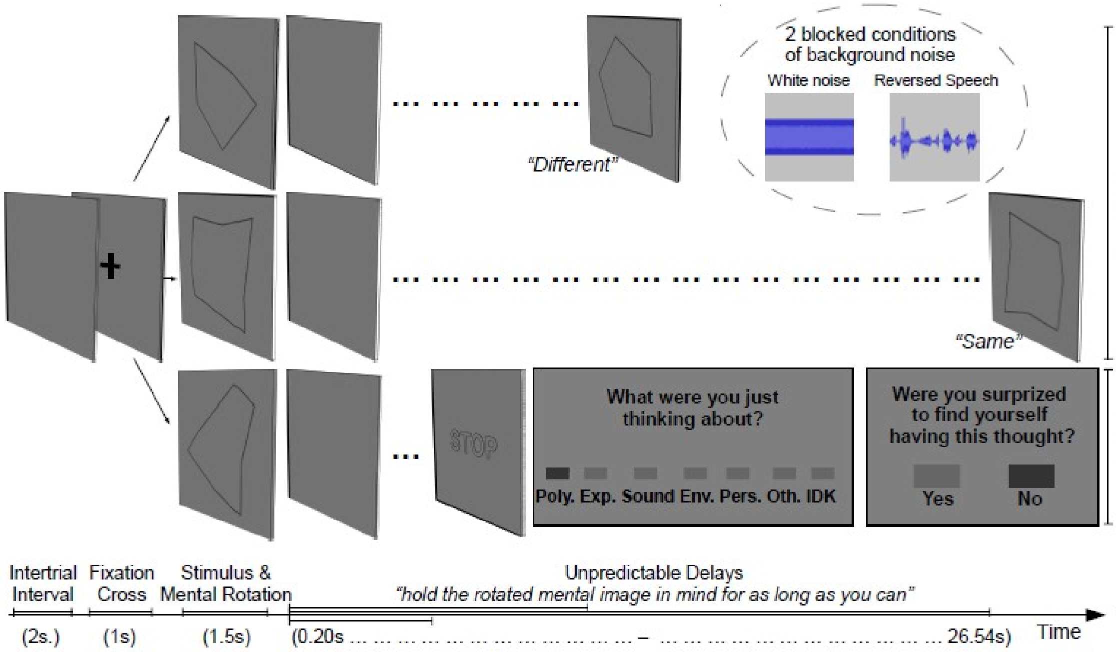


Figure 1: Paradigm. *Each line represents a typical trial. After a 2s blank inter-trial interval, the trial starts with a 1s fixation cross. Then a polygon is displayed for 1.5 seconds. Participants are required to mentally rotate the polygon, and hold in mind the resulting mental image for the duration of the trial. After an unpredictable delay (from .2 to 26.54 s), participants were either presented with a match-to sample task (test trial : 1st and 2nd lines) or with a probe about their last immediate thought (3rd line). Participants underwent four blocks alternating two noise conditions : a low (white noise) and a high (reversed speech) noise condition (top right bubble).*

%	Mean	SE	[Min - Max]
Focus	60.5	4.1	[13.8 - 95.0]
TRI	11.1	1.3	[1.7 - 24.1]
SRD	8.1	1.2	[0 - 19.1]
ED	7.4	1.1	[0 - 21.1]
MW	8.9	1.5	[0 – 33.9]
Other	2.7	0.8	[0 - 17.5]
IDK	1.2	0.3	[0 - 5.2]

Table 1. Proportion of Reported mental contents. *Abbreviations: TRI: Task-related Interferences, SRD: Sound-related Distractions, ED: External Distractions, MW: Mind-wandering, IDK: "I don't know (what I was thinking about)".*

Results can be grouped into three main classes: First focus is progressively lost as time elapses. Second, among off-focused thoughts, awareness of mind-wandering progressively builds up. Third, high levels of noise deplete executive resources and aware mind-wandering, not unaware mind-wandering.

Focus declines with time delay. ***Table 1*** presents the likelihood of all mental reports. Consistent with previous literature (McElree, 2006), increasing time delay progressively removed the target mental image from the focus of attention. This phenomenon was first evidenced by subjective reports: the likelihood to report "focus" decreased by an odds ratio of .92, CI(95) = [.91 – .94] with each second of time delay increment ($\chi^2(1) = 111.82$, $p < .001$). Second, response times (RT) to test trials increased by 22 ms, CI(95) = [13 – 31] with each second of time delay increment ($\chi^2(1) = 15.48$, $p < .001$). Yet, accuracy was not significantly affected by time delay ($p > .7$), suggesting that time only affected mental representations availability, not accessibility.

Aware mind-wandering builds up with time. As can be seen in ***Figure 2***, increasing time delay did not only decrease the likelihood to report a focused mental state, it also specifically increased the likelihood to report aware episodes of mind-wandering at an odds ratio of 1.08 (CI(95) = [1.05 – 1.12]) per second of time delay increment ($\chi^2(1) = 25.75$, $p < .001$, see ***Figure 2A***). Crucially, this impact of time delay was markedly smaller for unaware episodes of mind-wandering (odds ratio: 1.03, CI(95) = [1.00 – 1.07], $\chi^2(1) = 4.01$, $p < .05$, ***Figure 2B***), as evidenced by the significant difference between the slopes of the two effects (odds ratio: 1.05, CI(95) = [1.00 – 1.10], $\chi^2(1) = 4.36$, $p < .05$).

This difference between aware and unaware episodes of mind-wandering was further confirmed by the observation that, within all aware states, mind-wandering was more likely as time increased (odds ratio: 1.09, CI(95) = [1.06 – 1.13], $\chi^2(1) = 29.07$, $p < .001$), whereas, among all unaware thoughts, the likelihood of mind-wandering remained constant (odds ratio: 1.01, CI(95) = [.97 – 1.05], $p > .7$, interaction between time delay and thoughts' awareness: odds ratio: 1.08, CI(95) = [1.02 – 1.13], $\chi^2(1) = 8.71$, $p < .01$). Lastly, all these effects resulted in aware episodes of mind-wandering occurring at later time delays on average (mean = 16.15s, SE = .93) than unaware episodes of mind-wandering (13.73s ± 1.31; 2.86 s, CI(95) = [.18 – 5.51], $\chi^2(1) = 4.39$, $p < .05$).

Noise depletes executive resources. As should be expected, high levels of noise increased the likelihood of Sound-Related Distractions (odds ratio: 2.78, CI(95) = [1.84 – 4.27], $\chi^2(1) = 25.35$, $p < .001$). High levels of noise also decreased accuracy (reversed speech: 76.5% correct, SE = 1.7 ;

white noise: 82.4% (2.1), odds ratio = .71, CI(95) = [.55 – .91], $\chi^2(1) = 7.18$, $p < .01$). However, noise had no significant impact on RT ($p > .5$) or on "focus" reports ($p > .4$).

More importantly, high levels of noise also decreased the likelihood to report aware episodes of mind-wandering compared to low levels of noise (odds ratio: .58, CI(95) = [.35 – .96], $\chi^2(1) = 4.55$, $p < .05$). Interestingly, this was not the case for unaware episodes (odds ratio: 1.33, CI(95) = [.79 – 2.26], $\chi^2(1) = 1.2$, $p > .28$). These effects led high levels of noise to decrease overall awareness of mind-wandering episodes (odds ratio: .34, CI(95) = [.13 – .83], $\chi^2(1) = 5.63$, $p < .05$). At no point did time delay and noise interact in the above analyses (all *p*s > .4).

Going one step further, we reasoned that mind-wandering cannot increase monotonously. Indeed, the literature (Vanhaudenhuyse et al., 2011; Bastian and Sackur, 2013) describes oscillations between on- and off-task thoughts at a period around 0.03Hz (30-40 seconds). To capture this fluctuating pattern at the time scale of our experiment, we added a quadratic component to the previous GLMM. This complementary analysis confirmed that the likelihood of unaware episodes of mind-wandering is barely affected by time delay (linear component: $p > .4$, quadratic component: $p > .7$), and that noise does not affect their dynamics (interaction with both components: *p*s > .3, ***Figure 2D***). Crucially, this analysis also revealed an extremum peaking at 18.5s (***Figure 2C***) for aware episodes of mind-wandering in the low noise condition (linear: $\beta = 3.59$, SE = 1.05, $z = 3.41$, $p < .001$, quadratic: $\beta = -.96 \pm .35$, $z = -2.74$, $p < .01$). This pattern disappeared in the high noise condition (both components: $p > .6$). The fact that this peaking pattern was specific to aware episodes under low noise was further confirmed by the triple interactions between episode's awareness, level of noise and the linear/quadratic components (linear: $\beta = 3.58 \pm 1.92$, $z = 1.86$, $p = 0.063$, quadratic: $\beta = -1.40 \pm 0.67$, $z = -2.08$, $p < .05$).

Discussion

In this study, we designed an innovative paradigm in which we collected thought reports on a trial-by-trial basis. We were thus able to chart out the micro-dynamics of mind-wandering in two perceptual interference conditions. We show that 1) aware episodes of mind-wandering are increasingly frequent as time elapses, with a peak at 18.5s ; 2) high auditory noise suppresses this increase of aware episodes ; 3) unaware mind-wandering episodes increase less with time and were not impacted by noise.

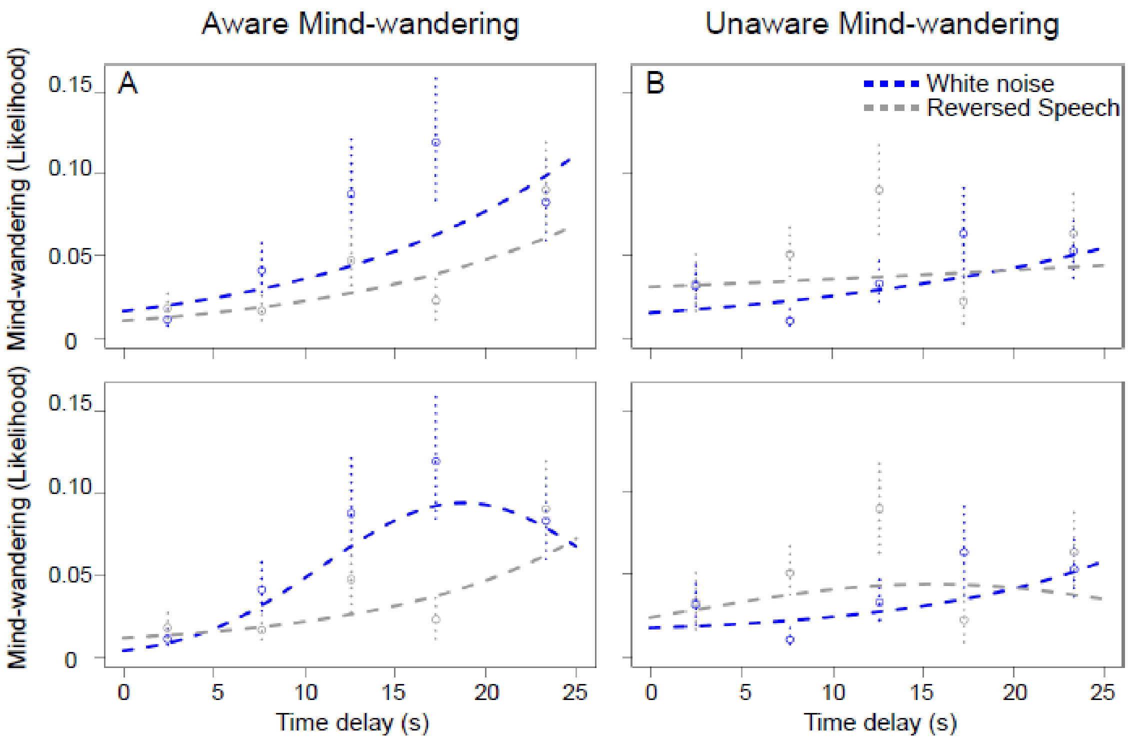


Figure 2: Results. *Aware episodes of mind-wandering (left) were more heavily influenced by delay and condition than unaware episodes of mind-wandering (right). Points are mean proportion of either aware (left) or unaware (right) proportions of mind-wandering, within 5 seconds bins, in the low (white noise: blue) and high noise conditions (reversed speech: grey). Errors bars are Standard Errors. Dotted lines represent GLMM fits with unbinned time delays as linear predictor (A, B) or as linear and quadratic (= time delay^2) predictors (C, D).*

These effects support a theory where executive functions are differentially involved in the generation of aware and unaware mind-wandering. While unaware mind-wandering are caused by executive failures occurring with constant probability, aware mind-wandering requires executive functions recruitment. This executive recruitment is confirmed by the effect of noise that only affects aware episodes of mind-wandering. That awareness requires executive resources has already been suggested by their common neural substrate: a Fronto-Parietal Network (FPN) is involved both in perceptual consciousness (Sergent et al., 2005) and in executive functions (Garavan et al., 2000). Our study confirms that executive functions and hence the FPN are likely to be recruited in conscious episodes of mind-wandering (Smallwood et al., 2012a). Further research is needed to explore whether the disruption of the same network is at the root of unaware episodes.

Our description of the micro-dynamics of mind-wandering concurs with previously described macro-dynamics – slow fluctuations at around ,03Hz (30-40s) – of both mind-wandering (Bastian and Sackur, 2013) and of its presumed neural correlate – the Default Mode Network (DMN, Vanhaudenhuyse et al., 2011). Indeed, a peak at 18.5s is consistent with the first period of a .03Hz fluctuation. This peak only appears among aware episodes of mind-wandering and disappears under high noise. This suggests that spontaneous slow fluctuations may only occur at rest or under low cognitive load. We speculate that the causal impact of the FPN on DMN activity and connectivity (Chen et al., 2013) explains why DMN slow fluctuations are both consciously accessible and depend on executive resources.

Finally, unaware episodes of mind-wandering were reported on average at shorter delays than aware episodes. This naturally raises the question whether the same train of thoughts can change its awareness status, starting as unaware, before being accessible to consciousness (Hasenkamp et al., 2012). Our methodology does not allow to keep track of individual episodes, precluding a direct answer to this question. However, we did not observe a decrease of unaware episodes with increasing time delays, which should be expected if the same episodes changed status. Similarly, noise decreased aware episodes without significantly increasing unaware episodes. This suggests that unaware and aware episodes of mind-wandering may indeed proceed from distinct mechanisms, but further investigations are needed to fully resolve this issue.

Acknowledgments. *This work was supported by grants from the Agence Nationale de la Recherche (France): "Dynamind" ANR-10-BLAN-1902-01, ANR-10-LABX-0087 IEC and ANR-10-IDEX-0001-02 PSL*. MB was funded by the Direction Générale de l'Armement.*

CHAPTER 4: A SUBJECTIVE MARKER OF ADHD: MIND-BLANKING

This chapter is a draft of a research article (Bastian & Van Den Driessche, Peyre, Stordeur, Delorme & Sackur, in prep). It is based on a collaborative work with Charlotte Van Den Driessche, who tested most of the participants during her Master 2 internship at the laboratory under my and Jérôme Sackur's supervision. Physicians Dr. Hugo Peyre, Dr. Coline Stordeur and Pr. Richard Delorme also contributed to participants recruitment and testing at the Robert Debré Hospital in Paris. We sought to show that ADHD patients do not suffer from more mind-wandering, because mind-wandering requires excecutive resources that are deficient in ADHD, but instead that they experience more mind-blanking, or mind-wandering without mental content. Indeed, we found in two studies – one with children participants hospitalized at Robert Debré Hospital, and one with non-pathological adults recruited from the LSCP listings – greater amounts of mind-blanking in ADHD groups compared to controls, while amounts of mind-wandering were similar, and if anything lower in ADHD groups.

Abstract. *Attention Deficit / Hyperactivity Disorder (ADHD) patients have a deficit in sustaining attention over tasks. However, what happens to their attentional focus when they lose track of the task is unclear. They could have intrusive thoughts about the task, be distracted or, as suggested by previous literature, their minds could wander to their personal concerns. Yet, mind-wandering requires executive resources that are precisely deficient in ADHD. We therefore investigated the fourth possibility that, when ADHD patients lose track of a task, they might experience mind-wandering without self-generated content (mind-blanking), which could explain an apparent high rate of mind-wandering with low executive resources. We explored ADHD patients' mental contents with thought-sampling during a sustained attention to response task (SART). We ran two studies, one with a hospitalized group of ADHD children with and without methylphenidate treatment (Study 1) and one with a non-hospitalized group of adults, but with a diagnosis of ADHD (Study 2). Naive ADHD participants reported higher rates of mind-blanking in both studies, but not higher amounts of mind-wandering. In contrast, methylphenidate treatment for ADHD decreased mind-blanking but increased mind-wandering. Mind-blanking therefore appears as a marker of ADHD both consistent through life-time and sensitive to medication. Our studies also show the value of distinguishing this mental state from mind-wandering, and provide further support for the view that mind-wandering requires executive resources.*

Keywords: *Attention Deficit Hyperactivity Disorder (ADHD), attention, consciousness, mind-blanking, mind-wandering*

Introduction

According to the Diagnostic and Statistical Manual of Mental Disorders, 5th ed. (American Psychiatric Association, 2013), Attention-Deficit / Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder typically diagnosed around age 7 to 12 and that can continue through adulthood. ADHD presents 18 symptoms divided into two symptoms domains: inattention, as evidenced by careless or unfocused behaviors, and hyperactivity, as evidenced by impatient, impulsive and restless behaviors (American Psychiatric Association, 2013). ADHD prevalence is estimated between 5% and 7% world-wide (Polanczyk et al., 2007; Willcutt, 2012) and seems stable since the last three decades (Polanczyk et al., 2014). ADHD is associated with life dissatisfaction (Biederman et al., 2006) and major difficulties at home (Harpin, 2005), school (August et al., 1996) and later on at work (Barkley and Fischer, 2011).

A deficit in executive functions may be an important cause of these difficulties (Barkley and Fischer, 2011), leading to performance impairments in various tasks such as sustaining attention (Barkley, 1997), reading (Miller et al., 2013), or comprehending figurative language (Bignell and Cain, 2007). Critically, an impairment in executive functions is consistent with a fast disengagement of focused attention within the first seconds (Swanson et al., 1991), and raises the question of "where" this dissipated attention goes.

A first possibility is that task-related interferences (TRI) attract patients' attention. Indeed, poor performance likely elicits intrusive thoughts about one's error in the task, and ADHD patients' performance on a wide range of neuropsychological tests is usually lower than the performance of control participants (Schoechlin and Engel, 2005). Moreover, TRI are particularly frequent among anxious personalities (Sarason et al., 1986), and ADHD patients are more anxious than controls (Biederman et al., 1991). In addition, other populations that suffer from executive functions deficit, such as older adults (Hasher and Zacks, 1988) also experience greater amounts of TRI (McVay et al., 2013). Finally, cognitive interferences such as TRIs have been explicitly attributed to deficient inhibition of intrusive thoughts (Borella et al., 2013), that could be at play in ADHD.

A second possibility is that external stimuli would quickly distract ADHD patients. There is intriguingly little literature on this topic, and the distractibility of patients in laboratory settings has led to controversial results (van Mourik et al., 2007). Yet, some evidence suggests that ADHD patients are particularly distractible by emotional stimuli (López-Martín et al., 2013), and that distractibility may even possibly serve as a marker of ADHD (Cassuto et al., 2013).

Mind-wandering has recently been put forward as a third possibility to account for the fate of ADHD patients' attention when not focused on-task. Mind-wandering is the generation of mental contents beyond the current task and environment (Smallwood and Schooler, 2015), such as when thinking about an upcoming holiday or a previous conversation. As stressed by Seli and colleagues (Seli et al., 2015c), mind-wandering and ADHD both lead to similar behavioral patterns: (1) impulsivity (Cheyne et al., 2009), (2) poor sustained attention (Seli et al., 2013), and (3) hyperactive behavior (i.e., fidgeting, Carriere et al., 2013). Moreover, to date, three studies reported more mind-wandering in adults with a profile (Franklin et al., 2014) or a history of ADHD (Shaw and Giambra, 1993; Seli et al., 2015c), than in controls. Note however that mind-wandering did not increase as a whole, but more specifically, adult with a ADHD profile reported more “spontaneous” and “unaware” mind-wandering episodes. This qualification is important, because mind-wandering, very much like task-related focus, requires executive resources (Levinson et al., 2012), that are impaired in ADHD. Thus, it is plausible that “unaware” and “spontaneous” mind-wandering should be better understood as defocused mental states with low content---a possibility we now explore.

A fourth mental state could therefore be experienced by ADHD patients when they are not focused: mind-blanking. Mind-blanking has only recently been distinguished from mind-wandering (Ward and Wegner, 2013). When mind-wandering, participants can and do report mental contents. In contrast, participants sometimes also report that they were experiencing no conscious mental content – their mind was blank, yet they were obviously not focused. In healthy adults, mind-blanking occurs rarely, in less than 20 % of thoughts probes (Schooler et al., 2004; Ward and Wegner, 2013), whereas mind-wandering occurs for about 30% to 50% (Kane et al., 2007; Killingsworth and Gilbert, 2010).

With a view to advance on this issue, in two studies we assessed which of the above four type of off-task thoughts (task-related interferences, external distraction, mind-wandering and mind-blanking) was most experienced by ADHD patients. By proposing such a qualitative grid, we aimed at going one step further than the on-task *vs.* off-task dichotomy that has been used to date. Moreover, we did not restrict ourselves to indirect markers of mind-wandering: using experience sampling, we also directly assessed participants' thoughts. Furthermore, we also aimed at testing clinically diagnosed ADHD patients, including children (6-12 years), being true to ADHD as first and foremost a neurodevelopmental disorder.

To anticipate the results, we found in both studies that ADHD participants reported more mind-blanking than controls. In study 1 clinically diagnosed ADHD children were contrasted with non-clinical peers, clinical but non-ADHD peers, and ADHD peers treated with methylphenidate. In Study 2, we contrasted young adults with a high or low level of ADHD symptomatology, as self-reported on the DIVA questionnaire, a diagnosing test of ADHD, and we found, again, that mind-blanking was higher in ADHD young adults. In contrast, mind-wandering did not prove to be a marker of ADHD, in neither study.

Study 1

Material & Methods

Participants

Inclusion criteria. Children were included in the study if they were i) 6 to 12 years old ii) not co-morbid with Autistic Spectrum, psychotic disorders, neurological or genetic syndrome, as assessed with the K.SADS (K-SADS – Schedule for Affective Disorders and Schizophrenia for School-Age Children, (Kaufman et al., 1996), french version "Kiddie-SADS" (Mouren-Siméoni, 2002), iii) with intellectual ability scores of 70 or higher, as measured with by the Verbal Comprehension (VCI) and Perceptual Reasoning Indexes (PRI) of the WISC-IV (Wechsler, 2004).

ADHD & Control groups. For all children, a clinical assessment by a psychiatrist set up the diagnosis of ADHD or excluded it. Two groups of ADHD children were constituted, one that never received any methylphenidate (referred below as "ADHD", N = 20, 4 females, mean age = 8.9), and one receiving an extended-release form of methylphenidate at the posology of 1 mg/kg a day, who served as a first control group ("ADHD-T", N = 20, 6 females, mean age = 8.9). A second control group was constituted of non-ADHD but hospitalized children ("Clin.-C", N = 20, 4 females, mean age = 9.8). These three groups were recruited among patients hospitalized or in consultation at the pediatric psychiatry unit of the Robert Debré Hospital-Paris. Finally, a third control group was constituted of non-ADHD non-clinical healthy children ("Health-C", N = 20, 8 females, mean age = 8.5), recruited via announces in the Department of Cognitive Sciences of the ENS. As expected, scores on the ADHD-rating scale (ADHD-rs, (DuPaul et al., 1998), completed by the caregivers) were higher for the ADHD (mean = 35.2) and ADHD-T groups (31.6) compared to both the Clin.-C (non-ADHD patients: 22.1, respectively $t(33.8) = 3.97$, $p < .05$ and $t(32.3) = 2.96$, $p < .05$) and the Health-C groups (non-ADHD and non-clinical children: 11.6, respectively $t(33.3) = 9.87$, $p < .05$ and $t(34.8) = 8.82$, $p < .05$).

Group matching. ***Table 1*** provides the detailed demographic and clinical information for the four groups. Groups were matched in age ($F(3, 60) = 2.09$, $p > .1$), sex-ratio ($\chi(1;3) = 2.76$, $p = .4$) and IQ on the Perceptual Reasoning Index (PRI, $F(3, 60) = 0.49$, $p = .6$). Groups differed on the Verbal Comprehension Index (VCI, $F(3, 60) = 4.34$, $p < .05$): scores of the two ADHD groups did not differ significantly ($t(27.6) = 1$, $p = .3$), nor did scores of the two non-ADHD groups ($t(25) = -.64$, $p = .5$). However, ICV in ADHD groups were lower compared to the two non-ADHD groups (ADHD – Clin.-C: $t(23.8) = -1.44$, $p = .16$; ADHD-T – Clin.-C: $t(28.7) = -2.18$, $p < .05$; ADHD – Health-C: $t(28.2) = -2.5$, $p < .05$; ADHD-T – Health-C: $t(29.7) = -3.15$, $p < .05$). Although the Health-C were less depressed, as assessed by the Children's Depression Inventory scale (CDI, Kovacs, 1985), and less anxious, as assessed by the ECAP (Vera, 1996) than clinical groups, no group had significant scores for depressive (> 19) or anxious syndromes (> 124).

Group	**Age**	**Female /20**	**VCI**	**PRI**	**ADHD-rs**	**CDI**	**ECAP**
ADHD	8.9	4	108.7	96.5	35.2	15.2	93.9
ADHD-T	8.9	6	102.4	100.6	31.6	11.9	94.9
Clin.-C	9.8	4	117.8	103.9	22.1	16.5	121.4
Health-C	8.5	8	121.8	101.1	11.6	8.5	55.5
p-value	***ns***	***ns***	*	***ns***	***	***	***

Table 1: Demographic and clinical information for Study 1. *Groups were matched in age, gender and on the Perceptual Reasoning Index of IQ (PRI), despite higher scores of the non-ADHD groups, compared to the ADHD groups, on the Verbal Comprehension Index (VCI). ADHD groups had higher scores than non-ADHD groups on the ADHD-rating scale (ADHD-rs). No group was above diagnostic scores for depressive (> 19 on CDI) or anxious syndromes (> 124 on ECAP). Statistical differences in sex-ratio were tested with Chi-test, and with ANOVAs for age, VCI, PRI, ADHD-rs, CDI and ECAP. * : p < .05, ** : p < .01, ***: p < .001*

Experimental Material and methods.

Task. We used an adaptation of the Sustained Attention to Response Task (SART, Robertson et al., 1997), with embedded thought probes (Christoff et al., 2009). The SART is a go/no-go task with rare (<10%) no-go trials. A digit between 0 and 9 was presented on a computer screen for 500 ms and children were required to press the space bar as fast as possible for each digit, but to withhold their response when the digit was "3" (no-go target). Two block paces were used in alternation: digits appeared either every second (fast block pace) or every 2 seconds (slow block pace).

Thought-probes. Each block was randomly interrupted by 6 thought-probes: a first screen with a question mark required children to describe verbally their thought at the moment of the interruption. A second screen asked them to classify their thought based on five categories: "focus" (On-task), "Task-Related Interference" (TRI), "External Distraction" (ED), "Mind-wandering" and "Mind-blanking". Categories were represented with line drawings of a teddy bear experiencing each mental content (Appendix 1). The child thus pointed at the drawing best representing his/her own mental state, and the experimenter then validated the report by pressing the corresponding button.

Procedure

Instructions first presented the task and the categories of mental contents with the help of the drawings of the teddy bear. Children then were presented with a training session of 55 trials with 5 no-go trials and three thought-probes. The testing session comprised four blocks (two slow pace, and two fast pace, in alternation, the order of which was counterbalanced across participants), for a total of 32 mental reports. The entire session lasted approximately 1 hour.

All assessments were conducted in quiet area of the hospital unit. Children were tested in silence, in the presence of the experimenter. Experimenters comments were kept to a minimum during the task, and exclusively helped clarifying children reports when unclear. Children with ADHD medication ingested it as usual.

Clinical scales (IQ, CDI, ECAP, K-SADS, ADHD-rs) were completed during independent sessions in the three clinical groups, but were completed together with the task for the healthy controls.

Results

Task performance

Accuracy. Overall accuracy on go trials was high (95.8% correct) and low on no-go trials (41.2% correct). A logistic regression with Trial type (Go vs. No-go), Block pace (Fast vs. Slow trials), and Group (ADHD, ADHD-T, Clin.-C, Health-C) on accuracy confirmed the effect of Trial type (β = -3.93, SE = .14, z = -27.26, $p < .10^{-16}$), that was modulated by block pace (interaction block pace X trial type: β = -.79 ± .10, z = -8.13, $p < 10^{-15}$): while slowing pace increased performance on go-trials (β = .35 ± .09, z = 3.94, $p < 10^{-4}$), it decreased performance on no-go trials (β = -.44 ± .09, z = -5.06, $p < 10^{-6}$). In turn, this block pace X trial type interaction was modulated by group. While it was not significant in the ADHD group (β = -.28 ± .18, z = -1.58, p = .11), it was greater and significant in all other groups (double- / triple-interaction-to-ADHD: ADHD-T: β = -.83 ± .19, z = -4.43, p < 10 -5 / β = -.51 ± .25, z = -2.04, $p < .05$; Clin.-C: β = -.79 ± .22, z = -3.49, $p < .001$ / β = -.55 ± .27, z = -1.99, $p < .05$, Health-C: β = -1.25 ± .19, z = -6.59, p = 10 -10 / β = -.86 ± .25, z = -3.48, $p < .001$). Beyond these modulations of trial type effect, there was no main effect of block pace ($p > .45$), nor any significant difference between overall performance of the ADHD group and control groups (all ps > .13). Overall these results suggest that, compared to the three control groups, ADHD children adapted less their responses to the task demands.

Response times. There was no effect of group on response times (RT), as assessed by ANOVAs on correct go-trials with the mean, the standard deviation or the coefficient of variation of RTs (respectively p >.55, p> .42, p>.25, all interactions with possible block effects ps >.79).

Subjective reports

Overall, children reported being on-task for the majority of the probes (49.64 %, SE = 2.46), and then, in decreasing order, they experienced Task-Related Interferences (19.33 % ± 1.49), Mind-Blanking (11.55 % ± 1.30), External Distractions (10.35 % ± 1.10), and Mind-Wandering (9.12 % ± 1.17).

A logistic regression on the likelihood to report mind-blanking with group and block pace as predictor evidenced that mind-blanking was experienced more by ADHD children (19.16% ± 3.33) than by any other control group (10.96 ± 2.32 in ADHD-T: β = -0.72 ± .34, z = -2.11, $p < .05$; 8.13

± 2.19 in Clin.-C: -0.99 ± .35, z = -2.78, p <.01 ; 7.97 ± 1.56 in Health-C: β = -1.02 ± .34, z = -2.96, p < .01, ***Figure 1a left***). There was no significant difference between these control groups (all ps > .4). Block pace had no effect (p > .35) nor did it interact with group (p > .25).

Next, we tested that the increase of mind-blanking episodes in ADHD children came from decreased amounts of resource demanding thoughts. To do so, we grouped focus and mind-wandering as drawing on executive resources, and task related interferences (TRI) and external distraction (ED) as less demanding with respect to executive resources. ADHD children reported less Focus + mind-wandering than control groups (ADHD-T : β = .53 ± .25, z = 2.13, p < .05 ; Clin.-C: β = .38 ± .25, z = 1.54, p = .124 ; Health-C: β = .66 ± .25, z = 2.68, p < .01, ***Figure 1b left***), but similar amounts of TRI + ED (ADHD-T: β = -.21 ± .25, z = -0.85, p > .39 ; Clin.-C: β = .05 ± .25, z = .19, p > .85; Health-C: β = -0.21 ± .24, z = -0.86, p > .39, ***Figure 1d left***).

Finally we found that methylphenidate treatment increased the likelihood to report mind-wandering (from 6.12% ± 1.48 to 15.03% ± 3.36, β = 1.01 ± .40, z = 2.56, p < .02). In fact, ADHD children under methylphenidate also had more mind-wandering than non-ADHD children (Clin.-C: β = -.84 ± .39, z = -2.15, p <.05; Health-C: β = -.75 ± .38, z = -1.97, p < .05 , ***Figure 1c left***).

Discussion

Mental content of clinical and non-clinical children was assessed in Study 1. We found that 1) ADHD children experienced more mind-blanking than all three control groups, and 2) that this increase in mind-blanking arose from a decrease in experiencing demanding thoughts such as on-task thoughts and mind-wandering. Finally, methylphenidate was shown to increase mind-wandering. This effect may first seem paradoxical: methylphenidate is a stimulant that aims at improving focus. As such, it was said to decrease “staring and daydreaming”, as rated by external observers (Ahmann et al., 1993; Conners, 1997). The present study shows how asking children about their subjectivity draws a finer picture of methylphenidate side effects: instead of reflecting daydreaming, staring, in non-treated ADHD patients, could reflect mind-blanking, which, as we show, does decrease under methylphenidate treatment. Moreover, by increasing executive capacities for focus, methylphenidate could also increase executive capacities for mind-wandering. Mind-wandering has been shown to increase blink rate (Smilek et al., 2010), and further research should explore whether mind-blanking could, on the contrary, be associated with decreased blink rate.

Study 2 aimed at replicating the previous findings with young adults with the exact same task and thoughts categories.

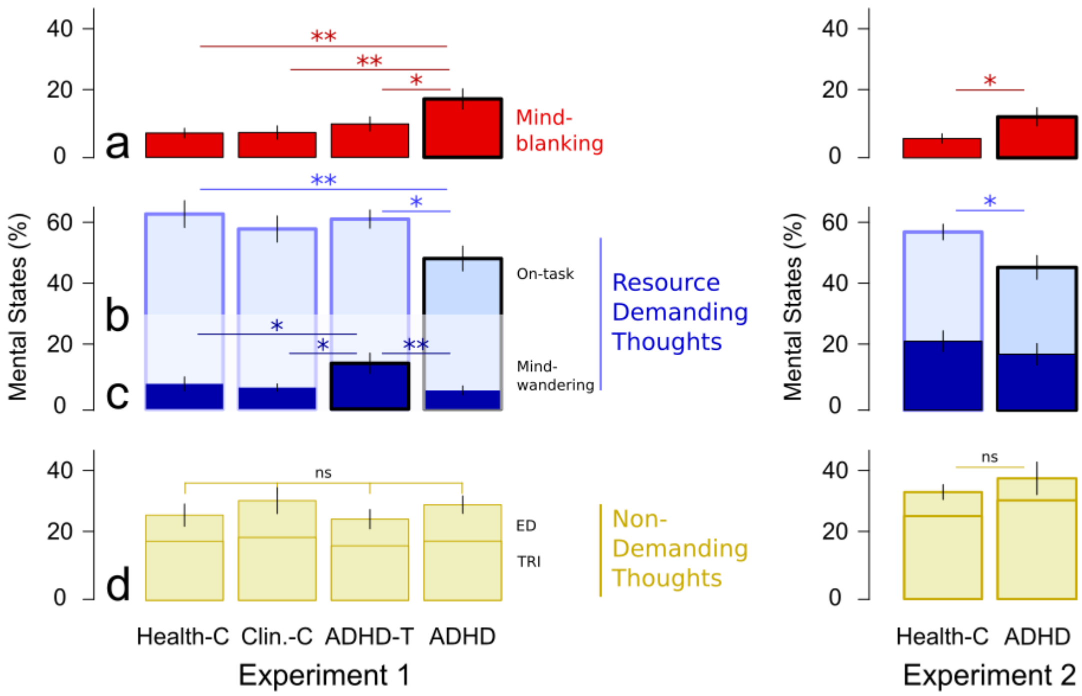


Figure 1. Effect of group on subjective reports. *a) ADHD reported more mind-blanking (red) than control groups in both Study 1 (left) and 2 (right). b) ADHD reported less demanding thoughts (MW/On-task, blue surrounding) than control groups. c) Methylphenidate increased mind-wandering. d) Non-demanding thoughts proportions (TRI: Task-Related Interferences/External Distractions, yellow) were similar across groups. Abbreviations: Health-C: Healthy control – non-ADHD – children (left) or adults (right) ; Clin.-C: Clinical control – non-ADHD – children ; ADHD-T: ADHD children treated with methylphenidate ; ADHD: ADHD children (left) or adults (right), naive of methylphenidate treatment.*

Study 2

Material & Methods

Participants. 40 participants (22 females, age = 23.8 ± 3.6, detailed demographic and clinical information in ***Table 2***) were recruited from the listings of the LSCP (Paris). They all spoke fluent French and had normal or corrected-to-normal vision. No participant reported any psychiatric disorder, and one participant who reported being under psycho-stimulant medication was excluded.

We used self reports of ADHD symptoms on the French version of the DIVA questionnaire (Diagnostic Interview Voor ADHD in Adults (Kooij and Francken, 2010) to identify two sub-groups: in accord with the DIVA guidelines, participants with a score equal or greater than 5 on a scale of 9 for either inattention or hyperactivity constituted the ADHD profile group ("ADHD", N = 15, 5 females, age: 22.5 ± 3.7), while the other participants constituted the non-ADHD group ("Health-C", N = 25, 17 females, age: 24.6 ± 3.4). There was no significant difference in age ($t(27.34) = 1.78$, $p = .08$), but a significantly higher sex ratio in the ADHD-like group (2.2 vs. 0.5 males/females, $\chi(1) = 4.55$, $p < 0.05$), as is found in clinical populations. The ADHD-like group was also significantly more anxious ($t(24.6) = -3.13$, $p < .01$), and more depressed ($t(24.9) = -2.2$, $p < .05$, as assessed by HAD (Hospital and Anxiety Depression scale, Snaith and Zigmond, 1986), but no participant reached criterion for clinical anxiety or depression.

Group	**Age**	**Female**	**Left-H.**	**A-Ad.**	**A-Ch.**	**H-Ad.**	**H-Ch.**	**Anxiety**	**Depression**
ADHD	22.5	5/15	2	6.5	5.3	5.3	5.3	12.13	6.8
Health-C	24.6	17/25	3	1.5	1.1	1.2	0.7	7.72	3.9
test	***ns***	*	***ns***	/	/	/	/	**	*

Table 2: Demographic and clinical information for Study 2. *Groups were matched in age and handedness (Left H.). However sex ratio was higher in the ADHD group, as well as anxiety and depression. Abbreviations for the sub-scales of the DIVA questionnaire: A-Ad.: Attention score based on current adult life, A-Ch.: Attention score based on childhood, H-Ad.: Hyperactivity score based on current adult life, A-Ch.: Hyperactivity score based on childhood.*

Experimental material and methods

Task and thought-probes were were strictly identical to those used in Study 1.

Procedure. Participants were tested alone in a quiet experimental booth. Order of the test and questionnaire were counterbalanced between participants. Adults were aware that this test was a control for a study with children, and that the Teddy Bear used in probes was there for this reason.

Results

Task performance

Accuracy. A logistic regression with Trial type, Block pace and Group (ADHD, Health-C) on accuracy replicated the finding of greater performance on go (99.29% correct) compared to no-go trials (57.16%, $\beta = -5.38 \pm .22$, $z = -24.70$, $p < .10$ -16). Performance was also higher for controls compared to ADHD ($\beta = .52 \pm .20$, $z = 2.54$, $p < .01$), for both no-go (61.62% vs. 49.72%, $\beta = .47 \pm .19$, $z = 2.39$, $p < .01$) and go trials (99.56 % vs. 98.82 %, $\beta = 1.10 \pm .42$, $z = 2.61$, $p < .01$, with no significant group X trial type interaction: $p > .1$). Slowing pace had no effect on overall performance ($p > .15$), but affected the go/no-go difference in performance, and this differentially for the two groups (triple interaction: $\beta = .92 \pm .39$, $z = 2.35$, $p < .05$): while the go/no-go difference increased with slower pace in the ADHD group ($\beta = .90 \pm .27$, $z = 3.34$, $p < .001$), there was no effect in the control group ($\beta = -0.02 \pm .30$, $z = -0.06$, $p > .9$). Such a modulation is reminiscent of Study 1, with slowing pace improving go performance on one side ($\beta = .74 \pm .27$, $z = 2.78$, $p <.01$), but decreasing no-go performance on the other side ($\beta = -0.17 \pm .18$, $z = -0.95$, $p = .34$).

Response times. As in Study 1, we did not find group effects on response times: ANOVAs revealed no significant effect of group on correct go-trials means, standard deviation or coefficient of variation (respectively $p > .5$, $p > .4$, $p > .1$, all interactions with possible block effects ps >.2).

Subjective reports

Overall, adult participants reported being on-task the majority of the probes (33.82 %, SE = 2.62), and then, they experienced Task-Related Interferences (27.5 % ± 1.72), Mind-wandering (21.48 % ± 2.49), Mind-Blanking (9.37% ± 1.58) and External Distractions (7.8 % ± 1.24).

As in Study 1, mind-blanking was more reported by ADHD (14.37% ± 2.26) than controls (6.37 ± 1.34 ; $\beta = -1.03 \pm .38$, $z = -2.69$, $p < .01$, ***Figure 1a right***), and this was likely due to a decreased experience of demanding thoughts (Focus + MW) in the ADHD group ($\beta = -0.35 \pm .15$, $z = -2.27$, $p < .05$, ***Figure 1b right***), given that similar amounts of non demanding thoughts (TRI + ED) were reported by both groups ($\beta = .02 \pm .18$, $z = .15$, $p > .8$, ***Figure 1d right***).

Finally, block pace never interacted with group effects on subjective reports (ps > .2), but, consistent with the view that mind-wandering requires resources, fast blocks did decreased the likelihood to report mind-wandering (from 25.15% ± 3.02 in slow blocks to 17.81% ± 2.40 in fast blocks, $\beta = .49 \pm .14$, $z = 3.42$, $p < .01$).

General Discussion

Our studies evidenced differences between ADHD and control groups at the level of mental content. Study 1 evidenced that clinically diagnosed ADHD children reported more mind-blanking than clinical and non clinical non-ADHD children, and importantly, more than ADHD children with a methylphenidate treatment. Greater levels of mind-blanking were also found in Study 2 for young adults reporting ADHD symptomatology on a diagnostic scale of ADHD. As such, mind-blanking appears as a reliable subjective marker of ADHD.

Previous subjective markers had been proposed for ADHD. Notably, it has been reported that mind-wandering is particularly frequent in adults with ADHD profile (Franklin et al., 2014) or history (Shaw and Giambra, 1993; Seli et al., 2015c). However, these findings were at odds with the view that mind-wandering requires executive resources (Christoff et al., 2009; Levinson et al., 2012), that are precisely impaired in ADHD (Barkley, 1997). The spontaneous (Shaw and Giambra, 1993; Seli et al., 2015c) and unaware (Franklin et al., 2014) aspects of ADHD mind-wandering were therefore particularly stressed. The present study further clarifies these contradictory findings: a mis-categorization of mind-blanking as mind-wandering accounts for the apparent greater amount of mind-wandering in ADHD. Dissociating stimulus independent and task-unrelated thoughts with mental content – mind-wandering – from thoughts without mental content – mind-blanking (Ward and Wegner, 2013) – it appears that only mind-blanking is more reported by naive ADHD groups, while these groups tend to report less mind-wandering than others. The only exception was found in Study 1, where methylphenidate treatment increased mind-wandering. Thus, ironically, if ADHD children ever report more mind-wandering, this might likely be due to the side effects of their methylphenidate treatment against ADHD symptoms.

Our findings also evidenced that both in children and adults, the sum of mind-wandering and focused thoughts was less in ADHD groups, whereas the sum of task related interferences and distractions did not vary significantly across groups. This general pattern of findings suggests that greater mind-blanking in ADHD arises from less thoughts that are demanding with respect to executive resources. Thus, while task demands may modify where executive resources are allocated (towards more focus or more mind-wandering), ADHD would reduce this pool of resources with the consequence of reducing the amount of focus in some contexts, and of mind-wandering in other contexts.

Yet, what mind-blanking really reflects remains an open question. First, mind-blanking could reflect deficiencies in introspection: normal adults often fail to notice their mind-wandering (Baird et al., 2013a), and ADHD could present a greater deficit of the same nature, failing to acknowledge their mind-wandering episodes. This view would be consistent with a few studies that suggest meta-cognitive deficits in ADHD (Antshel and Nastasi, 2008), and with the role of prefrontal regions in meta-cognition (Rounis et al., 2010). Second, ADHD patients could have higher thresholds for the detection of their mind-wandering: not that they would not be able to distinguish mind-wandering from focused attention, but they would need stronger and more vivid episodes of mind-wandering before acknowledging this experience. Indeed, fronto-parietal networks are also involved in mental contents' access and reportability (Sergent et al., 2005; Dehaene et al., 2006), and mind-blanking reports in ADHD could reflect higher threshold for conscious access, as observed among schizophrenic patients (Del Cul et al., 2006). However, it is also possible that mind-blanking involves truly blank representations, or no representation, such as deficiencies in mind-wandering generation. This would be consistent with observed decreased connectivity of the default mode network in ADHD (Uddin et al., 2008), a key network involved in mind-wandering (Christoff et al., 2009; Fox et al., 2015). The fronto-parietal network is also thought to buffer representations (Smallwood et al., 2012a). Buffering of mind-wandering thoughts, as well as on-task thoughts, could be deficient in ADHD. This would likely decrease thoughts salience, and make their identification more difficult. Finally, in a fourth possibility, mind-blanking could reflect transitional states between stable thoughts (James, 1892), and if executive functions were to stabilize trains of thoughts, shorter thoughts and a greater alternation would naturally increase the amount of transitional states, hence of mind-blanking.

In fact, at the heart of these hypotheses lies the accuracy of children's reports and of ADHD patients' reports. Note that whether or not ADHD have a deficit in introspection, we still observe a remarkable consistency between the children and adult studies. However, the classic decrement in mind-wandering under higher demands (Ruby et al., 2013) was found for the adult study only. Task demands may have been at ceiling for young children, and slowing pace may have not freed enough resources to mind-wander more. Children's subjective reports may also be more noisy (Zhang et al., 2015).

Yet, note that mind-blanking appears as a highly sensitive marker of ADHD subjectivity. While it has been for long time unclear whether ADHD continued in adulthood (Faraone et al., 2006), we observe that mind-blanking consistently marks ADHD symptomatology across ages. Future research could explore whether even older, untreated and non-clinical individuals also report more mind-blanking. Moreover, mind-blanking also appears to be sensitive to medication: while assessment of ADHD symptomatology by caregivers via the ADHD-rs did not evidenced any difference between ADHD groups with and without treatment, the amount of mind-blanking did, bringing ADHD children almost back to the level of non-ADHD children. Finally, this subjective marker also seems more sensitive than task performance: poorer inhibition in the go / no-go task was only found in the adult study, but not in the children study. This echoes the finding that ADHD performance in objective tasks is highly variable.

To conclude, the present study introduces a new – subjective – marker of ADHD: mind-blanking. This marker is consistently found in clinically diagnosed children, and non-clinical adults with ADHD symptoms, and is modulated by methylphenidate treatment. Future research should explore whether this diagnostic subjective state arises from deteriorated representations or deteriorated access to normal representations.

Acknowledgments. *We thank Eric Acquaviva and Sara Bahadori for insightful discussions. This work was supported by grants from the Agence Nationale de la Recherche (France): "Dynamind" ANR-10-BLAN-1902-01, ANR-10-LABX-0087 IEC and ANR-10-IDEX-0001-02 PSL*. MB was funded by the Direction Générale de l'Armement.*

CHAPTER 5: HOW LANGUAGE HELPS INTROSPECTION: NOTICING VERBAL MIND-WANDERING BETTER

This chapter is based on the draft of an article by Bastian, Lerique, Adam, Franklin, Schooler & Sackur (in prep). In this chapter, we studied the role of inner speech in mind-wandering awareness. Experiment 1 was a collaboration with Jonathan W. Schooler and Michael Franklin at the University of California, Santa Barbara, and we sought to show that articulatory suppression could decrease self-caught reports of mind-wandering. Experiment 2 was conducted by Jérôme Sackur and I, and we sought to show that with increased verbal stimuli, awareness of mind-wandering would increase. Finally, Study 3 was based on the data collected by the smartphone android-based application *Daydreaming*, developed by Sébastien Lerique (Centre Marc Bloch, Berlin) & Vincent Adam (Gatsby Computational Neuroscience Unit, University College London, London). Data from the application replicated the relation between inner speech vividness and awareness of mind-wandering.

Abstract. *Two cognitive functions are the pride of humankind: introspection and language. Yet, how they may relate remains unclear: inner speech could facilitate self-awareness, but there is in fact little empirical evidence for this claim. A concrete case of introspection lies in the puzzling finding that people often fail to notice that they are mind-wandering. In this paper, we tested whether inner speech facilitated mind-wandering awareness. In two Experiments, we either interfered with verbal working memory, via articulatory suppression (Exp. 1), or increased its content by presenting more verbal material (Exp. 2), and measured resulting awareness of mind-wandering. As predicted, articulatory suppression decreased the likelihood to self-catch mind-wandering (Exp. 1), whereas increased reading increased awareness of mind-wandering (Exp. 2). Episodes of mind-wandering that were spontaneously introspected were also more verbal than those requiring external intervention (Exp. 1). Finally, a smartphone study using the android-based application "Daydreaming" that we designed confirmed that only inner speech vividness predicted awareness of mind-wandering, not visual, or auditory vividness (Exp. 3). Together, these findings supports the view that inner speech facilitates introspection of one's thoughts, and therefore provides empirical evidence for a positive relation between language and consciousness.*

Keywords: *Mind wandering, consciousness, meta-awareness, inner speech, verbal working memory*

Introduction

The mind can escape the here-and-now and generate its own mental contents (Smallwood and Schooler, 2015). Some of these mental contents, such as those involved in planning or problem solving (Spreng et al., 2010; Gerlach et al., 2011), are generated intentionally to fulfill task demands. Other episodes also occur spontaneously (Seli et al., 2015a). Wanderings of the mind are all presumably reportable, and thus naturally belong to the range of conscious thoughts (Dehaene et al., 2006; Cohen and Dennett, 2012).

However, various observations suggest that task-unrelated thoughts are associated with different subjective experiences (Schooler et al., 2011). First, participants required to continuously monitor the emergence of task-unrelated thoughts often “forget” to spontaneously report these thoughts, while they likely acknowledge their mind-wandering with external thoughts-probes asking about their immediate mental contents (Schooler et al., 2004). This discrepancy between spontaneous “self-caught” reports and external “probe-caught” reports of mind-wandering suggest that some of the mind-wandering is better caught with an external and explicit measure of mental contents than with their internal and voluntary monitoring. Second, participants report various degrees of “surprise” when noticing their mind-wandering: sometimes they knew that they were mind-wandering, sometimes they did not know it before the external thought probe drew their attention to this fact (Christoff et al., 2009). How this feeling of surprise relates to the inability to self-catch all episodes of mind-wandering is currently unknown. Yet, it seems plausible that these two measures efficiently capture a common discrepancy experienced between one’s goals – such as reading a book – and one’s actual cognitive state – thinking about one’s current concerns while mindlessly skimming the text (Schooler, 2002).

The concept of *meta-awareness* (Schooler, 2002; Schooler et al., 2011) has been put forward to account for this discrepant phenomenon: conscious mental contents, such as mind wandering episodes, would always be consciously *experienced* – and indeed, they are in principle reportable. Yet, the ability to take stock of these thoughts, either by reporting them spontaneously or by not feeling surprised when noticing them, would be related to a capacity of re-representation of these mental contents, as a form of meta-awareness or meta-consciousness. Meta-awareness, as a second order re-description of particular thoughts as being either on or off-task, is thus a form of reflexive consciousness (Winkielman and Schooler, 2011).

However intuitive the notion that one may or may not notice that one's mind has started to drift away from its explicit goals, research on meta-awareness of mind-wandering is still in its infancy: the experimental manipulations of meta-awareness are few and not well understood from a functional standpoint. Recent research has demonstrated that meta-awareness of mind wandering can be experimentally manipulated, by means of physiological variables. Sayette and collaborators (Sayette et al., 2009) first demonstrated that alcohol intoxication increases the overall quantity of mind wandering without a concurrent increase in meta-aware mind wandering. Similarly, these authors demonstrated that smokers craving for cigarettes were less meta-aware of their mind wandering compared to non-craving smokers (Sayette et al., 2010). Meta-awareness also varies at the inter-individual level: adults with a ADHD profile report more unaware mind-wandering than controls (Franklin et al., 2014), and participants required to suppress thoughts about past romantic relationships are less likely to be aware of thoughts intrusions if they still experience feelings about the person (Baird et al., 2013a).

In this paper, more than physiological or inter-individual differences, we focused on how various aspects of mind-wandering phenomenology interact. Specifically, we hypothesized that verbal thoughts facilitate awareness of mind wandering. Two lines of reasoning lead to this prediction.

First, it has been suggested that inner speech is critical for self-awareness, that is the “capacity to become the object of one’s own attention” (Morin and Everett, 1990). Since the early theories on the role of inner speech (Vygotski, 1933), its role in cognition has been studied experimentally by interfering with the verbal component of working memory (Baddeley and Hitch, 1974; Baddeley, 1992). For example, articulatory suppression, which involves repetition of a vocal pattern (Baddeley et al., 1975), disables articulatory rehearsal processes (RepovŠ and Baddeley, 2006). Using this interference method, it has been shown that inner speech is beneficial to task-monitoring (Tullett and Inzlicht, 2010), task-switching (Emerson and Miyake, 2003), planning (Lidstone et al., 2010) and more broadly to cognitive control (Cragg and Nation, 2010). Thus, drawing on the suggestion that inner speech and self-awareness are tightly linked (Morin, 2005), we hypothesized that a similar relationship might exist between inner speech and meta-awareness. Indeed, meta-awareness is one special form of self-awareness, namely the awareness of the present cognitive state of the self (Morin and Hamper, 2012).

The second line of evidence comes from studies showing that language is preferentially processed compared to other stimuli. In continuous flash suppression paradigms, written words in the perceiver's language (ex. Chinese characters for Chinese readers) were shown to break suppression faster than in another language (ex. Hebrew words for Chinese readers) (Jiang et al., 2007). Similarly, meaningful ideograms broke suppression faster than inverted and scrambled ideograms (Yang and Yeh, 2011). These findings suggest that meaningful written words have a lower consciousness threshold. Furthermore, Tremblay and collaborators (Tremblay et al., 2000) evidenced that irrelevant natural speech is more disruptive than speech-like noise. Even though the authors suggested this effect might be due to greater acoustic complexity of natural speech, this does not exclude attentional processes specific to the processing of natural speech (see (Hughes and Jones, 2001) for a discussion of the properties of speech responsible for its disruptive effect). Similarly, Repovs and Baddeley (RepovŠ and Baddeley, 2006) observed that irrelevant *sound* effects (Salamé and Baddeley, 1982; Hanley, 1997), but not irrelevant *speech* effects (Hanley and Broadbent, 1987; Hanley and Bakopoulou, 2003), disappear under articulatory suppression. This suggests that speech has automatic and privileged access to the phonological store, bypassing the articulatory rehearsal process. In sum, as a stimulus, speech is particularly salient.

Whether *inner* speech is similarly salient so as to drive attention to the mind-wandering episode, and thus increases self-awareness, was tested in the present series of studies. Two laboratory experiments, using variations of the Sustained Attention to Response Task (SART, Robertson et al., 1997) as a primary task, aimed at interfering with – using articulatory suppression (RepovŠ and Baddeley, 2006) (Exp. 1) – or entraining – using presentation of verbal material (Pintner, 1913; Abramson and Goldinger, 1997) (Exp. 2) – the verbal component of working memory. Conjointly, we measured meta-awareness of mind-wandering episodes. Awareness of mind-wandering was hypothesized to decrease under articulatory suppression in Experiment 1, and increase with increasing verbal material in Experiment 2. Experiment 3 was an *in-vivo* crowd-sourced study running on Android smartphones, designed to replicate, in ecological settings, the positive correlation between inner speech vividness and awareness of mind-wandering.

Experiment 1

Materials and methods

Participants. 29 students (15 females, 21.5 y.o., SD = 4.4, range = [18-39]) from the Department of Psychology of the University of California, Santa Barbara (UCSB) participated in the study. All participants had normal or corrected-to-normal vision and spoke fluent English.

Materials

Primary Task. A version of the SART (Robertson et al., 1997) was used as the main task, with thought-probes embedded (Klinger, 1978; Hurlburt and Heavey, 2004). Digits were presented sequentially in white "courier new" font (30 points) at the center of a black computer screen (refresh rate of 60Hz) for 500 ms, every 2 seconds. Participants were required to press the space bar as fast as possible in response to each digit but to withhold their response when presented with the digit "3" (the target no-go stimulus). No-go targets were rare (7%: 8 out of 108 trials per block).

Secondary task – The SART was performed under three conditions in a within participant design: (1) single-task (hereafter ST) (2) foot tapping control dual-task (hereafter FT), and (3) articulatory suppression dual-task (hereafter AS). The foot tapping condition required participants to tap on a stapler fixed on the floor. The articulatory suppression condition required participants to repeat "a-b-c" out loud. The rhythm for both articulatory suppression and foot tapping conditions was one beat every 750ms and a metronome was set at the beginning of each block so that participants could get the "right rhythm". The metronome was stopped as soon as they judged their rhythm "correct enough". The disruptive effects of both foot tapping and articulatory suppression have been shown to be comparable (Emerson and Miyake, 2003; Miyake et al., 2004; Gaillard et al., 2012).

Instructions. The experiment was presented as a test of the participant's ability to keep a rhythm while engaged in an attention task. Each participant was audio recorded during the experiment. Recording was an explicit incentive to perform the dual tasks correctly, as well as a check for compliance with instructions.

*Thought-reports***.** The self-catching / probe-catching methodology (Smallwood and Schooler, 2006; Schooler et al., 2011) was used to collect thought-reports. Participants were instructed to press "Enter" on the keyboard to spontaneously report off-task thoughts whenever they noticed they had them. Moreover, four external thought-probes randomly interrupted each of the six blocks of the Experiment. These external thought-probes yielded a percentage of "probe-caught" episodes of mind wandering; while the spontaneous reports yielded a number of "self-caught" episodes of mind wandering. Following previous literature (Schooler et al., 2004; Sayette et al., 2009, 2010; Baird et al., 2013a), the percentage of probe-caught mind-wandering was taken to reflect the baseline experience of mind-wandering, while the number of self-caught mind-wandering was taken to reflect the episodes that participants noticed on their own, and thus awareness of mind wandering. Participants responded to the external probes with Likert and categorical scales. The order of the questions was fixed: first, participants reported "how focused they were on the task" using a 5-point Likert scale ranging from 1: "On-Task" to 5: "Off-Task". Instructions explicitly related "Off-Task" to daydreaming and mind-wandering. Second, after validating their response, participants reported how aware they were of their last thought on a 5-point Likert scale ranging from 1: "Aware" to 5: "Unaware". Critically, instructions stressed that this second scale was independent from the first. This second explicit awareness scale aimed at testing whether retrospective assessment of mind-wandering awareness would be consistent with the behavioral "self-caught" index of awareness. A third question required participants to describe the phenomenology of their last thought as (1) Inner Speech: i.e. talking to oneself in one's mind using words that one would have been able to report if needed, (2) Imagery: i.e. having the visual experience of a mental image or a "movie-like" memory (3) Other: using neither inner speech or imagery to think, or failing to introspect phenomenology. Participants could combine these categories to report complex subjective experiences. Finally, a fourth question asked about the time orientation of the thought, as being (1) Past-, (2) Present-, (3) or Future-oriented, or (4) Timeless. This last piece of data was collected for a different project and was not analyzed for this study.

Spontaneous reports of mind-wandering only featured the phenomenology and temporal orientation questions, as they were by construction aware mind-wandering episodes. Both spontaneous and external probes interrupted the primary tasks (SART, articulatory suppression, foot-tapping). The metronome was used after each probe to reset rhythm.

Procedure. Participants were tested individually in a quiet, dimly-lit room. Training consisted of three blocks (one per condition, in random order) of 24 SART trials each. Testing consisted in six experimental blocks (two per condition) of 108 trials each. Block order was pseudo-randomized so that two blocks of the same condition could not directly follow each other. The experimental session lasted around 29 minutes (SD = 3, range = [20 – 40]) depending on 1) the durations of metronome adjustments, 2) participants' propensity to make spontaneous reports, and 3) participant's speed in categorizing their thoughts. After the experimental session, participants were debriefed, and paid 10 USD or given course credits.

Results

Data analysis was performed with *R* (R Core Team, 2014) with the *lme4* (Bates et al., 2014) package for mixed models. All regressions are mixed models with participants as a random factor, and we present *p*-values that are considered significant at the $\alpha = 0.05$ level. Four participants were excluded due to noncompliance with the instructions of the dual task.

First, we assessed the effect of the experimental conditions on the first-order SART. As can be seen in ***Table 1***, response times in the single task were faster than in the two dual tasks ($p < .01$), suggestive of a dual task cost. We also observe a speed-accuracy trade-off in the foot tapping condition, slower (all ps < .01) and more accurate than both the articulatory suppression ($\beta = .45$, SE = .16, $z = 2.90$, $p < .01$) and single task ($\beta = .32 \pm .15$, $z = 2.10$, $p < .05$, AS/ST: $p > .4$). This suggests more controlled processing in the foot tapping than in the two other conditions.

Measure \ Condition	**Single-Task**	**Foot Tapping**	**Artic. Supp.**	***p-value***
RT go trials (ms)	366 (44)	440 (76)	390 (52)	***
Accuracy no-go (% correct)	42.20	48.19	39.92	**
Mind-wandering (mid-scale as MW, %)	37.56	39.51	33.67	***ns***
Awareness in MW (mid-scale AW excluded, %)	61.75	58.90	53.58	***ns***
Inner Speech (%)	31.94	33.33	29.98	***ns***
Number of Spontaneous Reports	3.04	3.00	1.96	***

Table 1: Effects of conditions on performance and introspective measures (Exp. 1). *Response Times (RT) were significantly different in each condition (all ps < .01), and Foot Tapping increased accuracy compared to both AS (p < .01) and ST conditions (p < .05, AS/ST: p > .4). Retrospective scales evidenced no significant differences in mind-wandering amount, mind-wandering awareness nor inner speech proportion. Crucially however, the number of spontaneous reports significantly decreased in the AS condition compared to both ST (p < .05) and FT conditions (p < .05, ST/FT: p>.9). * : p<.05, ** : p<.01, ***: p<.001*

Second, we analyzed reports of mind wandering from external probes, considering them as a baseline (Sayette et al., 2009, 2010). To do so, we binned reports on the mind wandering scale (< 3 categorized as "On-task" (N = 401), ≥ 3 "Off-task" (N = 252)), so as to create a binary mind wandering variable. Percentage of mind wandering were 37.56% (ST), 39.51% (FT), and 33.67% (AS). Pairwise logistic regressions did not reveal any significant differences between the conditions (AS/ST: $p > .4$, AS/FT: $p = .07$, FT/ST: $p > .2$), suggesting that our experimental manipulation did not impact participants' proneness to mind-wander.

Next, we tested whether awareness of mind wandering episodes was modulated by our experimental conditions. Crucially, a Poisson regression for count data revealed that participants were less likely to self-catch mind wandering under Articulatory Suppression (mean spontaneous reports = 1.96, SE = .55) than in the single task (3.04 ± .73, $\beta = -.44 \pm .18$, $z = -2.40$, $p < .05$) or the foot tapping conditions (3.00 ± .66, $\beta = -.43 \pm .18$, $z = -2.32$, $p < .05$, difference between Single Task and Foot Tapping $p > .9$, ***Figure 1a***).

The awareness scale of external probes led to similar, albeit non-significant results. Indeed, a binary index of awareness (excluding middle value) of mind-wandering evidenced the lowest index of awareness in the Articulatory Suppression condition (53.58% aware) compared to the Foot Tapping (58.90%) and Single-Task conditions (61.75%, all *p*s > .8).

Regarding phenomenology, proportion of inner speech across spontaneous and external reports of mind-wandering was reported to be lowest in the Articulatory Suppression condition (22.89 ± 4.43% vs. 31.97 ± 4.99% in Single Task and 30.53 ± 6.10% in Foot Tapping), but these differences failed to reach significance (all *p*s > .2). Along a similar line, proportion of visual imagery was higher in Articulatory suppression (43.37 ± 6.11) than in both Single task (38.70 ± 5.49) and Foot Tapping condition (32.47 ± 5.61), this latter difference being significant ($\beta = -.71 \pm .26$, $z = -2.74$, $p < .01$, ST-AS: $\beta = -0.36 \pm .25$, $z = -1.44$, $p = 0.15$).

Finally, self-caught reports, compared to probe-caught reports of mind-wandering, were significantly more verbal (36.20 ± 4.98% vs. 18.41 ± 4.23%, $\beta = 1.08 \pm .25$, $z = 4.37$, $p < .001$, ***Figure 1b***), less imaged (33.25 ± 5.43% vs. 37.39 ± 4.60%, $\beta = -0.53 \pm .24$, $z = -2.23$, $p < .05$) and less abstract (strict 'Else' response: 33.33 ± 7.54 vs. 44.92 ± 6.64%, $\beta = -0.80 \pm .26$, $z = -3.09$, $p < .01$). As such, the verbal aspect of mind-wandering episodes that were self-caught reports likely made them more vivid, though less imaged.

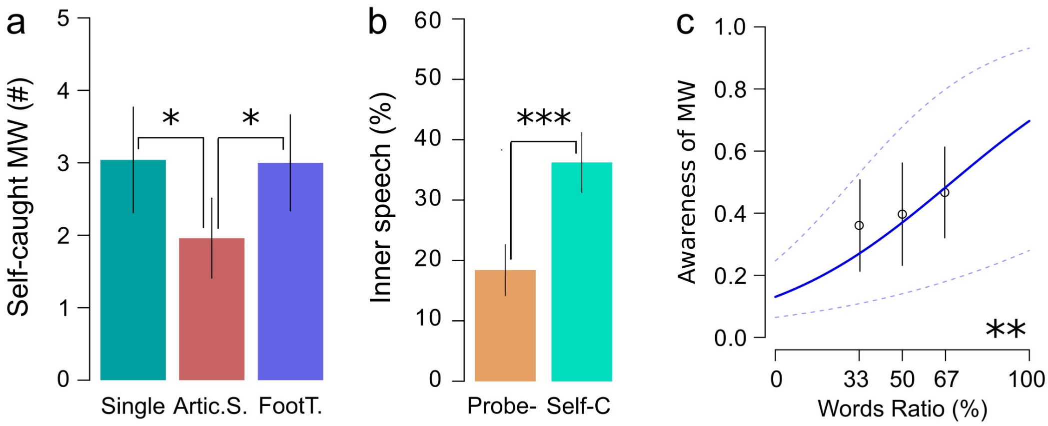


Figure 1: Results of Experiment 1 & 2. *a) Articulatory suppression decreased the number of self-caught reports of mind-wandering compared to the two control conditions. b) Self-caught reports of mind-wandering were more verbal than probe-caught reports of mind-wandering. Abbreviations: Artic.S.: Articulatory Suppression, FootT: Foot tapping, Probe-: Probe-caught reports of mind-wandering, Self-C: Self-caught reports of mind-wandering. c) Exp. 2: awareness of mind-wandering increased with the ratio of word to pictures among SART stimuli*

Discussion

Experiment 1 presents evidence that articulatory suppression, compared to control single and dual task conditions, decreased the number of spontaneous reports of mind-wandering, and which is a known index of meta-awareness of mind wandering (Schooler et al., 2004, 2011; Sayette et al., 2009, 2010; Baird et al., 2013a). Moreover, these self-caught episodes of mind-wandering were reported to be more verbal than probe-caught episodes of mind-wandering, which, by definition are less aware. This pattern of findings suggests that 1) inner speech facilitates access to mind-wandering and 2) interfering with verbal working memory is detrimental to mind-wandering awareness.

These findings are further vindicated by the absence of significant change in the likelihood to report mind-wandering on external thought-probes, thus suggesting that baseline experience of mind-wandering remained unaffected by experimental conditions.

However, the present experiment did not evidence significant decreases in retrospective assessment of inner speech, nor awareness, across experimental conditions. We speculate that the production of a vocal stream in the AS condition, so that it was difficult for them to assess whether they were *thinking* verbally or not.

Experiment 2 was designed as more implicit manipulation of verbal working memory than articulatory suppression, and thus freed resources that dual tasking might have consumed. Finally, while Experiment 1 showed that we could decrease awareness of mind-wandering, Experiment 2 aimed at showing that we could *increase* awareness of mind-wandering. Experiment 2 rationale was that, given that reading automatically involves inner speech (Pintner, 1913; Abramson and Goldinger, 1997), greater ratio of verbal to imaged stimuli would increase activation of verbal working memory, and thus we predicted that it would increase meta-awareness of mind-wandering.

Experiment 2

Materials & Methods

Participants. 24 participants (17 females, 23.1 y.o. ± 3.9, [18-34]) were recruited from the listings of the LSCP, Paris. All had normal or corrected-to-normal vision and were paid 10 euros, for a one hour session.

Materials

Task. The SART was adapted so as to present concepts, in words or pictures. Stimuli were presented for 1.5 s every 3.5 s. Participants were required to press the space bar as fast as possible in response to each stimulus but to withhold their response when presented with one no-go target concept, randomly picked for each participants. 12 concepts were used: 3 categories (animal / object / scene) X 2 familiarities (high / low) X 2 instances---for example we had 2 concepts for highly familiar animals: “dog” and “cat”, see Appendix 1 for the complete table of stimuli. Furthermore, for each concept, there were 4 exemplars: 2 words (lowercase / uppercase, Arial, 20) and 2 different pictures. This combination of conditions resulted in a set of 48 items, 4 of which (e.g. “DOG”, “dog”, Dog-Picture1 and Dog-Picture2) were designated for a given participant as no-go targets (8.3%).

Pictures. A set of 24 colored pictures of 256×256 pixels were picked from Oliva and colleagues' (Brady et al., 2008) stimuli base[4]. Two pictures illustrated each one of four animals (dog, cat, bird and butterfly), four objects (key, clock, leaf and mushroom) and four scenes (city, street, mountain and beach). The sixteen animals and objects were displayed on a white background, whereas the eight scene pictures occupied the 256×256 pixels rectangle.

Word/Picture Ratio. Each participant was presented with a seamless experiment, in fact divided in three blocks of equal length. Six repetitions of the two exemplars of each of the twelve concepts composed the 144 trials (including the 12 targets) of each block. Due to randomization, transitions between blocks were inconspicuous. The three blocks differed with respect to their picture / word ratio, which was 33%, 50% and 67% which constituted the critical condition of this experiment. Given the small percentages difference, the randomness of the order of pictures and words within blocks, and the absence of any explicit demarcation between blocks, our experimental conditions were anticipated to be implicit.

Thought-reports. Twelve pseudo-randomly distributed external probes interrupted the task in each block: 6 immediately following picture-stimuli and 6 immediately following word-stimuli (regardless of the type of block). This controlled for priming by the immediately preceding stimulus. Mind wandering and meta-awareness scales were 5 grades Likert scales identical to the ones of Experiment 1. Similarly, the time orientation scale was identical to Experiment 1, and will not be further discussed. However, questions about phenomenology were now derived from Hurlburt and colleagues' descriptive studies (Heavey and Hurlburt, 2008). Six possibilities were provided on a randomly organized scale: (1) inner speech (2) visual imagery, (3) auditory imagery (e.g. having a tune in mind), (4) bodily sensation: focus on one's body, (5) emotion: focus on a particular emotion (e.g. sadness), (6) other: thought that was neither in words, images, sounds, and not even a sensation or an emotion. This last category could also be chosen when participants could not successfully introspect the form of their thought. As opposed to Experiment 1, these possibilities were mutually exclusive and participants had to report the most salient and obvious phenomenology. This was justified by the fact that in Experiment 1, only 14 of the 1010 thought-reports (<1.5%) were mixed forms thoughts. There was no spontaneous reports in this Experiment and awareness was exclusively measured with the awareness scale.

---

4 Available (Last updated : 05/18/15) at the web address :http://cvcl.mit.edu/MM/stimuli.html

Short version of the Individual Difference Questionnaire (IDQ). Participants' imaginal and verbal thinking habits and skills (i.e. "cognitive styles") were measured with the "verbal habits" and "imaging habits" subscales of the French version (Grebot, 2000) of the Individual Differences Questionnaire (Paivio and Harshman, 1983).

Procedure. Participants first performed a training session of 20 trials (2 no-go targets and 2 external probes). Then they completed the main experiment, which, depending on their speed in classifying their thoughts lasted 30 to 45 minutes. Debriefing questions ensuring implicitness of the manipulation and the short IDQ were then administered.

Results

Debriefing questions revealed that no participant identified the manipulation of picture / word ratio. Analyses were therefore conducted on the 24 participants.

Performances on the SART are presented in ***Table 2***. We found no significant effect of the experimental conditions on performance. Then, we tested whether the likelihood to report mind wandering was modulated by our experimental condition. We binned reports on the mind wandering scale (< 3 categorized as "On-task" (N = 357), ≥ 3 "Off-task" (N = 504)), so as to create a binary mind wandering variable. A logistic regression with percentage of words as predictor did not reveal any significant effect of the percentage of words on the proportion of mind wandering (59.03, 57.99 and 59.03% with respectively 33, 50 and 67% words, $p > .9$).

Next, we tested whether awareness of mind wandering was modulated by the proportion of word in a block. The 504 mind-wandering reports were binned along the awareness scale (< 3 categorized as "aware" (N = 166), > 3 "unaware" (N = 261); excluding 77 mid-scale reports). As predicted, a logistic regression revealed that mind-wandering awareness significantly increased with proportion of words (36.0, 39.7 and 46.7% in 33, 50 and 67 % words blocks, $\beta = 2.74 \pm 1.01$, $z = 2.70$, $p < .01$, ***Figure 1c***).

Further analyses on the likelihood to report verbal thoughts revealed no significant effect of word ratio ($p > .5$), and there was no significant correlation at the inter-individual level between awareness of mind-wandering and verbal ($p > .9$) or imaging ($p > .2$) cognitive styles.

Measures \ Words Percentage	*33%*	*50%*	*67%*	*p-value*
RT go (ms)	662 (156)	650 (162)	656 (142)	***ns***
Accuracy no-go (% correct)	91.00	86.86	87.23	***ns***
mind wandering (mid-scale as MW, %)	59.03	57.99	59.03	***ns***
Awareness in MW (mid-scale AW excluded, %)	36.06	39.68	46.69	**
Proportion of Inner Speech	31.94	33.33	29.98	***ns***

Table 2: Effects of conditions (Exp. 2). *Word ratio did not significantly affect RT, accuracy, mind-wandering or inner speech, but did increase mind-wandering awareness (p < .01).*

Discussion

Experiment 2 evidenced that while an implicit manipulation of the amount of verbal processing did not affect performance nor the amount of mind-wandering, greater word ratio – and thus greater activation of verbal working memory – increased awareness of mind-wandering: as the proportion of words in a block increased, awareness of mind wandering as assessed with external probes increased.

Given that in each block, half of the thought-probes were presented after a picture and half after a word, this effect cannot be due to the local priming from the immediately preceding stimulus, but instead to a contextual effect at the level of the block. Moreover, unlike Experiment 1, the critical manipulation was implicit, ruling out any explanation coming from the demand characteristics of the task.

Previous studies have reported effects of sensory stimuli on the temporal orientation of mind wandering (Smallwood et al., 2009b; Miles et al., 2010) but, to our knowledge, this experiment is the first to show that on-line first-order processing can impact awareness of mind wandering.

We did not find an effect of word ratio on reported inner speech. To decipher whether this was truly due to a lack of awareness of the role of verbal working memory in mind-wandering awareness, we designed Experiment 3 as a crowd-sourced ecological study. Although we could not create controlled experimental manipulations, Experiment 3 had two advantages: First, we could recruit more participants than in Experiment 1 & 2. Second, we could probe participants in their natural environment. Questions about phenomenology were also refined, so as to quantify thoughts' verbal, visual and auditory vividness independently from each other. We predicted that only verbal vividness would positively correlate with awareness of mind-wandering.

Experiment 3

Materials and methods

Participants. We designed an application, *Daydreaming* (http://daydreaming-the-app.net/), running on Android smartphones, that was officially released on January 20th, 2015. Promotion of the application was made via social networks and oral presentations. Promotion never mentioned the hypothesized relation between inner speech and mind-wandering awareness, but made clear that the application had a research goal.

On July 1st, 2015, the application had been downloaded 253 times. Here, the relation between thought vividness and mind-wandering is based on the data of the 93 participants (53 females, mean age: 28.7, SD = 10.1, range = [18, 60-69]) that completed at least one random probe. The analysis on the relation between thought vividness and awareness of mind-wandering is based on the data of the 78 participants (44 females, age = 28.5 ± 9.9, range = [18, 60-69]) that reported mind-wandering (a score inferior or equal to middle scale, 534 out of 1123 probes) at least once.

Methods

Three different types of interactions, all in English, were proposed by the *Daydreaming* application.

*Begin/End Questionnaires***.** First, upon downloading the application, participants were required to fill three standardized questionnaires: the 15-items Mindful Attention Awareness Scale (MAAS, Brown and Ryan, 2003), the 35-items Scale Of Dissociative Activities (SODAS, Mayer and Farmer, 2003), and the 24-items Rumination-Reflection Questionnaire (RRQ, Trapnell and Campbell, 1999). These three questionnaires were also proposed at the end of the 30-days study.

Morning/Evening Questionnaires. Second, three questions appeared on the application every morning (silent notification at 5am), asking about sleep duration, dreams vividness, and valence of dreams. Two questions appeared every evening (notification at 10pm), asking about overall happiness and amount of automatic pilot sensation during the day, and about the duration of various activities the participant might have had (eg. exercising, watching television, playing music, etc.).

Random Thought probes. Participants were randomly probed during the day. Unexpected notifications were triggered every 2 hours on average. If the probe was not completed, the notification disappeared and was reprogrammed. Probes asked about the context (location, number of people around, type of noise) and type of activity participants were engaged in. Crucially, we probed mental content: 1) "How focused were you on what you were doing?", on a 5 points scale: "My mind was totally wandering ; My mind was mostly wandering ; My mind was both focused & wandering ; My mind was mostly focused ; My mind was totally focused", 2) "How meta-aware were you of your mind wandering?", 4 points scales: "Not aware at all of my mind wandering ; The phone might have helped me notice ; I knew I was mind wandering somehow ; I knew explicitly I was mind wandering", 3) "How aware were you of your surroundings?" (surrounding question, not analyzed), 4) "Were you thinking in words?", 4 points: "Not at all ; In some abstract way ; With some precise words ; In clear and precise words", 5) "Were you thinking with visual images?" 4 points: "Not at all ; In some abstract way ; With some visual features ; With vivid images", 6) "Were you thinking with sounds?" 4 points scale: "Not at all ; In some abstract way ; With some acoustic features ; With vivid sounds" 7) "Who were you thinking about?" (not analyzed).

These questions appeared on the same screen, in random order, with the exception that the awareness of mind-wandering question always followed the mind-wandering question immediately. All subjective questions featured a “I don’t know” button distinct from the continuous cursors with hints. For questions about thought vividness, these responses were taken as a “Not at all”. Full completion of the thought probe lasted less than 1 minute. All questionnaires and most of the non-subjective questions were collected for a different project. The following results therefore focus on the relations between mind-wandering, mind-wandering awareness and verbal, visual and auditory vividness.

Procedure. Volunteers downloaded the application from the Google Play store and used it as much as they wished. After participating for 30 days and responding to 10 probes at least, a synthesis of the participant’s results was displayed on the application as a token for his/her participation.

Results

We first aimed at identifying the specific phenomenology of mind-wandering. A logistic regression with verbal, visual and auditory vividness as predictors evidenced that only visual vividness predicted mind-wandering (β = .34 ± .12, z = 2.94, p < .01), so that visual imagery was greater in mind-wandering (1.37, SE = .12, scale from 0 to 3) than in focused attention (.97 ± .10). Neither inner speech vividness (β = -.04) nor auditory vividness (β = .10) predicted mind-wandering (ps > .4).

Second, among mind-wandering responses, the awareness question was binarized so as to consider "I somehow knew ..." and "I knew explicitly" answers as reflecting aware mind-wandering. A logistic regression with verbal, visual and auditory vividness as co-predictors, now on the likelihood to be aware of mind-wandering episodes, revealed that only inner speech vividness was a significant (positive) predictor of awareness (β = .33 ± .15, z = 2.266, p < .05, ***Figure 2***): inner speech was more intense in aware (1.55 ± .12, scale from 0 to 3) than unaware mind-wandering (1.12 ± .11). Here, neither visual (β = .16) nor auditory vividness (β = .14) predicted mind-wandering awareness (ps > .25).

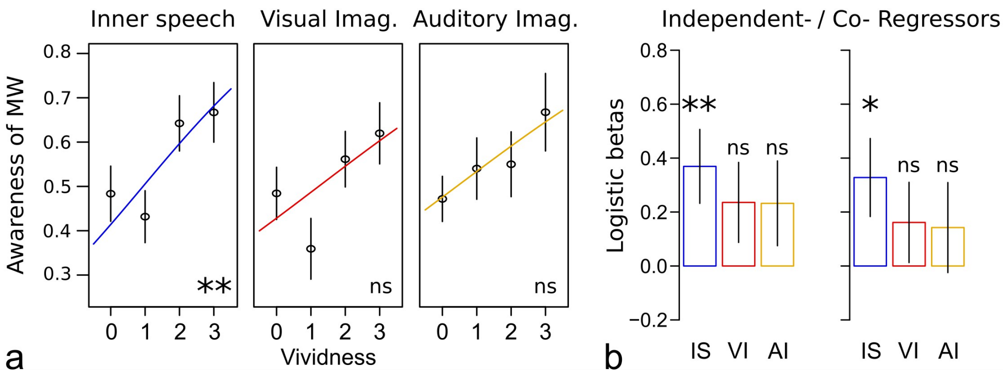


Figure 2. Results from the* Daydreaming *app. *a) Awareness of mind-wandering is significantly predicted by Inner speech vividness (left, blue), but not by Visual (middle, red), nor Auditory (right, gold) imagery. b) Plot of the logistic betas from the regressions on awareness of mind-wandering, with 1) each form of thought independently (left, three independent regressions), or 2) the three forms taken all together as co-regressors (right, a unique regression). The main text reports this last regression. Abbreviations: Imag.: imagery, IS: Inner Speech, VI/AI: Visual/Auditory Imagery.*

Discussion

As an *in-vivo* crowd-sourced study on a smartphone application, Experiment 3 provided further evidence of a positive relation between inner speech and awareness of mind-wandering. Indeed, reports from volunteers having downloaded the application consistently related inner speech vividness to their awareness of mind-wandering, while visual and auditory vividness did not predict awareness. As such, this effect cannot be accounted for by a non-specific effect of vividness.

Moreover, visual vividness was shown to predict the likelihood to report mind-wandering, as mind-wandering was significantly more visual than focused attention. Beyond proving the sensitivity of the visual vividness measure, this also confirms previous suggestions that most mind wandering involves mental imagery (Smallwood et al., 2004), and that on-task thoughts may be more similar to mind-wandering with awareness (sharing verbal components), than to mind-wandering without awareness (Christoff et al., 2009).

General Discussion

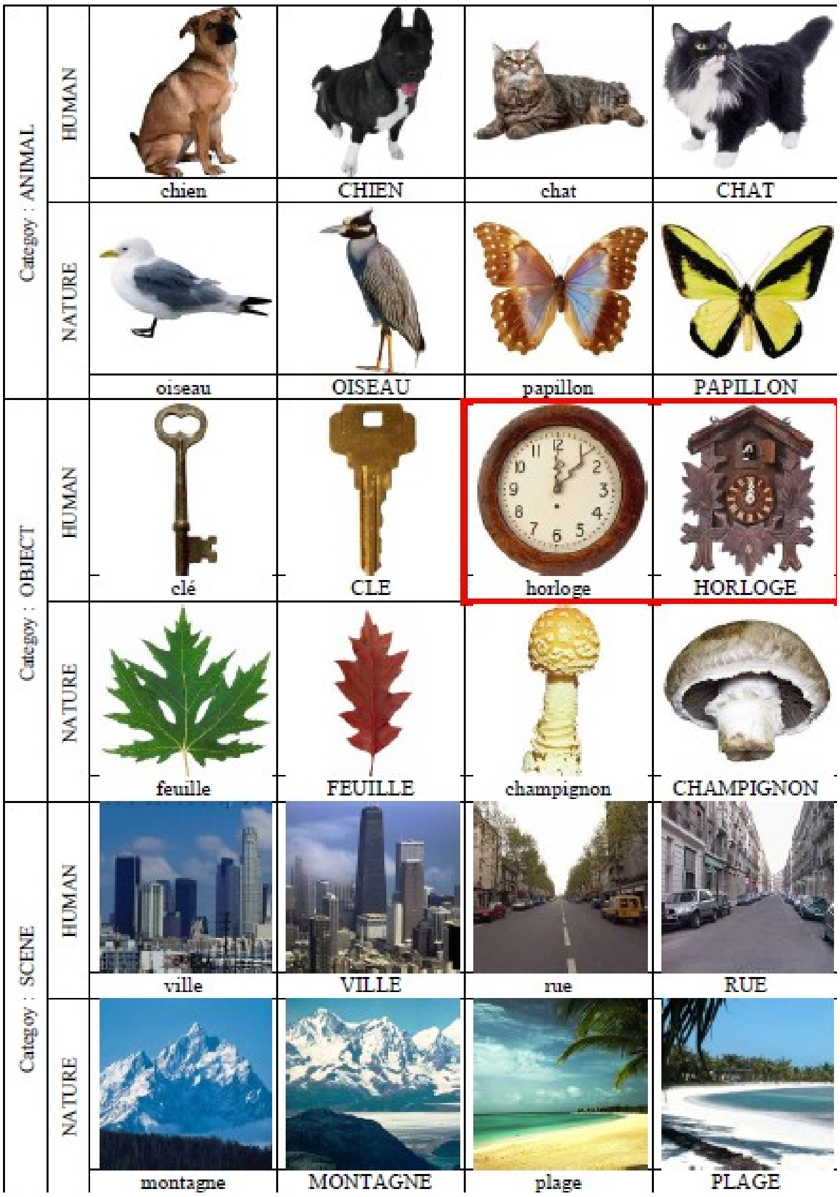
The hypothesis that inner speech facilitates awareness of mind wandering was tested in three experiments. Experiment 1 showed that articulatory suppression, known to interfere with verbal working memory, decreased the likelihood to spontaneously notice mind-wandering. Moreover, self-caught episodes, by definition more aware, were also reported to be more verbal than probe-caught reports of mind-wandering. Conversely, Experiment 2 showed that increased activation of verbal working memory increased awareness of mind-wandering. Finally, thought reports made on smartphones during participants' daily life evidenced a positive correlation between inner speech vividness and mind-wandering awareness, to the exclusion of visual or auditory vividness (Exp. 3). Together, these findings support the hypothesis that inner speech, unlike visual or auditory imagery, facilitates awareness of mind-wandering.

Our study suggests new lines of research on introspection. Showing that the introspective capacity to notice one's mind-wandering relates to the verbal capacity of expressing its content, the present study provides, to our knowledge, the first experimental evidence in favor the recently proposed view that consciousness serves cultural purposes such as sharing experiences and thoughts (Baumeister and Masicampo, 2010). Future research should explore whether this positive role of inner speech extends to the introspection of other mental contents. For instance, decreased amounts of inner speech could index psychological absorption and “flow” states (Nakamura and Csikszentmihalyi, 2002; Dietrich, 2004), or immersive experiences such as hypnosis (Demertzi et al., 2011). Similarly, the extent to which other forms of meta-cognition, such as confidence estimation (Fleming et al., 2012), subjective estimations of time (Miller et al., 2010; Wittmann, 2013), or feeling of knowing (Reder and Ritter, 1992) also involve inner speech should also be further tested.

The question of the psychological architecture of meta-cognition has obvious neurobiological implications. The rostro-lateral prefrontal cortex (rlPFC, Brodmann Area 10) has been proposed as a common neuro-imaging correlate for awareness of one's thoughts (McCaig et al., 2011), mindfulness and awareness of one's body (Fox et al., 2012) and confidence evaluation (Fleming et al., 2012). Furthermore the rlPFC has also been related to the processing of internal stimuli (Burgess et al., 2007). However, rlPFC was also found to be *more* activated during unaware mind wandering than during aware mind wandering (Christoff et al., 2009), suggesting ambivalent relations between rlPFC and introspection. The anterior insular cortex has also been related to awareness of mind wandering (Christoff et al., 2009; Hasenkamp et al., 2012), and to broader interoceptive awareness and consciousness (Craig, 2009). Interestingly, effects of laterality have been observed, with the activation in the left insula being related to mindful states on the one hand (Tang et al., 2009) and to inner speech and auditory hallucinations on the other hand (Mcguire et al., 1996). Our study suggests that further explorations of the neural correlates of introspection may benefit from systematic exploration of the functional links between language areas (Geva et al., 2011; Marvel and Desmond, 2012), the anterior insula and the rlPFC.

In conclusion, while we show a role of inner speech in the meta-awareness of mind wandering, the functional mechanisms are still to be further described. A first hypothesis would be that inner speech is salient to introspection, as speech and language are to perception (Jiang et al., 2007; Yang and Yeh, 2011). A verbal thought would therefore passively, and more easily, reach consciousness than other mental contents, in virtue of its verbal nature. That inner speech vividness correlates with mind-wandering awareness (Exp. 1) provides evidence for this hypothesis. Yet, inner speech could also belong to the machinery of noticing one’s thoughts (Carruthers, 2002), and this structuring role in the extraction of thoughts to introspection would therefore suggest that inner speech is an active tool for consciousness. Addressing these questions in further detail would clarify the relations between two of the most human cognitive characteristics: language and reflexive consciousness.

Acknowledgments. *We thank Mike Mrazek & Ben Baird for insightful discussions. This research was funded by a grant from the Agence Nationale de la Recherche (France) "Dynamind" ANR-10-BLAN-1902-01 to JS, by two grants to MB, one from the Fondation de l'École Normale Supérieure and one from the Direction Générale de l'Armement. The application visual design was created by Gislain Delaire, thanks to a funding of the Mairie de Paris for the project "Sciences en Poche", hosted by David Chavalarias.*



Appendix. Table of the 48 stimuli of Exp. 2. *The red frame indicates a set of possible targets (here "clock"). English translations of the French words are: dog, cat, bird, butterfly, key, clock, leaf, mushroom, city, street, mountain, beach.*

CHAPTER 6: A DECISION ACCOUNT OF MIND-WANDERING CONTROL: BEHAVIORAL AND PUPILLOMETRIC SIGNATURES OF CRITERION-BASED DETECTION OF TASK-UNRELATED THOUGHTS

This chapter is based on the draft of an article (Bastian, Wyart & Sackur, submitted) in collaboration with Valentin Wyart, from the Laboratoire de Neurosciences Cognitives (INSERM Unit 960, ENS). In this chapter, we propose that detecting mind-wandering is a decision, with an adjustable introspective criterion applied to a noisy internal variable. We attempted to manipulate participants' criterion in reporting mind-wandering, and found that indeed, participants could report more mind-wandering under similar performance, similar validity of their reports in regards to performance, and even similar amounts of mind-wandering as assessed retrospectively. Moreover, we found that conservative reports of mind-wandering required greater amounts of internal signal, as measured with greater amount of integration of task performance up to 30 seconds before the report (Exp. 1), greater inner noise and greater response lag (Exp. 2). Finally, pupillometry proved to be sensitive to introspective criterion change, as it is to perceptual criterion change, thus providing further physiological evidence of a decision mechanism when detecting mind-wandering.

Abstract. *How do humans access the content of their thoughts? We propose a process-based model, according to which the mechanisms of introspection are analogous to decision processes in perception. We collected introspective reports of attentional states (focused or mind-wandering), in two experiments using transient-free visual stimulation, that allowed fined-grained and continuous measures of performance and pupil dilation. We show that both explicit and implicit instructions shift participants' criterion for reporting mind-wandering, while pupil reactivity tracked criterion adjustment, as previously found for perceptual decisions. Furthermore, we show that the decision variable underlying introspective reports dynamically integrates fluctuations of attentional signals over up to 30 seconds, and that the strength of this integration is increased when participants are conservative in their mind-wandering reports. Introspection thus possesses two classical signatures of a decision process: the independence of the signal from the criterion, and the higher signal strength in conservative than liberal correct detections. Overall, these findings reveal, first, that when participants are asked to report their subjective mind-wandering states, they actually decide on the basis of internal attentional signals integrated over time; second, that pupil phasic reactivity is a marker of both the attentional state and of its cognitive detection mechanism.*

Key words: *attention; introspection; decision; mind-wandering; pupil size*

Introduction

How do humans assess their internal subjective states? Despite growing interest in conscious states (Lau and Rosenthal, 2011; Callard et al., 2013), the mechanisms of introspection remain largely unknown. Conscious contents often seem so salient that no complex mechanism would be needed to assess them: subjects would have a direct and error-free access to vivid thoughts. This so-called 'transparency' of thoughts has been challenged on philosophical grounds (Armstrong, 1963), but, to our knowledge, it has not been tested empirically. In this respect, introspection stands in stark contrast with perception, as perception has long been theorized as a decision process (Green and Swets, 1966b; Weiss et al., 2002; Dehaene et al., 2006). Perceivers are not in direct contact with the external world; rather percepts are the resultant of a criterion based separation of signal from a noisy environment (Brown and Steyvers, 2005). Here, capitalizing on recent advances in the field of mind wandering, we demonstrate that introspective reports on self-generated thoughts are similar end products of decision processes.

The very idea of a decision process implies that one should be able to manipulate the criterion, that participants adjust to their current conservative or liberal goals, separately from the signal, the (sensorial) basis of the decision (Green and Swets, 1966b). As a consequence, signal is on average greater for conservative than liberal correct detections. We propose that this framework can be applied to the introspection of mind-wandering: when asked to report whether they are off-task or not, participants actively monitor an internal attentional state variable, in an internal noisy environment. If this internal variable exceeds a criterion, participants report that they are off-task. Thus, the first step in the application of the decision framework to introspection of mind-wandering is to show that participants can adjust an introspective criterion when reporting mind-wandering, and second, that mind-wandering signal is on average greater for conservative than liberal mind-wandering reports.

Recent work has shown that mind wandering reports have predictive value on behavioral, neural and physiological observable markers (Bastian and Sackur, 2013; Mittner et al., 2014). This validates the use of behavioral indices, such as momentary performance, as a proxy for the internal attentional state variable. Now, according to our hypotheses, performance should not only predict mind-wandering, but also reflect criterion adjustment: performance should decrease when participants report that they are off-task, but more so when they adopt conservative than liberal attitudes. Yet, overall performance should remain unaffected by criterion change, as well as the predictive value of performance on subjective states. In sum, liberal or conservative attitudes towards off-task reports should only affect the depth of mind-wandering – that is the level of the attention state variable – needed to elicit an off-task report, while the overall amount of mind-wandering should remain unaffected.

We tested these hypotheses in two experiments with new paradigms using smooth and transient-free stimuli. Most mind-wandering studies are build around discrete, trial based tasks such as go/no-go task (Bastian and Sackur, 2013; Smallwood, 2013c; Mittner et al., 2014). However, salient events – such as trial transients – automatically capture attention (Smallwood, 2013c) and elicit large pupil responses, which can hinder the analysis of this potentially useful physiological marker of mind-wandering. Also, performance dynamics are often discretized according to the duration of discrete trials. Our paradigm overcomes these issues by allowing an event-free and fine-grained measure of task performance (***Figure 1a***). In Experiment 1, the orientation of a central low-contrast Gabor pattern varies continuously between -45° and +45° at an irregular speed (range: 0-100°/s, mean 21°/s). Participants' task is to continuously track this orientation with a joystick, whose position appears on screen. Stimulation smoothness is ensured by the addition of an auto-correlated spatially smoothed Gaussian noise (Wyart et al., 2012). Random auditory tones request participants to report their subjective experience as either on-task (focused) or off-task (mind-wandering) by pressing one of two buttons on the joystick.

Materials & Methods

Participants. Exp. 1: 40 participants (32 females; age: 22.5, SD = 2.9, range = [18-31]) participated in the two 90-minutes sessions constituting Experiment 1. Two outliers who moved the joystick too fast were excluded from the analyses. *Exp. 2:* Two homogenous groups of 16 participants constituted the liberal framing group (12 females; age: 23.9 ± 3.3, [19-30]) and the conservative framing group (12 females; age: 24.0 ± 4.4, [18-33], age difference: $p > .9$). Filling of the MW-deliberate and MW-spontaneous scales (Carriere et al., 2013) at the end of the experiment revealed no significant difference between everyday amount of mind-wandering between the two groups (two-sample t-tests: $ps > .5$). All participants had normal or corrected to normal vision (no glasses).

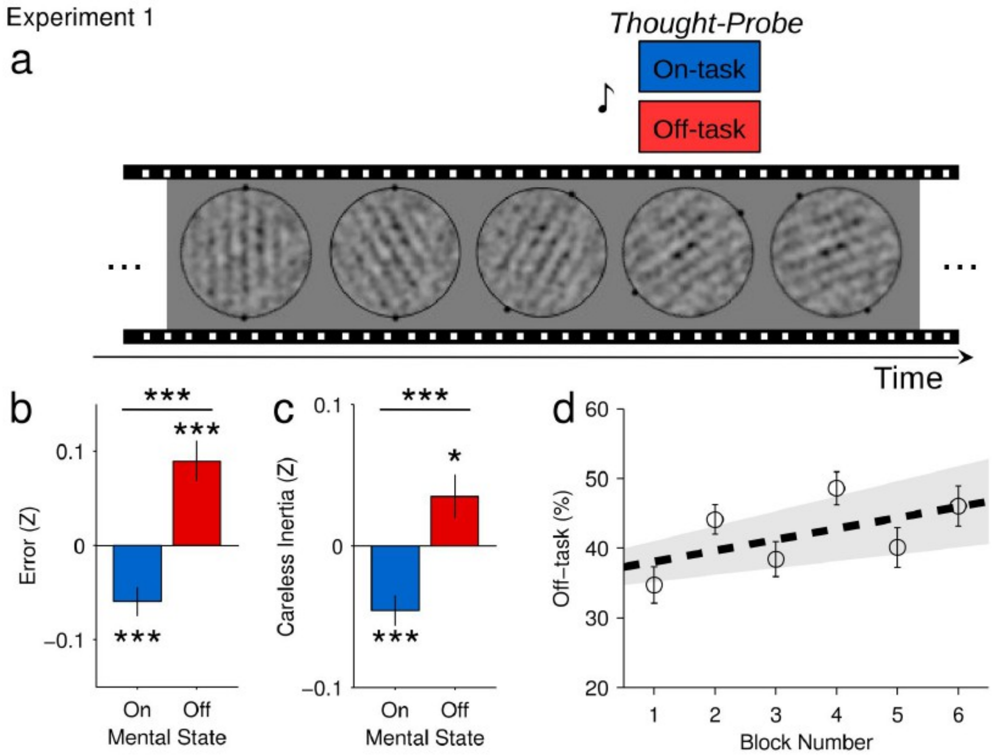


Figure 1: Paradigm & mind-wandering effects. Experiment 1. *a) Paradigm: participants were required to track the Gabor orientation by continuously aligning the joystick to the current orientation. The joystick position was displayed by two black ticks at the periphery of the Gabor. At times, while still performing the task, an auditory tone probed participants' mental content. b, c) Error and inertia were higher prior on-task reports than off-task reports. d) Off-task reports increased during the experiment.*

Stimuli. Both experiments used a central low-contrast Gabor patch mixed with randomly moving auto-correlated spatially smoothed Gaussian noise (Wyart et al., 2012). In Experiment 1, contrast of the central Gabor was kept constant above participants' threshold at 20%, but the first training block at 30%. Stimulus orientation constantly changed between -45° to +45° around the vertical axis at an irregular speed (from 0-100°/s, mean 21°/s). The only constraint to these changes was that the stimulus orientation had to cross the vertical line every 1 to 5 seconds (uniform distribution). In Experiment 2, contrast was constantly adapted to a 75 % correct performance with a "1-down/3-up" staircase procedure. Stimulus orientation changed every 2.5 to 5 seconds (uniform distribution) between -30 and +30° around the vertical axis, by progressively decreasing/increasing the adjusted contrasts of the previous/current stimuli. Luminance was constant across both experiments.

Apparatus. All stimuli were displayed against a grey background (refresh rate .05 Hz) on a computer running Matlab with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Eye movements were recorded monocularly with an eye-tracker (Eyelink 1000 system, SR research, Ontario, Canada) controlled with Eyelink toolbox (sampling rate 500 Hz).

Thought probes. In both experiments, external thoughts probes were brief auditory tones displayed at comfortable volume in the room. Each probe was to be answered as a two alternatives force choice (2AFC) between "currently experiencing on-task" or "off-task thought". The phenomenological aspect of off-task thoughts was explicit, describing mind-wandering as "thoughts unrelated to the here and now or the task, such as thoughts about a friend, the context (heat, luminosity), the experimental design, the participant's past or future". In Experiment 1, reports were made on the joystick, whereas they were made on the keyboard in Experiment 2.

Inter-probe interval. Exp. 1: predefined inter-probe intervals (15, 30, 45, 60, 75 and 90 seconds) were presented in random order, with a 1-minute probe-free period at the beginning of each block, leading to an amount of 12 probes for each of all 6 experimental blocks. *Exp. 2:* inter-probe interval was randomly sampled in a uniform distribution from 15 to 35 seconds, leading to an amount of 24 probes for the two blocks that featured external probes. There were no probes in the two blocks requiring spontaneous off-task reports.

Procedure. Exp. 1. Both sessions started with two 2-minutes training blocks: one teaching about joystick use with no mention of subjective reports, and one with 3 thought-probes introducing off-task thoughts definition, and the "liberal" or "conservative" strategy targeted in the session. The "liberal" strategy required participants to make off-task reports when they were sure they were not on-task (with an "ideal off-task proportion" of 2/3 of the probes), and the "conservative" strategy required participants to make off-task reports when they were sure they were off-task (with an "ideal off-task proportion" of 1/3 of the probes). Strategy order was counterbalanced across participants. The two training blocks were followed by six 12-minutes experimental blocks. At the end of the second session, participants were extensively debriefed about their subjective experience and the strategies they used to conform to the targeted numbers of off-task reports. They were then paid 30 euros.

Exp. 2: Participants received two training blocks, a first 6-minutes one with 12 auditory probes and a second 5-minutes one without probes, but with the requested spontaneous reports of mind-wandering. These two training blocks were followed by four 10-minutes experimental blocks, alternating blocks with and without external probes, the order of which as counterbalanced across participants within each group of framing. All blocks were followed by a screen presenting the current contrast, the current amount of pupil loss, and a framing mock feedback announcing an amount of mind-wandering around 50% (conservative) or 75% of the time (liberal group). This feedback was made more plausible by displaying first, for a few seconds, a progression bar "computing off-task thoughts percentage and number based on participants' responses and pupillometry". After the Experiment, participants filled the MW-D and MW-S (Carriere et al., 2013), were debriefed and payed 10 euros.

Behavioral analyses.

Exp. 1: Error was computed as the absolute difference in angle between the stimulus and the joystick, after correcting for the lag in their cross-correlation. Similarly, inertia was the residual of the derivative of the joystick, unexplained by the derivative of the stimulus. Inertia was signed so that a joystick going in the other direction than the stimulus was negative. Given that noise randomly varied the amount of evidence (or energy) about the orientation of the stimulus, sometimes improving, sometimes masking Gabor contrast; error and inertia were corrected by the amount of variance explained by changes in stimulus energy.

Integration analysis: one-minute probe-free times series excluding potential probe related rhythms (band-stop filter at 1/15 Hz) were analyzed. . The memory-less model consisted in the assignment of a given time series of error preceding a probe, to either an "on-task" or "off-task" label. This assignment was based on whether the last data point of the time series – error immediately preceding the probe – was above a given threshold. This threshold was determined, for each subject, with the estimates of the logistic regression where last instant error predicted the likelihood of off-task reports. Integration was then computed as the difference between the memory-less model and the participant error at each moment in time, for on-task and off-task reports separately.

Exp. 2: Percept switches were modeled as follows:

$$DV_{(t)} = [\ E1_{(t-l)} - E2_{(t-l)}\ ] * -b + g + N(1,0)$$

where *DV* stands for the Decision Variable eliciting the change in response (0 / 1), *t* the current time, *E1(t)* et *E2(t)* the energies of the two orthogonal orientations at time *t*, l the lag at which the difference in energy in the past best predicts the current response (in ms), b the inner noise, or the factor that best predicts how important is the difference in energy in the current response switch, g the tendency to keep the response the same across all times (the inertia), and *N* the scaling parameter. Faster changes being after 2.5 seconds, the three free parameters g, b and l were first fitted on a -2.5:2.5s window around *all* stimulus reversals to measure overall performance, separately for blocks with probes and with spontaneous reports – difference between blocks was not significant. Fixing the fitted g (inertia), we then re-fitted the model on the last stimulus reversal preceding either on-task probes, off-task probes, or spontaneous off-task reports, to compute variations of lag (l) and gain (b) around overall performance taken as a baseline.

Pupillometry. Missing data around blinks (-100:300ms) was interpolated. Beyond smoothing with a 50ms running window, the unfiltered data was only z-scored by block to account for inter-individual & inter-blocks variations.

Bayesian Statistics. Bayes Factors (BF) are Bayesian statistics which indicate whether the data supports the tested (H1) hypothesis over the null (H0) hypothesis (high BF > 1) or the null hypothesis over the tested hypothesis (BF < 1, close to 0). All BF with no prior were based on model comparisons: the Bayesian Information Criterion (BIC) of the model with the predictor (tested hypothesis) was compared to the BIC of the model without the predictor (null hypothesis) with the following standard formula:

$$\text{Bayes Factor} = \exp(-0.5 * [\ \text{BIC(H1)} - \text{BIC(H0)}\ ]\ )$$

Finally, given that previous literature had made claims on an effect of mind-wandering on tonic pupil size, we used an online calculator of Bayes Factors that included Priors (Dienes, 2014).

Results

Mind-wandering alters performance and increases with time.

As expected, mind-wandering correlated with poorer task performance. Participants' error was higher before off-task reports than before on-task reports (9.7 ± .5° vs 8.6 ± .3° mean angular disparity, between the stimulus and the response one second before the probe; paired t-test, $t(37) = 5.6$, $p < 10^{-5}$, ***Figure 1b***). Moreover, we analyzed participants' corrective behavior as the residual joystick velocity with respect to the signed velocity of the stimulus. The cross correlation between this residual velocity and error peaked at +550 ms (r = -.124, SE = .004), indicating that participants increased increased inertia predicted greater error half a second later. As with error, this "careless" inertia was higher in the last second before off-task reports compared to on-task reports ($t(37) = 3.8$, $p < .001$, ***Figure 1c***), indicating less corrective behavior during mind-wandering. Furthermore, participants reported being more often off-task at the end of the experiment: the likelihood of off-task reports increased with time (logistic regression with block number as factor, β = .05, SE = .02, $z = 2.6$, $p < .05$, ***Figure 1d***). Overall, these findings confirm and extend recent observations on the effects of mind-wandering on performance, and on the effects of time spent on the task on mind-wandering (Farley et al., 2013).

Adjusting mind-wandering reports without altering overall performance nor momentary performance predictive value.

Subjective reports are thus rooted in behavioral performance. But what are the mechanisms behind these reports? We proposed above that the classification of one's thoughts is a decision that requires the setting of an adjustable criterion on an internal variable. In Experiment 1, we used a within-participant, explicit design: in one session participants were requested to adopt a conservative strategy and report being off-task only when certain that they were mind-wandering; in the other session the strategy we asked for was the opposite, liberal one: participants were asked to report "off-task", when they were certain not to be on-task.

As predicted by a decision framework for introspection, participants successfully followed the instructions and were more likely to report off-task thoughts in the liberal (mean = 53.0%, SE = 2.2) than in the conservative session (30.6% ± 2.2, logistic regression predicting the likelihood to make off-task reports, β = 1.03, SE = .13, $c^2(1) = 35.9$, $p < .10^{-8}$, ***Figure 2a***). Note that using a between-participant, implicit design, Experiment 2 replicated the effect of external manipulation on the likelihood to report mind-wandering (51.0% ± 3.9 vs. 38.2% ± 3.7, β = 2.29, SE = .89, $\chi^2(1) = 6.0$, $p < .05$) and extended it to spontaneous reports of mind-wandering (48.7 ± 6.1 vs. 26.5 ± 2.5 reports, Poisson regression: β = 2.37, CI(95) = [1.1 – 3.6], $\chi^2(1) = 12.4$, $p < .001$, ***Figure 2a***, results of Exp. 2 are detailed below).

However, the increase in the likelihood to *report* mind-wandering were not due to an increase of mind-wandering *experiences* in the liberal session: retrospectively, participants did not report having had more mind-wandering in the liberal session (signed-rank test, $p > 0.9$, one-tailed).

Moreover, overall performance was not significantly higher in the liberal than in the conservative session (paired t-test: p > .95, one-tailed), despite being highly correlated across participants between the two sessions ($r = .72$, $p < 10^{-6}$),

Finally, the explicit instruction to shift the criterion for off-task reports did not disrupt participants' introspective sensitivity: greater error predicted off-task reports to a same extent in both sessions (liberal session: $\beta = 0.18$, SE = .05, $\chi^2(1) = 12.1$, $p < .001$, Bayes Factor = 8.8, conservative session: $\beta = 0.20$, SE = .06, $\chi^2(1) = 11.3$, $p < .001$, BF = 6.0). Similarly, higher careless inertia also predicted off-task reports to a same extend in both sessions (liberal: $\beta = 0.39$, SE = .10, $\chi^2(1) = 13.3$, $p < .001$, BF = 16.4, conservative: $\beta = 0.48$, SE = .15, $\chi^2(1) = 11.7$, $p < .001$, BF = 7.3). Moreover, although both session and error/inertia were predictive of off-task reports likelihood, Bayesian analyses provided evidence that the predictive values of both error and inertia did not interact with session (both Bayes Factors < .16 ; meaning BFs > 65 in favor of the absence of interaction). In sum, participants had similar task performances and similar predictive values of task performances on introspective reports in both sessions. Yet, instructions did increase the likelihood to report off-task thoughts in the liberal session. These findings suggest that participants follow the instructions by shifting an introspective criterion, in a similar fashion as what is classically described in psychophysics when participants shift a perceptual criterion (Green and Swets, 1966b).

Temporal information integration & criterion adjustment

The independence of introspective sensitivity to instructions suggests that they did not create a response bias unrelated to the decision. Now, full validation of the decision framework classically relies on independent manipulation of the criterion, but also on observations of higher signal strength in conservative decisions. Here, the signal is the inner attentional state variable, which is known to fluctuate slowly (~ 0.1-0.01 Hz, Bastian and Sackur, 2013). We reasoned that participants might therefore base their decision on the integration over time of this attentional variable. Thus the strength of the integration, reflecting the build up of the decision variable, would be indicative of signal strength at the moment of the probe.

We took advantage from the possibility to compute error at any moment in time, providing time series of error up to the moment of the probe. Considering error as the input of the decision variable for on/off-task reports, we then modeled a memory-less introspective observer that would report its attentional state determined solely at the moment of the probe: error under a certain threshold elicits an off-task report, and an on-task report otherwise. By construction, the effect of mind-wandering on error was the exact same for participants and the memory-less model at the moment of the probe. We tested whether the time series leading to on- and off-task reports were identical between participants and the memory-less model, due to the temporal auto-correlation of the error signal, or whether the participants' time series were more segregated than predicted by the model, indicative of temporal integration of their attentional states (***Figure 2b***).

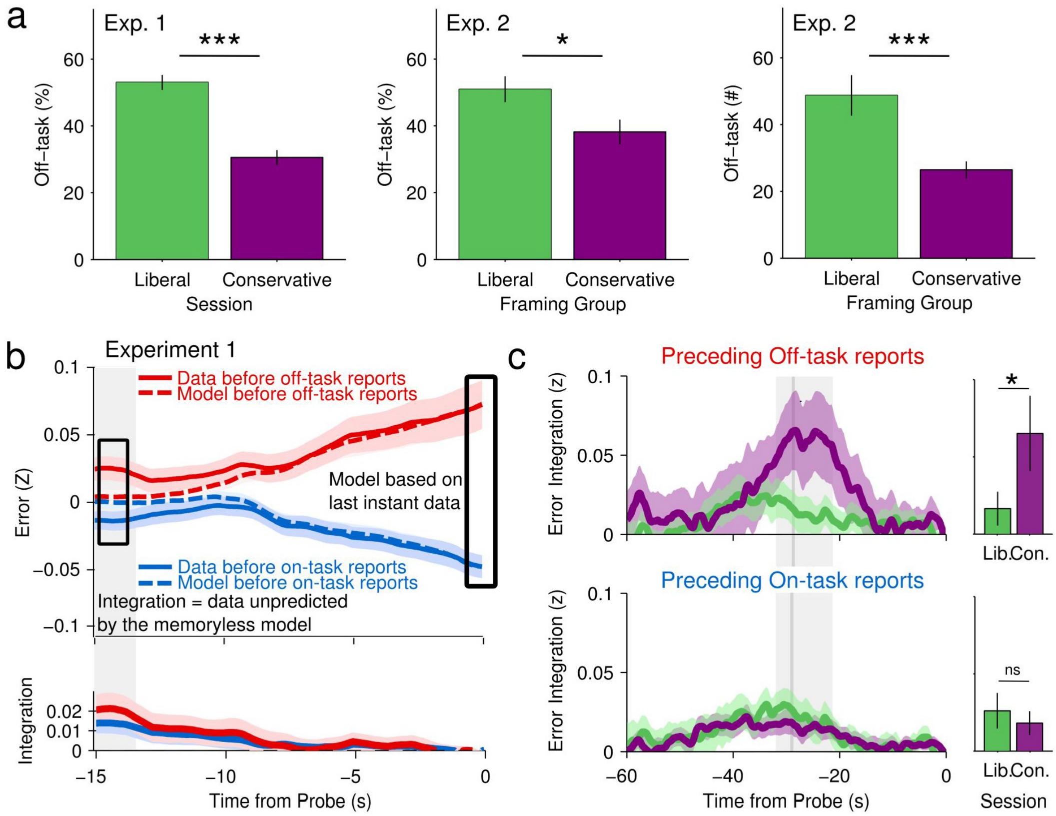


Figure 2: Off-task reports & temporal integration. *a) Liberal instructions increased the likelihood to report off-task thoughts.* ***Left & Middle:*** *proportion of probed off-task reports (Left: Exp. 1, Middle: Exp. 2).* ***Right:*** *number of spontaneous off-task reports (Exp. 2). b) Top: data (line) vs. memory-less model (ticks): both are confounded at 0, but then start to diverge. Integration is the extent of this divergence. Bottom: integration prior on-task (blue) and off-task (red) reports, as the difference between the data and the memory-less model c) Integration of task performance (error) prior on-task (top) and off-task reports (bottom): greater integration preceding off-task reports (bottom) for conservative (purple) than liberal (green) sessions. Side barplots at t = -29s.*

We did find a significant integration from 20s up to 47s prior the probe (clusters defined at $p < .05$, one-tail led to *cluster-level* $p < .001$, all cluster analyses were done with 1001 random shuffles). This suggests that participants integrated their momentary attentional states up to 47 s when making introspective reports. Moreover, as predicted by a decision-based account of introspection, integration preceding off-task reports was stronger in the conservative session that in the liberal session whereas this was not the case for on-task reports, yielding a significant introspective report X instruction interaction from 21 s up to 32 s before the probe (clusters defined at $p < .05$, led to *cluster-level* $p < .001$, ***Figure 2c***). This shows that the introspective decision variable is the result of dynamical tracking and integration of momentary attentional states. Critically, conservative or liberal introspective strategies is reflected in the strength of the dynamical integration, showing that conservative decision need higher signal strength.

Pupillometric evidence for criterion adjustment

A second, physiological, line of evidence also supports the idea that participants can adjust their introspective criterion. Pupillometry has recently been shown to reflect participants' perceptual criterion (de Gee et al., 2014). We therefore analyzed pupil size locked to participants subjective reports and observed a large response (***Figure 3a***). This response certainly reflected to some extent subjects' surprise, since longer inter-probe duration elicited greater pupil dilation from - 0.4 to + 14.0 *s* around the report (clusters defined at $p < .15$ led to *cluster-level* $p < .005$; clusters defined at $p < .05$ identified two smaller clusters: 2.07s-6.59 (*cluster-level* $p < .014$) and 7.21-12.66 (*cluster-level* $p < .006$) after report). When we controlled the effect of surprise, pupil response also predicted subjective mental states: off-task reports were associated with greater pupil dilation from 2.1 to 15.1 *s* following the report (clusters defined at $p < .05$ led to *cluster-level* $p < .002$, ***Figure 3a***, black bar). Crucially, the effect of subjective state on pupil size interacted with instructions from 0.4 to 4.7 seconds after the report (clusters defined at $p < .05$ led to *cluster-level* $p < .03$): pupil dilation was larger when participants made off-task reports in the conservative session than in the liberal session (***Figure 3a***, grey shading).

Interestingly, this effect was replicated inter-individually: the most conservative participants had greater pupil response differences between off- and on-task reports (slope = -1.06, r = .-34, $p < .05$, conservative: r = -.28, liberal: r = -.27, both $p < .05$ – one-tailed, ***Figure 3b***). Finally, this result, at the latency identified in Experiment 1, was replicated in Experiment 2 (slope = -.90, r = -.41, p < . 05, ***Figure 3c***). In sum, as was found in the perceptual domain (de Gee et al., 2014), participants' pupil dilation was larger when their response was against their strategy than when it was consistent with it. In sum, Experiment 1 provided both behavioral and physiological evidence supporting a decision framework for introspection.

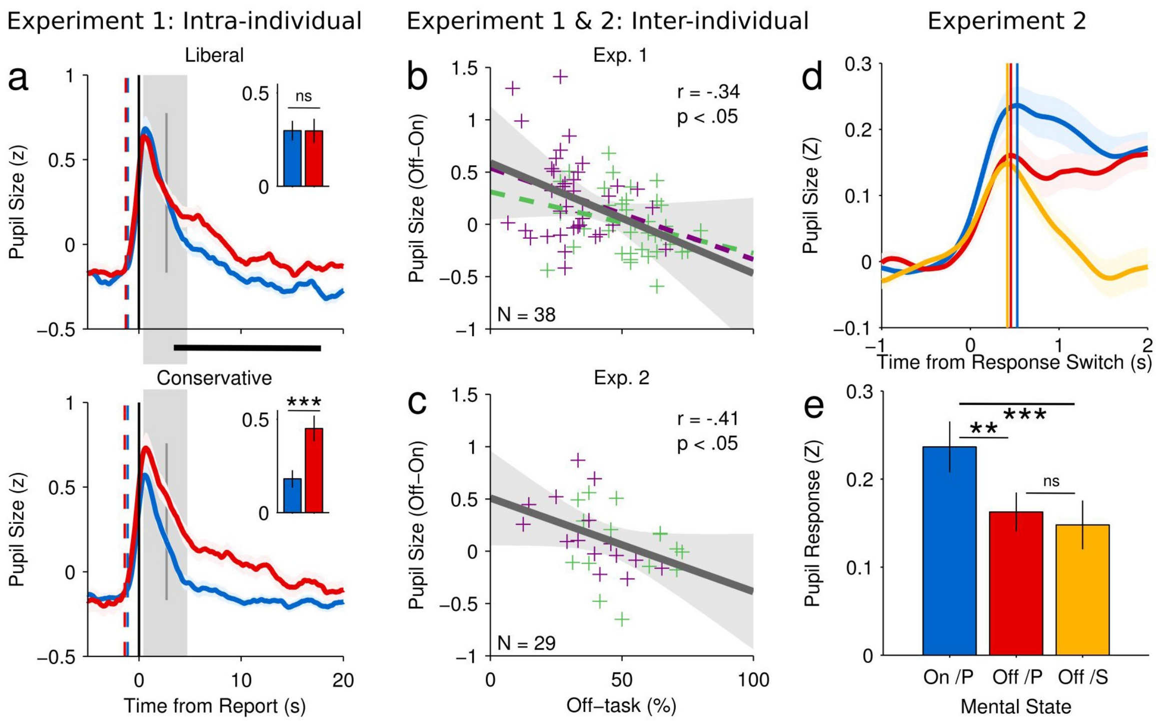


__Figure 3: Pupillometry.__ a) Pupil response locked to mind-wandering reports in the liberal (top) and conservative (bottom) sessions (Exp. 1). Black line: off-task reports are followed by greater pupil dilation than on-task reports (cluster-level p < .001). Grey shading: reports made against participants' strategy, such as off-task reports in the conservative session, are followed by greater pupil dilation (cluster-level p < .03). Insert: within-individual interaction between mental report and session at the maximum of the effect, 2.7 s after report. b, c) Pupil response difference between off- and on-task reports, computed at the maximum of the within-individual effect of Experiment 1 (2.7 s after report), as a function of overall proportion of mind-wandering across participants. Each dot is a participant in a given session (b, Exp.1) or group (c, Exp.2): conservative (purple) or liberal (green). d, e) In Experiment 2, peak pupil response to perceptual switches is lower during mind-wandering: d) Pupil response to perceptual switches before off-task (red: probed reports, gold: spontaneous) and on-task (blue) reports; the baseline is computed on the last second before the switch; vertical lines indicate the time of the peak pupil response for each report type across participants. e) Pupil response peak for each type of report. Abbrev.: On /P: probed on-task; Off /P: probed off-task; Off /S: spontaneous off-task.

In Experiment 2, we further tested whether our findings would replicate when introspective criterion adjustment was caused by an implicit instruction. We thus adopted an implicit manipulation of introspective criteria: two groups of subjects underwent different framing conditions. At the end of each block, a mock feedback regarding the proportion of mind-wandering was displayed to participants, supposedly estimated from their performance and pupillometry in the block. One group was framed with a mean mind-wandering frequency of 50% and the other group with a mean mind-wandering frequency of 75%. Moreover, half of the blocks required participants to report mind wandering spontaneously, as soon as they noticed it, in the absence of any probe (Reichle et al., 2010; Bastian and Sackur, 2013). This second manipulation enabled us to test whether our decision framework would still be valid in the absence of an explicit forced choice decision. In addition, Experiment 2 was also designed so as to prevent auto-observation: no visuomotor feedback was provided on screen (the cursors displayed in Exp. 1) and stimuli were continuously adjusted at threshold (75% correct). Finally, in order to study phasic behavioral and pupillary response, Experiment 2 was a discretized version of the original paradigm: clockwise (+45°) or counterclockwise (-45°) orientation of the central Gabor pattern now changed discretely (albeit with smooth transitions, that is without sharp luminance or contrast transients), at an irregular pace between 2.5 and 5 seconds. Yet, as in Experiment 1, participants continuously tracked their percept by making switches between two buttons.

Pupillometric indices of mind-wandering

The discrete perceptual switches elicited phasic pupil responses. Interestingly, mind-wandering blunted these physiological responses: pupil dilation responded less to percept switches during mind-wandering – i.e., for the last response switches preceding mind-wandering reports. Indeed, mean baseline-to-peak pupil response amplitude was smaller in the ten seconds before off-task than on-task reports ($t(29) = 2.89$, $p < .01$, ***Figure 3d,e***), and this was also true when we compared on-task and spontaneous off-task reports ($t(29) = 3.66$, $p < .001$). These findings are in line with the notion that mind-wandering is associated with perceptual decoupling (Smallwood et al., 2011a; Kucyi et al., 2013; Mittner et al., 2014). Notably, this contrasts with analyses of baseline (tonic) pupil size in the last, last five and last ten seconds prior introspective reports, which failed to reveal any difference preceding on-task versus off-task reports (all *p*s > .5 in both Exp. 1 & 2). In fact, computing Bayes Factors (Dienes, 2014) with a prior on the effect size ($h^2 = .3$, from Smallwood et al., 2011a), our results provided evidence for the null hypothesis, that mind-wandering did *not* affect tonic pupil size (all BFs < .33 in Exp. 1 & 2).

Inner noise and response lag reflect criterion adjustment

As mentioned above, Experiment 2 prevented participants from auto-observation: online calibration of stimulus contrast to participants perceptual threshold smoothly masked the discrete stimulus reversals. We could decompose performance in a principled manner with two internal parameters characterizing these perceptual decisions (***Figure 4a***): inner noise – corresponding to the efficiency of perceptual processing, negatively proportional to classical *d′* sensitivity index – and response lag – reflecting the speed of perceptual processing. High inner noise results in random switches, whereas high response lag results in slower responses to the stimulus reversals.

Across subjects and framing groups, inner noise was found to be higher on the last stimulus preceding probed off-task compared to probed on-task reports ($t(29) = 2.32$, $p < .05$, ***Figure 4b left***). In addition, response lag was higher preceding off-task reports ($t(29) = 4.27$, $p < .001$, ***Figure 4b right***). Note that this pattern of noisier and slower processing preceding *probed* off-task reports was also found before *spontaneous* off-task reports (gain: $t(29) = 3.37$, $p < .01$, lag: $t(29) = 2.70$, $p < .05$, ***Figure 4b***), while performance preceding spontaneous and probed off-task reports did not differ significantly (gain: $p > .8$, lag: $p > .7$, both BFs < .08). This shows that: 1) non-observable indices of task performance predicted mind-wandering reports, and 2) off-task reports were preceded with both slow and low perceptual processing efficiency.

Now, did we observe consistent (implicit) criterion adjustment in Experiment 2? As mentioned above (see **"Adjusting mind-wandering reports"** section, ***Figure 2a***), frequencies of both probed and spontaneous off-task reports were greater in the liberal than the conservative group of framing. Internal perceptual parameters showed that this effect of framing shared properties of criterion adjustment: there was no significant difference in overall performance between the two groups (overall inner noise: $p > .77$; response lag: $p > .99$, both BFs < .20) and the above effect of mind-wandering on both inner noise and response lag was present for both groups and did not interact with framing (repeated-measures ANOVA, both $p > .2$, all BFs < .04).

In order to validate the predictions of higher signal strength in conservative reports in Experiment 2, we used these internal parameters as indices of signal strength. Based on the previous paragraph, signal strength seemed to be distributed equally in the two groups. Thus, criterion adjustment should result in condition-based averages higher when liberal (see ***Figure 4c*** for a schematic illustration of this prediction). As predicted by criterion adjustment, we found signal strength shifts between the two groups of framing: compared to liberal reports, conservative reports were associated with higher inner noise (.27 ± .05 vs. -.25 ± .17; $t(29) = 2.7$, $p < .05$, ***Figure 4d, top***) and higher response lag (+47 ± 26 ms vs. -11 ± 18 ms; $t(29) = 1.8$, $p < .05$, one-tailed, ***Figure 4d, bottom***).

In sum, Experiment 2 further supported the existence of an adjustable introspective criterion. This criterion applies to spontaneous reports of mind-wandering and can be manipulated implicitly.

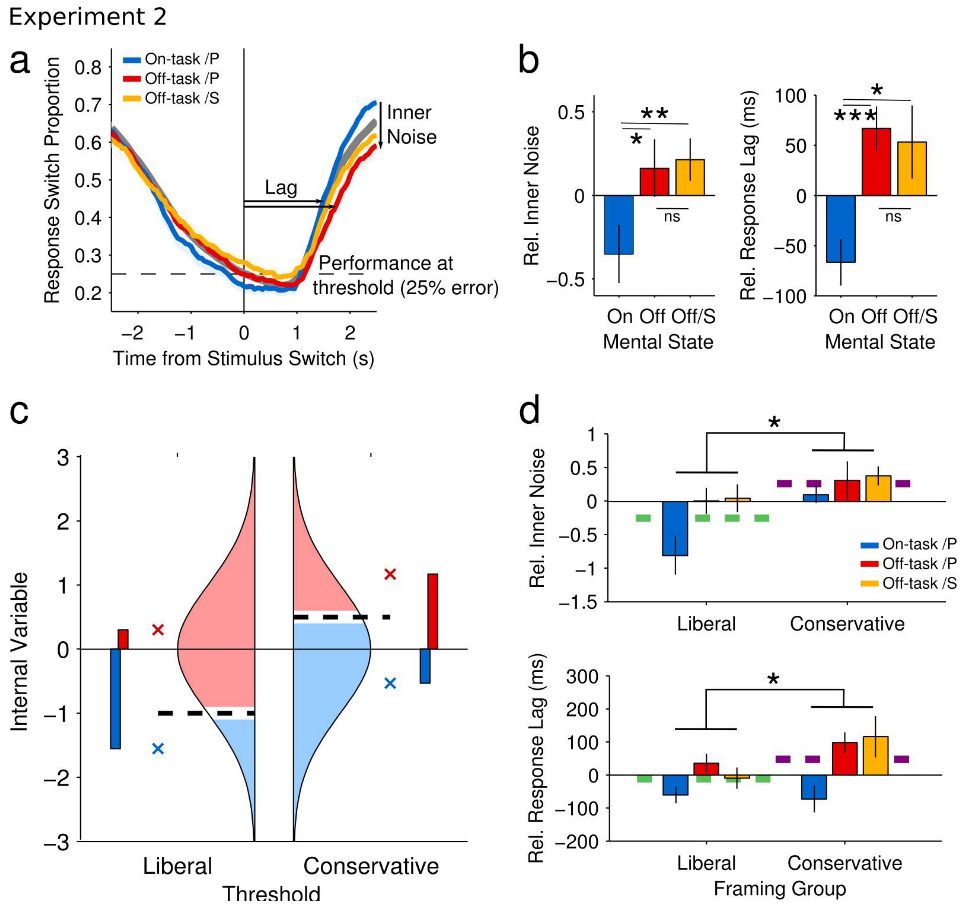


Figure 4: Inner noise and response lag. *a) Response switches proportion aligned to stimulus reversals, preceding probed on-task (blue), probed off-task (red), and spontaneous off-task reports (gold). These behavioral switches profiles contained two types of information: an inner noise – information is more or less noisy – and a lag – information is taken into account with a delay. b, c) Both inner noise (left) and response lag (right), estimated from the data in (a), increase preceding off-task (probed or spontaneous) versus on-task reports. c) Theoretical illustration that differences in criterion on the same normally distributed variable predict different threshold-based averages. d) As predicted in (c), inner noise (top) and response lag (bottom) estimates separated by framing group (liberal: left, conservative: right) suggest a criterion shift.*

Discussion

The present study makes two primary contributions. First, it adds to the growing literature on the cognitive mechanisms of mind-wandering. Second, we show that introspection – here, of mind-wandering – can be explained with a decision theoretical framework.

Our study uncovers new correlates of mind-wandering. At the behavioral level, increases in the error of sensorimotor tracking (Exp. 1) and of inner noise (Exp. 2) confirm that performance decrements observed during mind-wandering (Reichle et al., 2010; Schad et al., 2012) are partly due to a state of perceptual "decoupling" – i.e. decreased impact of sensory input on the contents of perception. Interestingly, decrements in corrective actions (Exp. 1) and increments in sensory motor latency (Exp. 2), provide precise and quantifiable evidence that higher cognitive functions, such as the speed of cognitive processing, also are impacted during mind-wandering. At the physiological level, decreases in phasic pupil responses to perceptual switches preceding off-task reports support existing evidence that pupillometry can be a valid index of mind-wandering (Smallwood et al., 2011a; Mittner et al., 2014). However, note that in contrast to previous work (Smallwood et al., 2011a, 2012b; Franklin et al., 2013a), baseline (tonic) pupil fluctuations were not affected by mind-wandering. Reviewing the literature, we identified contradictory results on mind-wandering being associated with greater (Smallwood et al., 2011a, 2012b; Franklin et al., 2013a), smaller (Grandchamp et al., 2014; Mittner et al., 2014), or similar (Uzzaman and Joordens, 2011) pupil baseline levels than on-task thoughts. A few more studies which reported effects of mind-wandering on blinks (Smilek et al., 2010) or saccadic movements (Reichle et al., 2010; Schad et al., 2012) were silent about possible differences in baseline levels. Our continuous and transient-free paradigm aimed at resolving whether mind-wandering impacts tonic pupil fluctuations. In neither of our two Experiments could we identify any significant effect of mind-wandering on tonic pupil dilation *preceding* off-task reports. In fact, our data even provided support in favor of the null hypothesis, indicating that pupil dilation is neither greater nor smaller during mind-wandering. Notwithstanding possible false positive (Ioannidis, 2005), we speculate that the tonic pupil dilation described *before* reports of mind-wandering (Franklin et al., 2013a) could be of the same nature as the pupil dilation we describe *after* reports of mind-wandering. Indeed, all previous studies reporting mind-wandering effects on pupil size used tasks with discrete trials. As a consequence, baseline pupil dilation measures made in such tasks might have been contaminated by phasic responses to previous trials – which extend over several seconds.

The main import of our study is that introspections are decisions. We indeed found two signatures of a decision framework: adjustments of criteria and correlative variable signal strength. With respect to introspective criteria, we found that participants could adapt their propensity to report mind wandering without any alteration in their underlying subjective experience. This flexibility of introspective reports is at odds with a "transparent" account of introspection, but note that it is consonant with recent observations that mind-wandering reports are associated with varying degrees of confidence (Seli et al., 2015b). Importantly, the flexibility of introspective report exists both for explicitly (Exp. 1) or implicitly (Exp. 2) adjusted criteria, and for reports of task-unrelated thoughts made in response to external thought-probes as well as made spontaneously. We thus show that this introspective criterion shares the characteristics of the decision criterion that was previously described in perceptual settings (Brown and Steyvers, 2005; de Gee et al., 2014). This strong similarity between introspective and perceptual criteria is also evidenced at the physiological level, with pupillometry being sensitive to both introspective and perceptual conservativeness (de Gee et al., 2014). Future research should explore whether perceptual and introspective criteria also share neural correlates.

The application of the decision framework to introspective reports raises a fundamental question regarding the nature of the internal signal. At the subjective level, our findings suggest that mind-wandering episodes are associated with the fluctuations of an internal attentional state variable. We thus speculate that a single attentional state variable could underlie introspective off-task reports corresponding to qualitatively different contents. At the brain level, the relation between mind-wandering and the Default Mode Network (DMN) (Christoff et al., 2009) suggests that slow temporal fluctuations in DMN activation could account for the variability in this internal variable. On the basis of our findings, we propose that the comparison between a criterion and activation in core hubs of the DMN underlies the detection of mind-wandering episodes, irrespective of their particular contents (Andrews-Hanna et al., 2010). In fact, recent findings already show that these core hubs of the DMN are involved in 'meta-memory' (i.e., introspection of mnemonic contents) capabilities (Baird et al., 2013b).

We have also shown that the introspective decision variable integrates sensory and error-related information over nearly 30 seconds. This echoes the observation that DMN activity fluctuates spontaneously at a similar time constant. This similarity motivates the testable hypothesis that DMN activity results from the integration of information across brain regions at a slow ($< .1$ Hz) time scale (Ko et al., 2011). This hypothesis is consistent with findings in non-human primates that regions of the DMN have characteristic time constants which allow them to integrate information over large timescales – in contrast to other, e.g. sensory, regions (Bernacchia et al., 2011; Murray et al., 2014). At the subjective level, the dynamical integration of past mental states provides, a strong empirical evidence in favor of a 'stream' of consciousness (James, 1892; Strange, 1978), within which present thoughts are the continuation of previous thoughts, as opposed to a train of 'atomic' thoughts, where successive mental contents would be independent from one another.

Finally, our framework suggests new functional hypotheses regarding human introspection. Although humans are rarely probed about the contents of their thoughts, the ability to escape the here and now represents an advantage (Mooneyham and Schooler, 2013), but also generates a momentary state of vulnerability for the organism. Our decision framework for introspection suggests that noticing mind-wandering is part of a monitoring and control loop: internal detection of mind-wandering episodes by comparison of a state variable to an adjustable criterion permits re-engagement in the task. The ability to flexibly adjust the introspective detection threshold would optimize resources allocation: when task and environmental demands are low, one could optimize resources allocation by redirecting executive attention to the task only when the internal attentional state variable is particularly low (using a 'conservative' introspective criterion). On the contrary, under high environmental and task demands, one would benefit from terminating even the weakest, shortest episodes of mind-wandering (using a 'liberal' introspective criterion). Thus a flexible, criterion-based detection of mind-wandering episodes acts as an internal feedback signal, predictive of poor momentary task performance, thereby adding a degree of freedom to error monitoring capabilities which does not rely on external feedback signals from the environment.

Acknowledgments. *This work was supported by grants from the Agence Nationale de la Recherche (France): "Dynamind" ANR-10-BLAN-1902-01, ANR-10-LABX-0087 IEC and ANR-10-IDEX-0001-02 PSL*. M.B. was funded by the Direction Générale de l'Armement.*

CHAPTER 7: GENERAL DISCUSSION

1. Main findings of the thesis

The aim of this thesis was to better understand how thoughts follow each other and how people assess these thoughts. Mind-wandering, as a salient and spontaneous generation of conscious thoughts was ideally suited for the study of thought dynamics and monitoring.

The two first studies evidenced that attentional states responsible for the generation of off-task thoughts likely oscillate at around 30s. By using the response times of each trial of a 1-hour-long go/no-go task, we could first build a model that evidenced that on-task thoughts lasted for about 20 seconds, whereas episodes of mind-wandering lasted for about 10 seconds, and had more variable durations (Chapter 2). Another approach capitalized on a delayed match-to-sample task to control the attentional starting point of each trial and ensure that all trials started in a focused state of attention. From this first focused mental state, we could measure when and how mind-wandering was generated (Chapter 3). Although at a smaller – trial – scale, this complementary approach evidenced that mind-wandering certainly increased with time while participants tried to hold on one specific representation, but then eventually decreased after 18 seconds of delay. These findings are suggestive of the first period of an alternation between on- and off-task thoughts oscillating at 30-40s. Interestingly however, the peak at 18s was only observed for aware, not unaware mind-wandering, and was affected by auditory noise, suggesting that the typical slow dynamics of mind-wandering may be related subjectively to awareness and functionally to executive resources.

The nature of self-generated content was next studied in a population with both executive deficits and an alteration of DMN slow fluctuations: ADHD patients (Chapter 4). We found that, compared to control groups, both hospitalized children and adults clinically diagnosed as ADHD reported more mind-blanking, an absence of self-generated content, or the generation of “empty thoughts”. Providing support to the view that mind-wandering requires executive resources, we found that mind-wandering, as on-task thoughts, tended to be less reported by participants with ADHD. Finally, methylphenidate, a pharmaceutical treatment aiming at increasing focused attention in patients with ADHD, also increased mind-wandering. Interestingly, these findings could support two alternative interpretations: patients with ADHD could suffer from deficient representations, possibly due to more unstable thoughts, or deficient introspective access. The following studies therefore sought to understand introspective mechanisms engaged in mind wandering reports.

Taking inspiration from possible links between language and self-awareness, we showed that inner speech does facilitate awareness of mind-wandering (Chapter 5). In a first study, articulatory suppression decreased the likelihood to catch oneself mind-wandering. Still, the episodes that were self-caught were shown to be more verbal than less aware probe-caught episodes. In a second study using a go / no-go task, activation of verbal working memory via greater amounts of verbal stimuli increased awareness of mind-wandering. Finally, a smartphone study using the Android-based application *Daydreaming* evidenced that, even in everyday life, mind-wandering awareness was facilitated by inner speech vividness, and not by visual or auditory vividness. Beyond the demonstration of the importance of language in executive functions, these results also suggest that detecting mind-wandering may consist in setting an introspective criterion on vividness of inner representations. This led us to our final study were we sought to formalize this notion of detection of mind-wandering as a decision mechanism on attentional states.

We proposed a decision mechanism to account for mind-wandering detection (Chapter 6). We showed that an introspective criterion could be adjusted in order to vary the proportion of mind-wandering reports, without modifying the underlying attentional states and their subjectivity. We further discovered that dynamical integration of information up to 30 seconds before subjective reports is critical in mind-wandering reports. Finally, we evidenced that conservative reports of mind-wandering required more inner evidence than liberal reports, as predicted by a model of decision based on a signal detection mechanism.

Overall, these results shed a new light on human introspection. Irrespective of whether one considers it fallible or not, introspection is still most often considered as a unitary faculty, that makes direct contact with thoughts. The present work, on the opposite, suggests that reporting one's thoughts is a dynamical mechanism that capitalizes on slow fluctuations of the cognitive system (Chapters 2, 3, 6), requires executive functions (Chapters 3, 4, 5), and culminates in a decision (Chapter 6). Introspection links inner states to observable behaviors, and I will therefore discuss in the next section how the current findings stress both the value of subjective reports and the value of indirect markers of mind-wandering. Finally, our studies will allow me to draft in the last section a complete mechanistic account of mind-wandering generation and introspection.

2. *To what extent can external measures account for introspection?*

a) Subjective reports as gold standard?

As presented in the Introduction, the validity of introspection has been challenged on both theoretical (Comte, 1819; Watson, 1913) and empirical grounds (Nisbett and Wilson, 1977; Johansson et al., 2005). To account for participants' plausible verbal reports (Nisbett and Wilson, 1977) and accurate confidence (Koriat, 2012), these theories stressed the importance of folk psychology and auto-observation (Johansson et al., 2006): people do not look inside their mind, but infer their own states as they would do with other people's mental states. Interestingly, in order to administer a proof of the deficiency of introspection, researchers had to design precise control over external stimuli or responses. Participants' reporting of the critical stimuli, responses or their relations could therefore be objectively characterized as correct or incorrect, with respect to the objective experimental manipulations. This approach evidenced that most psychological processes are unconscious (Baumeister and Masicampo, 2010). However, isn't such an approach in a sense self-defeating? Could it ever attain non-trivial properties of introspection? Could it meaningfully address the question of introspection of *conscious* phenomena, or introspection in the absence of observable performance?

A second line of research therefore sought to study these meta-cognitive capabilities to judge one's own performance. Attempts at validating meta-cognitive accuracy when performance is implicit and auto-observation impossible were successful: for instance, participants could still assess the number of stimuli they screened in visual search paradigms, even when controlling for self-observation (Reyes and Sackur, 2014). In a different line of research, it was shown that subjective reports on attentional focus on one's own limbs correlated with alpha suppression in contra-lateral somato-sensory regions (Whitmarsh et al., 2014), thus proving accurate (validated by neurophysiological data), non trivial and fine-grained introspective capacities.

In this context, the study of mind-wandering was and remains particularly complex. Subjective reports are the gold standard in consciousness research: indeed, if participants report that they did not see a visual stimulus, should we trust the external behavioral/neural measures that suggest that they did see the stimulus (Lamme, 2006), or should we primarily trust subjective reports and adjust our theories (Cohen and Dennett, 2012)? This question is especially acute in mind-wandering research, where we do not (yet) possess established neurophysiological markers. Indeed, beyond the fundamental problem of reverse inference, (associations of a given neural activation to a certain psychological mechanism are always fragile, see Poldrack, 2011), inferring subjective states of mind-wandering from DMN activations may be specifically limited (Fox et al., 2015), at least for two reasons. First, mind-wandering involves other regions than the DMN, such as the FPN (Mason et al., 2007; Christoff et al., 2009), and predictions of mind-wandering reports are greatly improved from activity, and even connectivity of these other networks beyond the DMN (Mittner et al., 2014). Second, given that the DMN is also activated in goal directed tasks such as planning (Gerlach et al., 2011) or mentalizing (Dumontheil et al., 2010), its activity does not unambiguously predict undirected and spontaneous task-unrelated thoughts. Moreover, at a behavioral level, while in perceptual consciousness studies it is admitted that stimulus energy has a monotonic link to subjective awareness – as a stimulus gets stronger on a physical dimension, the more probable it that it should generate a conscious representation – we have currently no external control over the internal stimulus in mind-wandering studies.

In sum, subjective reports of mind-wandering are precious both because they constitute primary evidence of a subjective phenomenon, and because external control of this phenomenon is limited. Thus, the goal of mind-wandering research is to bootstrap *models* of subjective and introspective reports from the consistency of subjective reports as *primary data*.

Indeed, taking participants' reports at face value, with little hope of a fixed benchmark, we obtained rich and consistent subjective reports. For instance, our delayed match-to-sample task (Chapter 3) evidenced, with subjective reports as primary information, that mind-wandering fluctuations may mostly apply to aware mind-wandering and require executive resources, as expected from theories based on neural evidence (Dehaene et al., 2006; Smallwood et al., 2012a; Chen et al., 2013). Also, fine subjective differences between mind-blanking and both mind-wandering and on-task thoughts, were a consistent marker of ADHD through both childhood and pathology (Chapter 4). Finally, by capitalizing on the introspection of mind-wandering phenomenology, we observed that inner speech facilitates introspection of mind-wandering (Chapter 5), and used this result as a preliminary attempt at finding external controls for inner salience. We believe that these diverse but coherent results exemplify the trustworthiness of subjective reports, so much so that we could try to formulate a theoretical model.

b) Bootstrapping a model of subjective reports

Let us rephrase the paradoxes of pure introspection for an empirical researcher: Should we trust participants' reports to the point of asking them to draw the boundaries of their own introspection? Beyond being a subjective and internal phenomenon, mind-wandering is also spontaneous. Often it goes unnoticed. In spite of its overall internal consistency, it therefore seems that introspection of mind-wandering is still a risky enterprise at best. Yet, how are we to sort out participants' possibly contradictory subjective reports? Given all the suspicion that retrospective reports have raised (Ericsson and Simon, 1980), why should we trust the presence of mind-wandering as indexed by a retrospective probe more than the absence of mind-wandering as indexed by the absence of a spontaneous report?

A prudent empirical stance consists in trying to unravel the mechanisms behind these seemingly contradictory reports: under which contexts do participants report mind-wandering? We found that greater executive resources increased the likelihood to report aware mind-wandering (match-to-sample study, Chapter 3) with a defined content (ADHD study, Chapter 4). Similarly, inner speech reports were correlated with awareness of mind-wandering (Chapter 5).

Putting preconceived ideas on the nature of inner experience aside, we may not know whether participants *really* experience the mental state – nor even what it feels like to *really experience a mental state* – but we may be able to predict the subjective reports. Taking a comparison with perception, the extent to which signals are really seen or rather guessed in the Signal Detection Theory is not of primary importance: what matters is the response. This attitude led us to attempt crash-testing introspective reports, and measure the nature of the signal that participants were using in order to respond. For instance, could we ask participants to report more mind-wandering that they would have volunteered? The fact is that participants could adjust their reports, and did so with such consistency that we could infer the underlying decision mechanism: more conservative reports were associated with stronger evidence of mind-wandering. Thus, even though we did not have steadfast physiological correlates, or proven external controls on mind-wandering reports, we were able to show their core decision mechanism, and we did so based on the intrinsic systematicity of their response to our criterion manipulation. This model provides a unifying account of many puzzles about introspection in mind-wandering: for one, it provides an alternative explanation to the self-caught / probe-caught opposition: we suggest that spontaneous reports of mind-wandering require more evidence than reports of mind-wandering based on an external retrospective probe.

Greater conservativeness in spontaneous than triggered reports would exactly result in participants seemingly mysterious failures to catch their mind-wandering, while still reporting mind-wandering to external probes. Second, our decision framework also accounts for participants' ability to generate confidence judgments on their mind-wandering reports (Seli et al., 2015b): as in confidence in perceptual decision studies (Fleming and Lau, 2014), confidence in mind-wandering reports may simply be the distance of their inner evidence to their introspective criterion. And at last, our decision account of introspection leads to the counter-intuitive notion of inner false alarms, that is to mind-wandering reports in the absence of such an experience. These false alarms could possibly explain why children with positive attitudes towards mind-wandering provide invalid – too liberal? - subjective reports (Zhang et al., 2015). In sum, beyond providing explanations to puzzles about subjective reports, questioning the introspective mechanism also allows to clarify the nature of inner thought and to use the full predictive power of the various indirect markers of subjectivity.

c) Indirect markers of mind-wandering and their limits

Interestingly, our approach also evidenced that mind-wandering episodes may not be constituted of clearly defined thoughts immediately preceding thought probes. Indeed, we found that the dynamics of mind-wandering not only vary according to whether one is aware or not of one's mind-wandering (match to sample study, Chapter 3), but also that information in the last 30 seconds is integrated in mind-wandering reports (decision study, Chapter 6). However, whether mind-wandering is an absolute, relative, or integrated state at the subjective level remains unclear: are participants truly experiencing a stream of consciousness, or is the information unconsciously integrated? At this stage, we only capitalized on the objective but *indirect* markers of mind-wandering: response time variability, error, etc. However, these markers do not reflect mind-wandering *per se*, but instead the state of decoupling that is associated with mind-wandering.

This subtlety could matter. First, if perceptual decoupling precedes the generation of mind-wandering, we would infer mind-wandering where it is not *yet*. Second, our decision framework is blind to whether participants base their reports on the strength of their coupling, rather than on their subjective experience. This leads to a testable prediction for fMRI: if conservative reports of mind-wandering are associated with greater deactivation of sensory regions, while there is no evidence of greater activation in the DMN, then we could conclude that participants' reports mostly follow the state of their decoupling rather than a subjectively rich mind-wandering experience. Note however that data from our *Daydreaming* application seems to speak against this possibility: we found a positive correlation between thoughts vividness and mind-wandering intensity, suggesting that introspective criteria would likely apply to mind-wandering subjective salience rather than to its sensory accompaniments, be they causes or consequences.

At a more fundamental level, the contribution of error monitoring in the noticing of mind-wandering remain unclear. In all likelihood, both a sense of decoupling – not understanding what was heard or read – and a certain subjective quality – thinking about an upcoming meeting – may determine mind-wandering reports. It may be the case that the admixture of these two components should be context and task dependent. Moreover, what may often matter the most is the behavior of individuals – whether they will remember the content of a lesson, have an accident or successfully engage in reading – rather than the vividness of their subjectivity. Although this would tend to reduce the study of mind-wandering to the fields of meta-cognition and error monitoring, research could benefit from an approach where we would seek the net gain of experiencing a subjective content above and beyond detecting errors. This would provide functions to subjective experience and introspection. Of course, research on subjective contents occurring during rest, or while no task is to be performed would complete the picture: in these cases, little error monitoring would be at hand. These two parallel lines of research map onto two concepts: "mind-wandering" – spontaneous thoughts occurring during a demanding task, whose detection also probably involves error monitoring – and "daydreaming" – deliberate thoughts occurring in easy tasks or at rest (Seli et al., 2014). A common mechanistic model of self-generated thought is discussed in the next section.

3. *Mechanistic accounts of mind-wandering*

a) How do on- and off-task thoughts alternate?

The results presented in this work can form the basis to draft a mechanistic account of mind-wandering generation, maintenance and introspection. First, mind-wandering may arise as an executive failure (Chapter 3), possibly associated to the activation of current concerns in the presence of relevant cues (Klinger, 1978; McVay and Kane, 2013). Our findings suggest that meta-awareness requires executive resources (Chapters 3, 5), and thus such executive failures may also be failures in one's meta-awareness (Winkielman and Schooler, 2011). Second, the maintenance of mind-wandering episodes may *require* executive resources: as we saw in Chapter 3 and 5, verbal working memory overload reduced the amount of aware mind-wandering, and medications known to increase executive functioning increased mind-wandering (Chapter 4, see also, Levinson et al., 2012). In a way, this is similar to distracting external stimuli that break executive shielding, but that still require at least minimal executive engagement to be processed. The recruitment of executive resources may also favor active perceptual decoupling (Smallwood, 2013a), preventing other stimuli from interrupting the stream of thought. Finally, our findings suggest that the strength of the mind-wandering episode explains its detection (Chapters 4-6). To this body of findings, we add the observation of a macro-dynamics of oscillations at around 30 seconds, suggesting pre-defined opportunities for mind-wandering to occur (Chapters 2, 3).

However, our work on ADHD stresses how fragile the distinction between the generation and maintenance of mind-wandering may be. ADHD patients reported more mind-blanking. It is certainly possible that, for them, mind-wandering episodes were correctly generated, but failed to be maintained. However, an alternative explanation is that the lack of executive functions truly undermines the generation and then the maintenance of mind-wandering. Insufficient maintenance would preclude the build up of vividness that could lead to an introspectible representation. In fact, our evidence of information integration over time suggests that the duration of mind-wandering may also be an index of vividness. Thus, shorter off-task – but also on-task – episodes could be harder to introspect in ADHD, and thus explain greater amounts of mind-blanking.

Going one step further, our work provides support for the counter-intuitive view that the 30-s fluctuations (Chapter 2) may not be fluctuations of mind-wandering generation *per se*, but rather fluctuations in the mechanism of conscious access to mind-wandering. Indeed, while unaware mind-wandering occurred with constant probability independently from executive resources, aware mind-wandering presented what seemed to be the first period of the 30-s fluctuation. A possible interpretation is that with time, thanks to the recruitment of executive resources, unaware episodes are more likely to reach awareness, and that opportunities for such access fluctuate.

Whether thoughts are precisely delimited or not, these explicit mechanisms of executive/meta-awareness failure, followed by a recruitment of executive functions to maintain/introspect mind-wandering make various predictions at the neural level. However, before presenting this final section, I will compare the above mechanisms to a recent computational model of mind-wandering.

b) An ACT-R model of mind-wandering

Mind-wandering being a cognitive function, the question is not whether, but *how* a computer would be able to experience mind-wandering. This challenge of implementing mind-wandering in a software was taken up by Marieke van Vugt (van Vugt et al., 2015), based in part on data from our SART experiments. Various attempts at programming a mind have been done: SOAR (Laird et al., 1987), CLARION (Sun et al., 2001), EPIC, (Kieras and Meyer, 1997). One of the most successful may be the ACT-R ("Adaptative Control of Thought – Rational") architecture (Anderson et al., 2004). The ACT-R architecture is a combination of encapsulated modules – perceptual, motor, imaginal, retrieval, goal... – that interact in a one by one fashion with a central production system via dedicated buffers. The model is therefore clearly symbolist and modular, yet connectionist rules hold within modules: for example, activation of a given memory or percept will facilitate later re-activations, thus providing an account of priming. Based on the best specialized literature in each field in neuroscience, the model does not aim at providing insights on the processes within specialized modules, but rather at understanding the dynamics of the between-modules interactions.

Therefore, the ACT-R model has mostly helped making predictions of the psychological and neural mechanisms involved in complex tasks. For example, using a symbol manipulation task, the ACT-R could predict the timing of activation of the neural regions corresponding to the modules, but also the differentiated effects of training on these modules/regions (Qin et al., 2003). Similarly, the ACT-R model showed how a strictly serial production of commands could give the impression of parallel processing in a dual task paradigm where a psychological refractory period was expected – and accurately predict the existence of odd behaviors that would have been discarded by the experimenters (Byrne and Anderson, 2001).

Thus, using the go/no-go-like Sustained Attention to Response Task (SART, Robertson et al., 1997) as a main task, Marieke van Vugt built an ACT-R model of mind-wandering and then compared the simulations to Mrazek and colleagues' data (Mrazek et al., 2012b) and to our own data (Bastian and Sackur, 2013). The model efficiently captured SART errors and Response Time variability. Yet, the time taken to respond on-task or off-task to the probe was clearly greater for participants (> 3 s) than for the model (< 1 s). Beyond its ability to capture this behavior, this model is interesting as a first foray into making the computational mechanisms of mind-wandering fully explicit.

Indeed, how did the ACT-R model mind-wander? Starting with state of focused attention – a command "do the task" in the goal module – activation of this command decreased with time due to passive decay of goal activation, up to a moment where another command, “retrieve memories”, became more activated. This is consistent with the notion that mind-wandering begins with a failure to maintain goal-directed thoughts. With this alternative goal being activated, the model retrieved memories while still performing the task: this dual task situation decreased performance without the need of active perceptual decoupling. The episode of mind-wandering terminated when a memory “do the task” was eventually retrieved, reinstating the primary goal in the goal module, and a new cycle started. The characteristics of duration, or vividness, of the mind-wandering memories preceding the last “do the task” memory therefore played no role in the stopping of mind-wandering.

Overall, making the mechanisms more explicit evidenced how similar and different this computational model is from the functional one I presented in the previous section. The main convergence consists in the mechanism for the generation and maintenance of mind-wandering: the rate of decay in the goal module corresponds to executive resources, and it explains the frequency of a switch from one state to the other. However there are striking divergences that I now list, with the hope that they should help future modelers and empirical researchers on mind-wandering. First, in the computational model, no perceptual decoupling was implemented (the inner workings of the visual module is not impacted by the current goal). However, in Chapter 6, we found that during mind-wandering the speed of processing was impacted. This is certainly compatible with a dual task interference, implemented at the central, production system level in van Vugt's model. But we also found that the sensory gain (a pure index of sensory efficacy) was worse during mind-wandering. Therefore further research is needed to test whether perceptual decoupling as a cause or consequence of mind-wandering adds to the realism of the simulations. Second, van Vugt's model implements the termination of mind-wandering episode with a form of semantic prospective memory. This markedly differs from our suggestion that introspective detection mechanisms are used to generate internal feedback signals. This leads us to the third and crucial difference which consists in the absence of an introspective mechanism in van Vugt's computational model. Instead of reflecting a passive assessment of participants’ on- or off-state, future models should include explicit decisions based on internal states of the model. This should enable better predictions of the introspective response data. It should also be useful in order to test the prediction we made at the end of Chapter 6: by adjusting its introspective criterion on mind-wandering, the system should be able to provide itself with an internal feedback signal that can be adapted to task demands.

c) Neural underpinnings of subjectivity

Coupling recent investigations on the DMN and on the neural correlates of mind-wandering, I describe in this last section the presumed neural underpinnings of the psychological mechanisms described above.

First, the involvement of the DMN before reports of mind-wandering is now confirmed by various studies (Fox et al., 2015). Yet, as outlined above, the DMN is not the network for mind-wandering *per se*, but rather for cognitions about the self and memories that happen *during mind-wandering.* Therefore, most of the specificity of mind-wandering may be due to the interactions between the DMN and other large scale networks, such as the Fronto-Parietal Network (FPN), the Salience Network (SN), the Dorsal Attention Network (DAN) and primary sensory regions (Yeo et al., 2011).

Indeed, consistent with the involvement of executive functions in the slow rise of mind-wandering that we described in Chapter 3, the FPN appears to "command" the activity of the SN and DMN, notably by slowing the dynamics of the DMN. Indeed, single pulse "excitatory" Transcranial Magnetic Stimulation (TMS) on the posterior Middle Frontal Gyrus (pMFG), a core hub of the FPN, resulted in decreased connectivity between the DMN and both the FPN and the SN ; while repeated (r-) "inhibitory" TMS on the pMFG led to dis-inhibition of the DMN, and more precisely to an acceleration of DMN fluctuations, from a classically observed slow fluctuation (.1 - .01Hz, ~ 10-100s) to faster fluctuations (.25 - .1Hz 4-10s, (Chen et al., 2013). As a consequence, the FPN is a suitable candidate for a stabilization of the trains of thought.

In contrast, the SN, comprising the dorsal Anterior Cingulate Cortex (dACC) and bilateral Anterior Insulae, may have a critical role in switching between trains of thoughts (Tang et al., 2012). Indeed, the very name of the "salience" network comes from its sudden activation when detecting salient stimuli such as oddball, or transitions between musical movements (Sridharan et al., 2008). In these cases, DMN activity is suppressed and both SN-FPN are activated. More precisely, using Granger causality analysis of fMRI data, the SN was shown to suppress activity of the DMN and recruit the FPN (Sridharan et al., 2008), and a similar transient activation of the SN was found when noticing mind-wandering preceded a re-orientation of attention on-task (Hasenkamp et al., 2012). Furthermore, single pulse TMS on the anterior Middle Frontal Gyrus (aMFG), a central node of the SN, increased within network connectivity of both the SN and the FPN, suggesting that the SN recruits the FPN – before the FPN stabilizes/inhibits the DMN; while rTMS on the aMFG also suppressed slow fluctuations of the DMN – though to a lesser extent than did the FPN (Chen et al., 2013). Finally, the SN may also be involved in the reversed switch when mind-wandering starts. Indeed, the first seconds after a demanding fMRI neurofeedback task that suppressed DMN activity evidenced that the first regions that recovered were the dACC and Anterior Insulae, then followed by the DMN (Van De Ville et al., 2012). This suggests that DMN recruitment after a demanding task may be mediated by the salience network, thus confirming its role as a "switch network".

In sum, what would a full neural mechanistic view of a participant performing the SART look like? The participant starts focused on the task. Attending to salient visual stimuli (numbers on the screen), the occipital regions are strongly activated (Lamme, 2006), the "global neuronal workspace" FPN is engaged (Sergent et al., 2005) – these stimuli are attended and reportable – and occipital activity is further enhanced (Sergent et al., 2005) while a motor command is sent to press the spacebar – the number was not a "3", the no-go stimulus. For this first stimulus, the FPN is likely coupled with the Dorsal Attention Network (Spreng et al., 2013), involved in attending to external stimuli. Waiting for the following stimulus, DMN activity may increase but be quickly suppressed by the activation of the SN at the sight of a new stimulus (Sridharan et al., 2008). Again, we would expect recruitment of the occipital/DAN, FPN, motor cortices.

After a few stimuli, the no-go signal occurs: a coupling between the salience network and the motor command may start bypassing the full occipital-FPN loop, and the frontal areas involved in the inhibition of behavior – inferior frontal cortex and pre-SMA – may certainly be activated (van Gaal et al., 2010), but not strongly enough to prevent from a commission error. At this moment, the participant may reflect on this error and experience task-related interferences (Sarason et al., 1986). This will likely be done by activating the SN to recruit the FPN and the frontal subsystem of the DMN – indeed, there is no reflection on the future and little on the past, thus no need for a temporal subsystem recruitment (Stawarczyk et al., 2011b).

Yet, after a couple more stimuli, executive failure could be reflected as a decreased coupling between the FPN and the DAN. Due to habituation of the salience network, response times may start fluctuating between fast detection-response (strong SN-motor commands coupling) and slow detection/slow response (SN habituation, (Bastian and Sackur, 2013) Chapter 2). Interestingly, the SN may transiently be activated to recruit the DMN (Van De Ville et al., 2012), and facilitate a FPN-DMN coupling (Smallwood et al., 2012a; Spreng et al., 2013): the participant is activating the hippocampus to build thoughts about his/her present/past self (Andrews-Hanna et al., 2010), and yet, still doing the task automatically. The FPN-DMN coupling allows for a stabilization of the trains of thoughts that might otherwise hinder the ability to generate vivid content (Chapter 4). However, correction of errors may cease, and stimuli be processed more slowly (Chapter 6), due to a FPN-DMN coupling in place of a FPN-DAN coupling. Also, stimuli, as well as possible distractors, are less well perceived (Barron et al., 2011; Kam et al., 2011), due to a state of perceptual decoupling. This state might be generated by an active inhibition of the FPN over the DAN, similar to the active inhibition of the FPN on the DMN when performing external tasks (Raichle et al., 2001).

Now how does this episode of mind-wandering terminate? A first possibility is a salient stimulus, such as a sudden red stimulus in a series of black stimuli (Smallwood, 2013c): this would likely activate the SN, which would suppress DMN activity and recruit the FPN and the DAN (Sridharan et al., 2008). This might be how most mind-wandering episodes are suppressed in everyday life. A second possibility is the spontaneous noticing of mind-wandering: the vividness of the episode reaches a certain threshold that allows for its detection (Chapter 6), and then the participant re-allocates attention on-task. In neural terms, DMN activity may increase up to a threshold above which the SN suppresses its activity and re-facilitate a FPN-DAN coupling. Interestingly, activity in the vmPFC may contribute to such noticing of mind-wandering, as this region of the DMN is involved in meta-memory (Baird et al., 2013b). This second possibility may be particularly used in a task with few distracting stimuli, such as reading. In fact, one could predict two different subjective experiences of noticing mind-wandering when reading: 1) error-related noticing, related to the comprehension of reading, then likely to occur at the end of sentences, and even more at the end of paragraphs, when comprehension is assessed and 2) vividness-related noticing, unrelated to reading, occurring at any moment. As a consequence, vividness of mind-wandering would likely be greater for spontaneous noticing that do not respect sentence constructions that those who do. A third rarer possibility is external probing: a salient stimulus – a blank screen, or an auditory tone – would activate the SN, and suppress DMN activity. Yet, interestingly, accessing one's subjective state may rely on re-activation of the DMN, and the vmPFC, in order to build a quick narrative on what was going on in one's mind. This narrative involves integration over the last 30 seconds, and if evidence of mind-wandering is provided over a threshold, a report of mind-wandering is triggered (Chapter 6). Finally, a last possibility may well be a mere ending of the 30 seconds fluctuation (Chapter 2): as sustained attention may fail after a few dozens of seconds, facilitating the emergence of mind-wandering, mind-wandering may also fail after a few dozens of seconds, and facilitate the re-allocation of attention to the external world, in the absence of both error, and salient stimulus. This might well be related to the inner noticing of mind-wandering due to salient thoughts. This situation might be the most common when driving, given that, hopefully, little error feedback is provided, and there are few salient stimuli.

A final question is the extent to which noticing mind-wandering necessarily interrupts it: attention can certainly be reset by external salient stimuli, but mental fluctuations may at the same time facilitate the recovery of a given train of thought after short interruptions.

4. *Concluding remarks*

Three main characteristics of mind-wandering complicate its study: it is a subjective, spontaneous and dynamic phenomenon. We attempted to overcome the problem of observation by capitalizing on the phenomenon of perceptual decoupling: mind-wandering being associated with decreased performance, tracking performance could inform us on subjectivity. Although obviously limited, this simple proxy allowed us to uncover the dynamics of mind-wandering (Chapter 2), and the use this dynamics in subjective reports (Chapter 6). Interestingly, external behavior and subjective assessments converged on many points, and notably on a 30s dynamics (Chapters 2, 3, 6) that seems to be integrated as part of the signal to elicit mental reports (Chapter 6). Similarly, we showed that mind-wandering reports depend on a decision process, where participants would compare the level of an attentional variable to their threshold (Chapters 5, 6).

This pattern of findings stresses the importance of the dynamics in mind-wandering introspective monitoring. We evidenced that 30-s fluctuations are related to conscious mind-wandering (Chapter 3), and that introspection integrates the dynamics of mind-wandering (Chapter 6). Also, the high rates of mind-blanking in ADHD (Chapter 4) may reflect decreased ability to sustain thoughts. Indeed, fragmented and racing thoughts are commonly reported by psychiatric patients, and FPN disorders often result in DMN disorders (Anticevic et al., 2012; Cole et al., 2014).

In this regard, my proposition is close to William James' view on the transitive and substantive elements of thought (James, 1892). Substantive elements are thoughts with a stable and clear content, whereas transitive parts are the swiftly changing transitions between two relatively stable thoughts. Note how William James associated the content of thought to its dynamics, substantive elements being typically longer than transitive elements of thoughts:

"When we take a general view of the wonderful stream of our consciousness, what strikes us first is the different pace of its parts. Like a bird's life, it seems to be an alternation of flights and perchings. (...) The resting-places are usually occupied by sensorial imaginations of some sort, whose peculiarity is that they can be held before the mind for an indefinite time, and contemplated without changing; the places of flight are filled with thoughts of relations, static or dynamic, that for the most part obtain between the matters contemplated in the periods of comparative rest. Let us call the resting-places the 'substantive parts,' and the places of flight the 'transitive parts,' of the stream of thought."

James, 1892

In James terms, I therefore suggest that mind-blanking could be the subjective correlate of a greater thought pace: a greater amount of "transitive" thoughts, or thoughts that are not "substantive" enough to be reported, would be indicative of faster dynamics. A fascinating series of follow-up studies could therefore measure whether the subjective experience of mind-blanking, that is prominent in ADHD, is due to more "transitive"/racing thoughts and less "substantive/resting" thoughts. Given the general role of inner speech in monitoring (Tullett and Inzlicht, 2010; Perrone-Bertolotti et al., 2014; Alderson-Day and Fernyhough, 2015), inner speech could contribute to slowing thought pace by eliciting longer vivid (verbal) "substantive" elements of thoughts. In turn, these substantive elements would be easier to introspect. The fact that ADHD patients often present comorbidities with language disorders (Westby and Cutler, 1994; Sciberras et al., 2014) is intriguing in this regard: could a lack of inner speech account for ADHD patients' less substantive stream of thought?

Thus, future research should certainly study how various mental strategies affect the dynamics of self-generated thoughts: the monitoring role of inner speech, but also how meditation, or hypnosis, can "substantiate" and slow down the dynamics of the stream of thoughts. Yet, another line of research could also study the extent to which the dynamics of thought determine thoughts contents: psychopathology often involves both racing thoughts and introspective confusion. These two lines of research call for a fascinating objectification of thoughts dynamics and duration, and for better explanations of the mechanisms allowing oneself to access one's thoughts.

And thus, let's daydream that these future findings on introspection's inner workings will eventually enhance our ability to introspect our own stream of consciousness, up to the expertise that William James once had.

REFERENCES

Abramson M, Goldinger SD (1997) What the reader's eye tells the mind's ear: Silent reading activates inner speech. Percept Psychophys 59:1059–1068.

Ahmann PA, Waltonen SJ, Theye FW, Olson KA, Erem AJV (1993) Placebo-Controlled Evaluation of Ritalin Side Effects. Pediatrics 91:1101–1106.

Alderson-Day B, Fernyhough C (2015) Inner Speech: Development, Cognitive Functions, Phenomenology, and Neurobiology. Psychol Bull.

American Psychiatric Association (2013) Diagnostic and Statistical Manual of Mental Disorders, 5th Ed., American Psychiatric Association. Arlington, VA.

Anderson JR, Bothell D, Byrne MD, Douglass S, Lebiere C, Qin Y (2004) An Integrated Theory of the Mind. Psychol Rev 111:1036–1060.

Andrews-Hanna JR, Reidler JS, Sepulcre J, Poulin R, Buckner RL (2010) Functional-Anatomic Fractionation of the Brain's Default Network. Neuron 65:550–562.

Anticevic A, Cole MW, Murray JD, Corlett PR, Wang X-J, Krystal JH (2012) The role of default network deactivation in cognition and disease. Trends Cogn Sci 16:584–592.

Antshel KM, Nastasi R (2008) Metamemory development in preschool children with ADHD. J Appl Dev Psychol 29:403–411.

Armstrong DM (1963) Is Introspective Knowledge Incorrigible? Philos Rev 72:417–432.

August GJ, Realmuto GM, MacDonald AW, Nugent SM, Crosby R (1996) Prevalence of ADHD and comorbid disorders among elementary school children screened for disruptive behavior. J Abnorm Child Psychol 24:571–595.

Baars BJ (1988) A Cognitive Theory of Consciousness, Cambridge University Press. New York, NY, US.

Baars BJ (2002) The conscious access hypothesis: origins and recent evidence. Trends Cogn Sci 6:47–52.

Baars BJ (2010) Spontaneous repetitive thoughts can be adaptive: Postscript on "mind wandering". Psychol Bull 136:208.

Baddeley A (1992) Working memory. Science 255:556–559.

Baddeley AD, Hitch G (1974) Working Memory. In: Psychology of Learning and Motivation (Bower GH, ed), pp 47–89. Academic Press.

Baddeley AD, Thomson N, Buchanan M (1975) Word length and the structure of short-term memory. J Verbal Learn Verbal Behav 14:575–589.

Baird B, Smallwood J, Fishman DJF, Mrazek MD, Schooler JW (2013a) Unnoticed intrusions: dissociations of meta-consciousness in thought suppression. Conscious Cogn 22:1003–1012.

Baird B, Smallwood J, Gorgolewski KJ, Margulies DS (2013b) Medial and Lateral Networks in Anterior Prefrontal Cortex Support Metacognitive Ability for Memory and Perception. J Neurosci 33:16657–16665.

Baird B, Smallwood J, Mrazek MD, Kam JWY, Franklin MS, Schooler JW (2012) Inspired by distraction: mind wandering facilitates creative incubation. Psychol Sci 23:1117–1122.

Baird B, Smallwood J, Schooler JW (2011) Back to the future: autobiographical planning and the functionality of mind-wandering. Conscious Cogn 20:1604–1611.

Barkley RA (1997) Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. Psychol Bull 121:65–94.

Barkley RA, Fischer M (2011) Predicting impairment in major life activities and occupational functioning in hyperactive children as adults: self-reported executive function (EF) deficits versus EF tests. Dev Neuropsychol 36:137–161.

Barron E, Riby LM, Greer J, Smallwood J (2011) Absorbed in thought: the effect of mind wandering on the processing of relevant and irrelevant events. Psychol Sci 22:596–601.

Bastian M, Sackur J (2013) Mind wandering at the fingertips: automatic parsing of subjective states based on response time variability. Front Psychol 4:573.

Bates D, Mächler M, Bolker B, Walker S (2014) Fitting Linear Mixed-Effects Models using lme4. ArXiv14065823 Stat Available at: http://arxiv.org/abs/1406.5823 [Accessed April 18, 2015].

Baumeister RF, Masicampo EJ (2010) Conscious thought is for facilitating social and cultural interactions: how mental simulations serve the animal-culture interface. Psychol Rev 117:945–971.

Bem DJ (2011) Feeling the future: experimental evidence for anomalous retroactive influences on cognition and affect. J Pers Soc Psychol 100:407–425.

Bernacchia A, Seo H, Lee D, Wang X-J (2011) A reservoir of time constants for memory traces in cortical neurons. Nat Neurosci 14:366–372.

Berthié G, Lemercier C, Paubel P-V, Cour M, Fort A, Galéra C, Lagarde E, Gabaude C, Maury B (2015) The restless mind while driving: drivers' thoughts behind the wheel. Accid Anal Prev 76:159–165.

Biederman J, Faraone SV, Spencer TJ, Mick E, Monuteaux MC, Aleardi M (2006) Functional impairments in adults with self-reports of diagnosed ADHD: A controlled study of 1001 adults in the community. J Clin Psychiatry 67:524–540.

Biederman J, Newcorn J, Sprich S (1991) Comorbidity of attention deficit hyperactivity disorder with conduct, depressive, anxiety, and other disorders. Am J Psychiatry 148:564–577.

Bignell S, Cain K (2007) Pragmatic aspects of communication and language comprehension in groups of children differentiated by teacher ratings of inattention and hyperactivity. Br J Dev Psychol 25:499–512.

Borella E, Carretti B, Cornoldi C, Beni RD (2013) Working memory, control of interference and everyday experience of thought interference: when age makes the difference. Aging Clin Exp Res 19:200–206.

Braboszcz C, Delorme A (2011) Lost in thoughts: neural markers of low alertness during mind wandering. NeuroImage 54:3040–3047.

Brady TF, Konkle T, Alvarez GA, Oliva A (2008) Visual long-term memory has a massive storage capacity for object details. Proc Natl Acad Sci 105:14325–14329.

Brainard DH (1997) The Psychophysics Toolbox. Spat Vis 10:433–436.

Broadway JM, Zedelius CM, Mooneyham BW, Mrazek MD, Schooler JW (2015) Stimulating minds to wander. Proc Natl Acad Sci 112:3182–3183.

Brookes MJ, Woolrich M, Luckhoo H, Price D, Hale JR, Stephenson MC, Barnes GR, Smith SM, Morris PG (2011) Investigating the electrophysiological basis of resting state networks using magnetoencephalography. Proc Natl Acad Sci 108:16783–16788.

Brown KW, Ryan RM (2003) The benefits of being present: mindfulness and its role in psychological well-being. J Pers Soc Psychol 84:822–848.

Brown S, Steyvers M (2005) The dynamics of experimentally induced criterion shifts. J Exp Psychol Learn Mem Cogn 31:587–599.

Buckner RL, Andrews-Hanna JR, Schacter DL (2008) The brain’s default network: anatomy, function, and relevance to disease. Ann N Y Acad Sci 1124:1–38.

Burgess PW, Dumontheil I, Gilbert SJ (2007) The gateway hypothesis of rostral prefrontal cortex (area 10) function. Trends Cogn Sci 11:290–298.

Byrne MD, Anderson JR (2001) Serial modules in parallel: the psychological refractory period and perfect time-sharing. Psychol Rev 108:847–869.

Callard F, Smallwood J, Golchert J, Margulies DS (2013) The era of the wandering mind? Twenty-first century research on self-generated mental activity. Front Psychol 4.

Carriere JSA, Seli P, Smilek D (2013) Wandering in both mind and body: individual differences in mind wandering and inattention predict fidgeting. Can J Exp Psychol 67:19–31.

Carruthers P (2002) The cognitive functions of language. Behav Brain Sci 25:657–674.

Casner SM, Schooler JW (2014) Thoughts in flight: automation use and pilots’ task-related and task-unrelated thought. Hum Factors 56:433–442.

Cassuto H, Ben-Simon A, Berger I (2013) Using environmental distractors in the diagnosis of ADHD. Front Hum Neurosci 7:805.

Chen AC, Oathes DJ, Chang C, Bradley T, Zhou Z-W, Williams LM, Glover GH, Deisseroth K, Etkin A (2013) Causal interactions between fronto-parietal central executive and default-mode networks in humans. Proc Natl Acad Sci U S A 110:19944–19949.

Cheyne JA, Solman GJF, Carriere JSA, Smilek D (2009) Anatomy of an error: A bidirectional state model of task engagement/disengagement and attention-related errors. Cognition 111:98–113.

Christoff K, Gordon AM, Smallwood J, Smith R, Schooler JW (2009) Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. Proc Natl Acad Sci 106:8719–8724.

Cleveland WS (1979) Robust Locally Weighted Regression and Smoothing Scatterplots. J Am Stat Assoc 74:829–836.

Cohen MA, Dennett DC (2012) Response to Fahrenfort and Lamme: defining reportability, accessibility and sufficiency in conscious awareness. Trends Cogn Sci 16:139–140.

Cole MW, Repovš G, Anticevic A (2014) The frontoparietal control system: a central role in mental health. Neurosci Rev J Bringing Neurobiol Neurol Psychiatry 20:652–664.

Comte A (1819) Lettre à Valat du 24 septembre 1819. In: Correspondance générlale, Paris, Mouton.

Conners CK (1997) Conners' Teacher Rating Scale–Revised (L). Multi-Health Systems North Tonawanda, NY.

Conte S, Ferlazzo F, Renzi P (1995) Ultradian rhythms of reaction times in performance in vigilance tasks. Biol Psychol 39:159–172.

Corallo G, Sackur J, Dehaene S, Sigman M (2008) Limits on Introspection Distorted Subjective Time During the Dual-Task Bottleneck. Psychol Sci 19:1110–1117.

Cox WM, Klinger E (1988) A motivational model of alcohol use. J Abnorm Psychol 97:168–180.

Cragg L, Nation K (2010) Language and the Development of Cognitive Control. Top Cogn Sci 2:631–642.

Craig ADB (2009) How do you feel--now? The anterior insula and human awareness. Nat Rev Neurosci 10:59–70.

Craigmile PF, Peruggia M, Van Zandt T (2010) Hierarchical Bayes Models for Response Time Data. Psychometrika 75:613–632.

Csikszentmihalyi M (1978) Attention and the Holistic Approach to Behavior. In: The Stream of Consciousness (Pope KS, Singer JL, eds), pp 335–358 Emotions, Personality, and Psychotherapy. Springer US.

Csikszentmihalyi M, Hunter J (2003) Happiness in Everyday Life: The Uses of Experience Sampling. J Happiness Stud 4:185–199.

Csikszentmihalyi M, Larson R (1987) Validity and reliability of the Experience-Sampling Method. J Nerv Ment Dis 175:526–536.

De Gee JW, Knapen T, Donner TH (2014) Decision-related pupil dilation reflects upcoming choice and individual bias. Proc Natl Acad Sci 111:E618–E625.

Dehaene S, Changeux J-P, Naccache L, Sackur J, Sergent C (2006) Conscious, preconscious, and subliminal processing: a testable taxonomy. Trends Cogn Sci 10:204–211.

Dehaene S, Naccache L (2001) Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. Cognition 79:1–37.

Del Cul A, Dehaene S, Leboyer M (2006) Preserved subliminal processing and impaired conscious access in schizophrenia. Arch Gen Psychiatry 63:1313–1323.

Demertzi A, Soddu A, Faymonville M-E, Bahri MA, Gosseries O, Vanhaudenhuyse A, Phillips C, Maquet P, Noirhomme Q, Luxen A, Laureys S (2011) Hypnotic modulation of resting state fMRI default mode and extrinsic network connectivity. Prog Brain Res 193:309–322.

Dienes Z (2014) Using Bayes to get the most out of non-significant results. Quant Psychol Meas 5:781.

Dietrich A (2004) Neurocognitive mechanisms underlying the experience of flow. Conscious Cogn 13:746–761.

Dumontheil I, Küster O, Apperly IA, Blakemore S-J (2010) Taking perspective into account in a communicative task. NeuroImage 52:1574–1583.

DuPaul GJ, Power TJ, Anastopoulos AD, Reid R (1998) ADHD Rating Scale—IV: Checklists, norms, and clinical interpretation. New York, NY, US: Guilford Press.

Durantin G, Dehais F, Delorme A (2015) Characterization of mind wandering using fNIRS. Front Syst Neurosci:45.

Emerson MJ, Miyake A (2003) The role of inner speech in task switching: A dual-task investigation. J Mem Lang 48:148–168.

Epel ES, Puterman E, Lin J, Blackburn E, Lazaro A, Mendes WB (2013) Wandering Minds and Aging Cells. Clin Psychol Sci 1:75–83.

Ericsson KA, Simon HA (1980) Verbal reports as data. Psychol Rev 87:215–251.

Faraone SV, Biederman J, Spencer T, Mick E, Murray K, Petty C, Adamson JJ, Monuteaux MC (2006) Diagnosing adult attention deficit hyperactivity disorder: are late onset and subthreshold diagnoses valid? Am J Psychiatry 163:1720–1729.

Farley J, Risko EF, Kingstone A (2013) Everyday attention and lecture retention: the effects of time, fidgeting, and mind wandering. Front Psychol 4:619.

Fleming SM, Huijgen J, Dolan RJ (2012) Prefrontal Contributions to Metacognition in Perceptual Decision Making. J Neurosci 32:6117–6125.

Fleming SM, Lau HC (2014) How to measure metacognition. Front Hum Neurosci 8:443.

Fleming SM, Weil RS, Nagy Z, Dolan RJ, Rees G (2010) Relating introspective accuracy to individual differences in brain structure. Science 329:1541–1543.

Forster S, Lavie N (2009) Harnessing the wandering mind: the role of perceptual load. Cognition 111:345–355.

Fox KCR, Christoff K (2015) Transcranial direct current stimulation to lateral prefrontal cortex could increase meta-awareness of mind wandering. Proc Natl Acad Sci 112:E2414–E2414.

Fox KCR, Spreng RN, Ellamil M, Andrews-Hanna JR, Christoff K (2015) The wandering brain: Meta-analysis of functional neuroimaging studies of mind-wandering and related spontaneous thought processes. NeuroImage 111:611–621.

Fox KCR, Zakarauskas P, Dixon M, Ellamil M, Thompson E, Christoff K (2012) Meditation Experience Predicts Introspective Accuracy. PLoS ONE 7:e45370.

Fox MC, Ericsson KA, Best R (2011) Do procedures for verbal reporting of thinking have to be reactive? A meta-analysis and recommendations for best reporting methods. Psychol Bull 137:316–344.

Fox MD, Raichle ME (2007) Spontaneous fluctuations in brain activity observed with functional magnetic resonance imaging. Nat Rev Neurosci 8:700–711.

Franklin MS, Broadway JM, Mrazek MD, Smallwood J, Schooler JW (2013a) Window to the wandering mind: pupillometry of spontaneous thought while reading. Q J Exp Psychol 2006 66:2289–2294.

Franklin MS, Mrazek MD, Anderson CL, Johnston C, Smallwood J, Kingstone A, Schooler JW (2014) Tracking Distraction: The Relationship Between Mind-Wandering, Meta-Awareness, and ADHD Symptomatology. J Atten Disord.

Franklin MS, Mrazek MD, Broadway JM, Schooler JW (2013b) Disentangling decoupling: comment on Smallwood (2013). Psychol Bull 139:536–541.

Gaillard V, Destrebecqz A, Cleeremans A (2012) The influence of articulatory suppression on the control of implicit sequence knowledge. Front Hum Neurosci 6.

Galéra C, Orriols L, M'Bailara K, Laborey M, Contrand B, Ribéreau-Gayon R, Masson F, Bakiri S, Gabaude C, Fort A, Maury B, Lemercier C, Cours M, Bouvard M-P, Lagarde E (2012) Mind wandering and driving: responsibility case-control study. BMJ 345:e8105.

Garavan H, Ross TJ, Li SJ, Stein EA (2000) A parametric manipulation of central executive functioning. Cereb Cortex N Y N 1991 10:585–592.

Gelman A, Rubin DB (1992) Inference from Iterative Simulation Using Multiple Sequences. Stat Sci 7:457–472.

Gerlach KD, Spreng RN, Gilmore AW, Schacter DL (2011) Solving future problems: default network and executive activity associated with goal-directed mental simulations. Neuroimage 55:1816–1824.

Geva S, Jones PS, Crinion JT, Price CJ, Baron J-C, Warburton EA (2011) The neural correlates of inner speech defined by voxel-based lesion–symptom mapping. Brain 134:3071–3082.

Giambra LM (1989) Task-unrelated thought frequency as a function of age: A laboratory study. Psychol Aging 4:136–143.

Giambra LM, Rosenberg EH, Kasper S, Yee W, Sack DA (1989) A Circadian Rhythm in the Frequency of Spontaneous Task-Unrelated Images and Thoughts. Imagin Cogn Personal 8:309–314.

Gilbert SJ, Dumontheil I, Simons JS, Frith CD, Burgess PW (2007) Comment on "Wandering minds: the default network and stimulus-independent thought." Science 317:43; author reply 43.

Gortner E-M, Rude SS, Pennebaker JW (2006) Benefits of Expressive Writing in Lowering Rumination and Depressive Symptoms. Behav Ther 37:292–303.

Grandchamp R, Braboszcz C, Delorme A (2014) Oculometric variations during mind wandering. Front Psychol 5:31.

Gratton G, Coles MG, Donchin E (1992) Optimizing the use of information: strategic control of activation of responses. J Exp Psychol Gen 121:480–506.

Grebot E (2000) Validation du questionnaire de style cognitif de Paivio auprès d'une population française. Eur Rev Appl Psychol 50:87–95.

Green DM, Swets JA (1966a) Signal Detection Theory and Psychophysics. John Wiley and Sons.

Green DM, Swets JA (1966b) Signal Detection Theory and Psychophysics. New York: Wiley.

Grof S (1972) Varieties of Transpersonal Experiences: observations from LSD psychotherapy. J Transpers Psychol 1:45–80.

Gusnard DA, Akbudak E, Shulman GL, Raichle ME (2001) Medial prefrontal cortex and self-referential mental activity: Relation to a default mode of brain function. Proc Natl Acad Sci U S A 98:4259–4264.

Gusnard DA, Raichle ME (2001) Searching for a baseline: Functional imaging and the resting human brain. Nat Rev Neurosci 2:685–694.

Hanley JR (1997) Does Articulatory Suppression Remove the Irrelevant Speech Effect? Memory 5:423–431.

Hanley JR, Bakopoulou E (2003) Irrelevant speech, articulatory suppression, and phonological similarity: A test of the phonological loop model and the feature model. Psychon Bull Rev 10:435–444.

Hanley JR, Broadbent C (1987) The effect of unattended speech on serial recall following auditory presentation. Br J Psychol 78:287–297.

Harpin VA (2005) The effect of ADHD on the life of an individual, their family, and community from preschool to adult life. Arch Dis Child 90 Suppl 1:i2–i7.

Hasenkamp W, Wilson-Mendenhall CD, Duncan E, Barsalou LW (2012) Mind wandering and attention during focused meditation: a fine-grained temporal analysis of fluctuating cognitive states. NeuroImage 59:750–760.

Hasher L, Zacks RT (1988) Working Memory, Comprehension, and Aging: A Review and a New View. Psychol Learn Motiv 22:193–225.

Heatherton TF, Wagner DD (2011) Cognitive Neuroscience of Self-Regulation Failure. Trends Cogn Sci 15:132–139.

Heavey CL, Hurlburt RT (2008) The phenomena of inner experience. Conscious Cogn 17:798–810.

He J, Becic E, Lee Y-C, McCarley JS (2011) Mind wandering behind the wheel: performance and oculomotor correlates. Hum Factors 53:13–21.

Hertel PT (1998) Relation between rumination and impaired memory in dysphoric moods. J Abnorm Psychol 107:166–172.

Hobson JA, McCarley RW (1977) The brain as a dream state generator: an activation-synthesis hypothesis of the dream process. Am J Psychiatry 134:1335–1348.

Hughes R, Jones DM (2001) The intrusiveness of sound : Laboratory findings and their implications for noise abatement. Noise Health 4:51.

Huijgen J, Samson S (2015) The hippocampus: A central node in a large-scale brain network for memory. Rev Neurol (Paris) 171:204–216.

Hu N, He S, Xu B (2012) Different efficiencies of attentional orienting in different wandering minds. Conscious Cogn 21:139–148.

Hurlburt RT, Heavey CL (2004) To Beep or Not To Beep: Obtaining Accurate Reports About Awareness. J Conscious Stud 11:113–128.

Hurlburt RT, Koch M, Heavey CL (2002) Descriptive Experience Sampling Demonstrates the Connection of Thinking to Externally Observable Behavior. Cogn Ther Res 26:117–134.

Hurlburt RT, Schwitzgebel E (2007) Describing inner experience? Proponent meets skeptic. Cambridge, MA, US: MIT Press.

Ioannidis JPA (2005) Why most published research findings are false. PLoS Med 2:e124.

Jackson JD, Balota DA (2012) Mind-wandering in younger and older adults: converging evidence from the Sustained Attention to Response Task and reading for comprehension. Psychol Aging 27:106–119.

James W (1892) The Stream of Consciousness. In: The Principles of Psychology, Harvard University Press. (James W, ed). George A. Miller.

Jerbi K, Vidal JR, Ossandon T, Dalal SS, Jung J, Hoffmann D, Minotti L, Bertrand O, Kahane P, Lachaux J-P (2010) Exploring the Electrophysiological Correlates of the Default-Mode Network with Intracerebral EEG. Front Syst Neurosci 4.

Jiang Y, Costello P, He S (2007) Processing of Invisible Stimuli: Advantage of Upright Faces and Recognizable Words in Overcoming Interocular Suppression. Psychol Sci 18:349–355.

Johansson P, Hall L, Sikström S, Olsson A (2005) Failure to detect mismatches between intention and outcome in a simple decision task. Science 310:116–119.

Johansson P, Hall L, Sikström S, Tärning B, Lind A (2006) How something can be said about telling more than we can know: On choice blindness and introspection. Conscious Cogn 15:673–692.

Kam JWY, Dao E, Farley J, Fitzpatrick K, Smallwood J, Schooler JW, Handy TC (2011) Slow fluctuations in attentional control of sensory cortex. J Cogn Neurosci 23:460–470.

Kane MJ, Brown LH, McVay JC, Silvia PJ, Myin-Germeys I, Kwapil TR (2007) For whom the mind wanders, and when: an experience-sampling study of working memory and executive control in daily life. Psychol Sci 18:614–621.

Kane MJ, McVay JC (2012) What Mind Wandering Reveals About Executive-Control Abilities and Failures. Curr Dir Psychol Sci 21:348–354.

Kaufman J, Birmaher B, Brent D, Rao U, Ryan N (1996) The Schedule for Affective Disorders and Schizophrenia for School-Age Children.

Kieras DE, Meyer DE (1997) An Overview of the EPIC Architecture for Cognition and Performance with Application to Human-computer Interaction. Hum-Comput Interact 12:391–438.

Killeen PR (2013) Absent without leave; a neuroenergetic theory of mind wandering. Front Psychol 4:373.

Killingsworth MA, Gilbert DT (2010) A wandering mind is an unhappy mind. Science 330:932–932.

Klinger E (1978) Modes of Normal Conscious Flow. In: The Stream of Consciousness: Scientific Investigation Into the Flow of Experience (Pope KS, Singer JL, eds). Plenum.

Klinger E (2009) Daydreaming and fantasizing: Thought flow and motivation. In: Handbook of imagination and mental simulation (Markman KD, Klein WMP, Suhr JA, eds), pp 225–239. New York, NY, US: Psychology Press.

Klinger E (2013) Goal Commitments and the content of thoughts and dreams: basic principles. Front Psychol 4.

Klinger E, Cox WM (1987) Dimensions of thought flow in everyday life. Imagin Cogn Personal 7:105–128.

Ko AL, Darvas F, Poliakov A, Ojemann J, Sorensen LB (2011) Quasi-periodic Fluctuations in Default Mode Network Electrophysiology. J Neurosci 31:11728–11732.

Kooij JJS, Francken MH (2010) Diagnostic interview for ADHD in adults 2.0 (DIVA 2.0). Adult ADHD Diagn Assess Treat Pearson Assess Inf BV Amst.

Koriat A (2012) The self-consistency model of subjective confidence. Psychol Rev 119:80–113.

Kovacs M (1985) The Children’s Depression, Inventory (CDI). Psychopharmacol Bull 21:995–998.

Kucyi A, Salomons TV, Davis KD (2013) Mind wandering away from pain dynamically engages antinociceptive and default mode brain networks. Proc Natl Acad Sci 110:18692–18697.

Laird JE, Newell A, Rosenbloom PS (1987) SOAR: An architecture for general intelligence. Artif Intell 33:1–64.

Lamme VAF (2006) Towards a true neural stance on consciousness. Trends Cogn Sci 10:494–501.

Lau H, Rosenthal D (2011) Empirical support for higher-order theories of conscious awareness. Trends Cogn Sci 15:365–373.

Lee MD, Wagenmakers E-J (2014) Bayesian Cognitive Modeling: A Practical Course, Cambridge University Press. Cambridge.

Leopold DA, Logothetis NK (1996) Activity changes in early visual cortex reflect monkeys’ percepts during binocular rivalry. Nature 379:549–553.

Leth-Steensen C, Elbaz ZK, Douglas VI (2000) Mean response times, variability, and skew in the responding of ADHD children: a response time distributional approach. Acta Psychol (Amst) 104:167–190.

Levelt WJ (1967) Note on the distribution of dominance times in binocular rivalry. Br J Psychol Lond Engl 1953 58:143–145.

Levinson DB, Smallwood J, Davidson RJ (2012) The persistence of thought: evidence for a role of working memory in the maintenance of task-unrelated thinking. Psychol Sci 23:375–380.

Levy R (2014) Using R formulae to test for main effects in the presence of higher-order interactions. ArXiv14052094 Stat.

Lidstone JSM, Meins E, Fernyhough C (2010) The roles of private speech and inner speech in planning during middle childhood: Evidence from a dual task paradigm. J Exp Child Psychol 107:438–451.

López-Martín S, Albert J, Fernández-Jaén A, Carretié L (2013) Emotional distraction in boys with ADHD: neural and behavioral correlates. Brain Cogn 83:10–20.

Luce RD (1986) Response Times: Their Role in Inferring Elementary Mental Organization, Oxford University Press. Oxford.

Mackworth NH (1948) The breakdown of vigilance durning prolonged visual search. Q J Exp Psychol 1:6–21.

Marti S, Sackur J, Sigman M, Dehaene S (2010) Mapping introspection’s blind spot: Reconstruction of dual-task phenomenology using quantified introspection. Cognition 115:303–313.

Marvel CL, Desmond JE (2012) From storage to manipulation: How the neural correlates of verbal working memory reflect varying demands on inner speech. Brain Lang 120:42–51.

Mason MF, Brown K, Mar RA, Smallwood J (2013) Driver of discontent or escape vehicle: the affective consequences of mindwandering. Front Psychol 4.

Mason MF, Norton MI, Van Horn JD, Wegner DM, Grafton ST, Macrae CN (2007) Wandering Minds: The Default Network and Stimulus-Independent Thought. Science 315:393–395.

Mayer JL, Farmer RF (2003) The development and psychometric evaluation of a new measure of dissociative activities. J Pers Assess 80:185–196.

McCaig RG, Dixon M, Keramatian K, Liu I, Christoff K (2011) Improved modulation of rostrolateral prefrontal cortex using real-time fMRI training and meta-cognitive awareness. NeuroImage 55:1298–1305.

McElree B (2006) Accessing Recent Events. Psychol Learn Motiv 46:155–200.

Mcguire PK, Silbersweig DA, Wright I, Murray RM, Frackowiak RSJ, Frith CD (1996) The neural correlates of Inner speech and auditory verbal imagery in schizophrenia : Relationship to auditory verbal hallucinations. Br J Psychiatry 169:148–159.

McMillan RL, Kaufman SB, Singer JL (2013) Ode to positive constructive daydreaming. Front Psychol 4:626.

McVay JC, Kane MJ (2010) Does Mind Wandering Reflect Executive Function or Executive Failure? Comment on and. Psychol Bull 136:188–207.

McVay JC, Kane MJ (2012) Drifting from slow to “D’oh!”: working memory capacity and mind wandering predict extreme reaction times and executive control errors. J Exp Psychol Learn Mem Cogn 38:525–549.

McVay JC, Kane MJ (2013) Dispatching the wandering mind? Toward a laboratory method for cuing “spontaneous” off-task thought. Front Psychol 4:570.

McVay JC, Meier ME, Touron DR, Kane MJ (2013) Aging ebbs the flow of thought: Adult age differences in mind wandering, executive control, and self-evaluation. Acta Psychol (Amst) 142:136–147.

Miles LK, Karpinska K, Lumsden J, Macrae CN (2010) The Meandering Mind: Vection and Mental Time Travel. PLoS ONE 5:e10825.

Miller AC, Keenan JM, Betjemann RS, Willcutt EG, Pennington BF, Olson RK (2013) Reading comprehension in children with ADHD: cognitive underpinnings of the centrality deficit. J Abnorm Child Psychol 41:473–483.

Miller J, Vieweg P, Kruize N, McLea B (2010) Subjective reports of stimulus, response, and decision times in speeded tasks: How accurate are decision time reports? Conscious Cogn 19:1013–1036.

Mittner M, Boekel W, Tucker AM, Turner BM, Heathcote A, Forstmann BU (2014) When the brain takes a break: a model-based analysis of mind wandering. J Neurosci 34:16286–16295.

Miyake A, Emerson MJ, Padilla F, Ahn J (2004) Inner speech as a retrieval aid for task goals: the effects of cue type and articulatory suppression in the random task cuing paradigm. Acta Psychol (Amst) 115:123–142.

Mooneyham BW, Schooler JW (2013) The costs and benefits of mind-wandering: a review. Can J Exp Psychol 67:11–18.

Morin A (2005) Possible Links Between Self-Awareness and Inner Speech Theoretical background, underlying mechanisms, and empirical evidence. J Conscious Stud 12:115–134.

Morin A, Everett J (1990) Inner speech as a mediator of self-awareness, self-consciousness, and self-knowledge: An hypothesis. New Ideas Psychol 8:337–356.

Morin A, Hamper B (2012) Self-Reflection and the Inner Voice: Activation of the Left Inferior Frontal Gyrus During Perceptual and Conceptual Self-Referential Thinking. Open Neuroimaging J 6:78–89.

Mouren-Siméoni M-C (2002) Kiddie-Sads - version vie entière - 6-18 ans (K-SADS-P/L).

Mrazek MD, Franklin MS, Phillips DT, Baird B, Schooler JW (2013) Mindfulness training improves working memory capacity and GRE performance while reducing mind wandering. Psychol Sci 24:776–781.

Mrazek MD, Smallwood J, Franklin MS, Chin JM, Baird B, Schooler JW (2012a) The role of mind-wandering in measurements of general aptitude. J Exp Psychol Gen 141:788–798.

Mrazek MD, Smallwood J, Schooler JW (2012b) Mindfulness and mind-wandering: finding convergence through opposing constructs. Emot Wash DC 12:442–448.

Murray JD, Bernacchia A, Freedman DJ, Romo R, Wallis JD, Cai X, Padoa-Schioppa C, Pasternak T, Seo H, Lee D, Wang X-J (2014) A hierarchy of intrinsic timescales across primate cortex. Nat Neurosci 17:1661–1663.

Nakamura J, Csikszentmihalyi M (2002) The concept of flow. In: Handbook of positive psychology (Snyder CR, Lopez SJ, eds), pp 89–105. New York, NY, US: Oxford University Press.

Nisbett RE, Wilson TD (1977) Telling more than we can know: Verbal reports on mental processes. Psychol Rev 84:231–259.

O'Connell RG, Dockree PM, Robertson IH, Bellgrove MA, Foxe JJ, Kelly SP (2009) Uncovering the Neural Signature of Lapsing Attention: Electrophysiological Signals Predict Errors up to 20 s before They Occur. J Neurosci 29:8604–8611.

Okawa M, Matousek M, Petersén I (1984) Spontaneous vigilance fluctuations in the daytime. Psychophysiology 21:207–211.

Owen AM, Coleman MR, Boly M, Davis MH, Laureys S, Pickard JD (2006) Detecting Awareness in the Vegetative State. Science 313:1402–1402.

Paivio A (1979) Imagery and Verbal Processes. Lawrence Erlbaum Associates, Inc.

Paivio A, Harshman R (1983) Factor analysis of a questionnaire on imagery and verbal habits and skills. Can J Psychol Can Psychol 37:461–483.

Pashler H (1994) Dual-task interference in simple tasks: data and theory. Psychol Bull 116:220–244.

Pelli DG (1997) The videotoolbox software for visual psychophysics: transforming numbers into movies. Spat Vis 10:437–442.

Perrone-Bertolotti M, Rapin L, Lachaux JP, Baciu M, Lœvenbruck H (2014) What is that little voice inside my head? Inner speech phenomenology, its role in cognitive performance, and its relation to self-monitoring. Behav Brain Res 261:220–239.

Pintner R (1913) Inner speech during silent reading. Psychol Rev 20:129–153.

Plummer M (2003) JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. Proc 3rd Int Workshop Distrib Stat Comput.

Polanczyk G, de Lima MS, Horta BL, Biederman J, Rohde LA (2007) The worldwide prevalence of ADHD: a systematic review and metaregression analysis. Am J Psychiatry 164:942–948.

Polanczyk GV, Willcutt EG, Salum GA, Kieling C, Rohde LA (2014) ADHD prevalence estimates across three decades: an updated systematic review and meta-regression analysis. Int J Epidemiol 43:434–442.

Poldrack RA (2011) Inferring mental states from neuroimaging data: from reverse inference to large-scale decoding. Neuron 72:692–697.

Pope KS (1978) How Gender, Solitude, and Posture Influence the Stream of Consciousness. In: The Stream of Consciousness: Scientific Investigation Into the Flow of Experience (Pope KS, Singer JL, eds). Plenum.

Pope KS, Singer JL (1978) The Stream of Consciousness: Scientific Investigations Into the Flow of Human Experience. Plenum Press.

Qin Y, Sohn M-H, Anderson JR, Stenger VA, Fissell K, Goode A, Carter CS (2003) Predicting the practice effects on the blood oxygenation level-dependent (BOLD) function of fMRI in a symbolic manipulation task. Proc Natl Acad Sci 100:4951–4956.

Raichle ME, MacLeod AM, Snyder AZ, Powers WJ, Gusnard DA, Shulman GL (2001) A default mode of brain function. Proc Natl Acad Sci 98:676–682.

Ramautar JR, Romeijn N, Gómez-Herrero G, Piantoni G, Van Someren EJW (2013) Coupling of infraslow fluctuations in autonomic and central vigilance markers: skin temperature, EEG β power and ERP P300 latency. Int J Psychophysiol Off J Int Organ Psychophysiol 89:158–164.

Raymond JE, Shapiro KL, Arnell KM (1992) Temporary suppression of visual processing in an RSVP task: an attentional blink? J Exp Psychol Hum Percept Perform 18:849–860.

R Core Team (2014) R: A Language and Environment for Statistical Computing. Available at: http://www.R-project.org.

Reder LM, Ritter FE (1992) What determines initial feeling of knowing? Familiarity with question terms, not with the answer. J Exp Psychol Learn Mem Cogn 18:435–451.

Reichle ED, Reineberg AE, Schooler JW (2010) Eye movements during mindless reading. Psychol Sci 21:1300–1310.

RepovŠ G, Baddeley A (2006) The multi-component model of working memory: Explorations in experimental cognitive psychology. Neuroscience 139:5–21.

Reyes G, Sackur J (2014) Introspection during visual search. Conscious Cogn 29:212–229.

Richard J-F (1980) L’attention. Presses Universitaires de France.

Risko EF, Buchanan D, Medimorec S, Kingstone A (2013) Everyday attention: Mind wandering and computer use during lectures. Comput Educ 68:275–283.

Robertson IH, Manly T, Andrade J, Baddeley BT, Yiend J (1997) “Oops!”: performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. Neuropsychologia 35:747–758.

Rounis E, Maniscalco B, Rothwell JC, Passingham RE, Lau H (2010) Theta-burst transcranial magnetic stimulation to the prefrontal cortex impairs metacognitive visual awareness. Cogn Neurosci 1:165–175.

Rousseau J-J (1755) Discours sur l’origine et les fondements de l’inégalité parmi les hommes, Garnier Flammarion.

Ruby FJM, Smallwood J, Sackur J, Singer T (2013) Is self-generated thought a means of social problem solving? Front Psychol 4:962.

Salamé P, Baddeley A (1982) Disruption of short-term memory by unattended speech: Implications for the structure of working memory. J Verbal Learn Verbal Behav 21:150–164.

Sarason IG, Sarason BR, Keefe DE, Hayes BE, Shearin EN (1986) Cognitive interference: Situational determinants and traitlike characteristics. J Pers Soc Psychol 51:215–226.

Sayette MA, Reichle ED, Schooler JW (2009) Lost in the Sauce The Effects of Alcohol on Mind Wandering? Psychol Sci 20:747–752.

Sayette MA, Schooler JW, Reichle ED (2010) Out for a smoke: the impact of cigarette craving on zoning out during reading. Psychol Sci 21:26–30.

Schacter DL, Addis DR, Hassabis D, Martin VC, Spreng RN, Szpunar KK (2012) The Future of Memory: Remembering, Imagining, and the Brain. Neuron 76.

Schad DJ, Nuthmann A, Engbert R (2012) Your mind wanders weakly, your mind wanders deeply: objective measures reveal mindless reading at different levels. Cognition 125:179–194.

Scheeringa R, Bastiaansen MCM, Petersson KM, Oostenveld R, Norris DG, Hagoort P (2008) Frontal theta EEG activity correlates negatively with the default mode network in resting state. Int J Psychophysiol 67:242–251.

Schoechlin C, Engel RR (2005) Neuropsychological performance in adult attention-deficit hyperactivity disorder: Meta-analysis of empirical data. Arch Clin Neuropsychol 20:727–744.

Schooler JW (2002) Re-representing consciousness: dissociations between experience and meta-consciousness. Trends Cogn Sci 6:339–344.

Schooler JW, Reichle ED, Halpern DV (2004) Zoning Out while Reading: Evidence for Dissociations between Experience and Metaconsciousness. In: Thinking and seeing: Visual metacognition in adults and children, pp 203–226. Cambridge, MA, US: MIT Press.

Schooler JW, Schreiber CA (2004) Experience, Meta-consciousness, and the Paradox of Introspection. J Conscious Stud 11:17–39.

Schooler JW, Smallwood J, Christoff K, Handy TC, Reichle ED, Sayette MA (2011) Meta-awareness, perceptual decoupling and the wandering mind. Trends Cogn Sci 15:319–326.

Schvaneveldt RW, Chase WG (1969) Sequential effects in choice reaction time. J Exp Psychol 80:1–8.

Sciberras E, Mueller KL, Efron D, Bisset M, Anderson V, Schilpzand EJ, Jongeling B, Nicholson JM (2014) Language Problems in Children With ADHD: A Community-Based Study. Pediatrics 133:793–800.

Seli P, Carriere JSA, Smilek D (2014) Not all mind wandering is created equal: dissociating deliberate from spontaneous mind wandering. Psychol Res.

Seli P, Cheyne JA, Smilek D (2013) Wandering minds and wavering rhythms: linking mind wandering and behavioral variability. J Exp Psychol Hum Percept Perform 39:1–5.

Seli P, Cheyne JA, Xu M, Purdon C, Smilek D (2015a) Motivation, Intentionality, and Mind Wandering: Implications for Assessments of Task-Unrelated Thought. J Exp Psychol Learn Mem Cogn.

Seli P, Jonker TR, Cheyne JA, Cortes K, Smilek D (2015b) Can Research Participants Comment Authoritatively on the Validity of Their Self-Reports of Mind Wandering and Task Engagement? J Exp Psychol Hum Percept Perform.

Seli P, Smallwood J, Cheyne JA, Smilek D (2015c) On the relation of mind wandering and ADHD symptomatology. Psychon Bull Rev.

Sergent C, Baillet S, Dehaene S (2005) Timing of the brain events underlying access to consciousness during the attentional blink. Nat Neurosci 8:1391–1400.

Shaw G A, Giambra LM (1993) Task-unrelated thoughts of college students diagnosed as hyperactive in childhood. Dev Neuropsychol 9:17–30.

Shulman GL, Fiez JA, Corbetta M, Buckner RL, Miezin FM, Raichle ME, Petersen SE (1997) Common Blood Flow Changes across Visual Tasks: II. Decreases in Cerebral Cortex. J Cogn Neurosci 9:648–663.

Singer JL (1974) Imagery and daydream methods in psychotherapy and behavior modification, New York: Academic Press.

Singer JL (1978) Experimental Studies of Daydreaming and the Stream of Thought. In: The Stream of Consciousness: Scientific Investigation Into the Flow of Experience (Pope KS, Singer JL, eds). Plenum.

Singer JL, Antrobus J (1966) Imaginal Process Inventory.

Skinner BF (1959) John Broadus Watson, behaviorist. Science 129:197–198.

Smallwood J (2011a) Mind-wandering While Reading: Attentional Decoupling, Mindless Reading and the Cascade Model of Inattention. Lang Linguist Compass 5:63–77.

Smallwood J (2011b) The footprints of a wandering mind: Further examination of the time course of an attentional lapse. Cogn Neurosci 2:91–97.

Smallwood J (2013a) Distinguishing how from why the mind wanders: a process-occurrence framework for self-generated mental activity. Psychol Bull 139:519–535.

Smallwood J (2013b) Searching for the elements of thought: reply to Franklin, Mrazek, Broadway, and Schooler (2013). Psychol Bull 139:542–547.

Smallwood J (2013c) Penetrating the fog of the decoupled mind: the effects of visual salience in the sustained attention to response task. Can J Exp Psychol 67:32–40.

Smallwood J, Brown K, Baird B, Schooler JW (2012a) Cooperation between the default mode network and the frontal-parietal network in the production of an internal train of thought. Brain Res 1428:60–70.

Smallwood J, Brown KS, Baird B, Mrazek MD, Franklin MS, Schooler JW (2012b) Insulation for daydreams: a role for tonic norepinephrine in the facilitation of internally guided thought. PloS One 7:e33706.

Smallwood J, Brown KS, Tipper C, Giesbrecht B, Franklin MS, Mrazek MD, Carlson JM, Schooler JW (2011a) Pupillometric evidence for the decoupling of attention from perceptual input during offline thought. PloS One 6:e18298.

Smallwood J, Fishman DJ, Schooler JW (2007a) Counting the cost of an absent mind: mind wandering as an underrecognized influence on educational performance. Psychon Bull Rev 14:230–236.

Smallwood J, Fitzgerald A, Miles LK, Phillips LH (2009a) Shifting moods, wandering minds: negative moods lead the mind to wander. Emot Wash DC 9:271–276.

Smallwood J, McSpadden M, Luus B, Schooler J (2008a) Segmenting the stream of consciousness: the psychological correlates of temporal structures in the time series data of a continuous performance task. Brain Cogn 66:50–56.

Smallwood J, McSpadden M, Schooler JW (2008b) When attention matters: the curious incident of the wandering mind. Mem Cognit 36:1144–1150.

Smallwood J, Mrazek MD, Schooler JW (2011b) Medicine for the wandering mind: mind wandering in medical practice. Med Educ 45:1072–1080.

Smallwood J, Nind L, O’Connor RC (2009b) When is your head at? An exploration of the factors associated with the temporal focus of the wandering mind. Conscious Cogn 18:118–125.

Smallwood J, O’Connor RC (2011) Imprisoned by the past: unhappy moods lead to a retrospective bias to mind wandering. Cogn Emot 25:1481–1490.

Smallwood J, O’Connor RC, Sudberry MV, Haskell C, Ballantyne C (2004) The consequences of encoding information on the maintenance of internally generated images and thoughts: The role of meaning complexes. Conscious Cogn 13:789–820.

Smallwood J, O’Connor RC, Sudbery MV, Obonsawin M (2007b) Mind-wandering and dysphoria. Cogn Emot 21:816–842.

Smallwood J, Ruby FJM, Singer T (2013) Letting go of the present: mind-wandering is associated with reduced delay discounting. Conscious Cogn 22:1–7.

Smallwood J, Schooler JW (2006) The restless mind. Psychol Bull 132:946–958.

Smallwood J, Schooler JW (2015) The science of mind wandering: empirically navigating the stream of consciousness. Annu Rev Psychol 66:487–518.

Smilek D, Carriere JSA, Cheyne JA (2010) Out of mind, out of sight: eye blinking as indicator and embodiment of mind wandering. Psychol Sci 21:786–789.

Snaith RP, Zigmond AS (1986) The hospital anxiety and depression scale. Br Med J Clin Res Ed 292:344.

Sokolov AN (1972) Inner Speech and Thought. Plenum Press: New York.

Song X, Wang X (2012) Mind wandering in Chinese daily lives--an experience sampling study. PloS One 7:e44423.

Spreng RN, Sepulcre J, Turner GR, Stevens WD, Schacter DL (2013) Intrinsic architecture underlying the relations among the default, dorsal attention, and frontoparietal control networks of the human brain. J Cogn Neurosci 25.

Spreng RN, Stevens WD, Chamberlain JP, Gilmore AW, Schacter DL (2010) Default network activity, coupled with the frontoparietal control network, supports goal-directed cognition. NeuroImage 53:303–317.

Sridharan D, Levitin DJ, Menon V (2008) A critical role for the right fronto-insular cortex in switching between central-executive and default-mode networks. Proc Natl Acad Sci U S A 105:12569–12574.

Starker S (1978) Dreams and Waking Fantasy. In: The Stream of Consciousness (Pope KS, Singer JL, eds), pp 301–319 Emotions, Personality, and Psychotherapy. Springer US.

Stawarczyk D, Majerus S, Maj M, Van der Linden M, D'Argembeau A (2011a) Mind-wandering: phenomenology and function as assessed with a novel experience sampling method. Acta Psychol (Amst) 136:370–381.

Stawarczyk D, Majerus S, Maquet P, D'Argembeau A (2011b) Neural Correlates of Ongoing Conscious Experience: Both Task-Unrelatedness and Stimulus-Independence Are Related to Default Network Activity. PLoS ONE 6:e16997.

Stevenson H, Russell PN, Helton WS (2011) Search asymmetry, sustained attention, and response inhibition. Brain Cogn 77:215–222.

Strange JR (1978) A Search for the Sources of the Stream of Consciousness. In: The Stream of Consciousness: Scientific Investigation Into the Flow of Experience (Pope KS, Singer JL, eds). Plenum.

Sun R, Merrill E, Peterson T (2001) From implicit skills to explicit knowledge: a bottom-up model of skill learning. Cogn Sci 25:203–244.

Swanson JM, Posner M, Potkin S, Bonforte S, Youpa D, Fiore C, Cantwell D, Crinella F (1991) Activating tasks for the study of visual-spatial attention in ADHD children: a cognitive anatomic approach. J Child Neurol 6 Suppl:S119–S127.

Szpunar KK, Khan NY, Schacter DL (2013) Interpolated memory tests reduce mind wandering and improve learning of online lectures. Proc Natl Acad Sci U S A 110:6313–6317.

Tang Y-Y, Ma Y, Fan Y, Feng H, Wang J, Feng S, Lu Q, Hu B, Lin Y, Li J, Zhang Y, Wang Y, Zhou L, Fan M (2009) Central and autonomic nervous system interaction is altered by short-term meditation. Proc Natl Acad Sci 106:8865–8870.

Tang Y-Y, Rothbart MK, Posner MI (2012) Neural correlates of establishing, maintaining, and switching brain states. Trends Cogn Sci 16:330–337.

Taylor E (1978) Asian Interpretations: Transcending the Stream of Consciousness. In: The Stream of Consciousness (Pope KS, Singer JL, eds), pp 31–54 Emotions, Personality, and Psychotherapy. Springer US.

Teasdale JD, Dritschel BH, Taylor MJ, Proctor L, Lloyd CA, Nimmo-Smith I, Baddeley AD (1995) Stimulus-independent thought depends on central executive resources. Mem Cognit 23:551–559.

Terhune DB, Croucher M, Marcusson-Clavertz D, Macdonald JSP (2014) Time Contracts when the Mind Wanders. Procedia - Soc Behav Sci 126:125–126.

Testu F (1994) Quelques constantes dans les fluctuations journalières et hebdomadaires de l'activité intellectuelle des élèves en Europe. Enfance 47:389–400.

Thomson DR, Seli P, Besner D, Smilek D (2014) On the link between mind wandering and task performance over time. Conscious Cogn 27:14–26.

Tong F, Nakayama K, Vaughan JT, Kanwisher N (1998) Binocular Rivalry and Visual Awareness in Human Extrastriate Cortex. Neuron 21:753–759.

Trapnell PD, Campbell JD (1999) Private self-consciousness and the five-factor model of personality: distinguishing rumination from reflection. J Pers Soc Psychol 76:284–304.

Tremblay S, Nicholls AP, Alford D, Jones DM (2000) The irrelevant sound effect: Does speech play a special role? J Exp Psychol Learn Mem Cogn 26:1750–1754.

Tullett AM, Inzlicht M (2010) The voice of self-control: blocking the inner voice increases impulsive responding. Acta Psychol (Amst) 135:252–256.

Uddin LQ, Kelly AMC, Biswal BB, Margulies DS, Shehzad Z, Shaw D, Ghaffari M, Rotrosen J, Adler LA, Castellanos FX, Milham MP (2008) Network homogeneity reveals decreased integrity of default-mode network in ADHD. J Neurosci Methods 169:249–254.

Uzzaman S, Joordens S (2011) The eyes know what you are thinking: Eye movements as an objective measure of mind wandering. Conscious Cogn 20:1882–1886.

Vandekerckhove J, Tuerlinckx F, Lee MD (2008) A Bayesian approach to diffusion process models of decision-making. Proc 30th Annu Conf Cogn Sci Soc:1429–1434.

Van De Ville D, Jhooti P, Haas T, Kopel R, Lovblad K-O, Scheffler K, Haller S (2012) Recovery of the default mode network after demanding neurofeedback training occurs in spatio-temporally segregated subnetworks. NeuroImage 63:1775–1781.

Van Gaal S, Ridderinkhof KR, Scholte HS, Lamme VAF (2010) Unconscious Activation of the Prefrontal No-Go Network. J Neurosci 30:4143–4150.

Vanhaudenhuyse A, Demertzi A, Schabus M, Noirhomme Q, Bredart S, Boly M, Phillips C, Soddu A, Luxen A, Moonen G, Laureys S (2011) Two distinct neuronal networks mediate the awareness of environment and of self. J Cogn Neurosci 23:570–578.

Vanhaudenhuyse A, Noirhomme Q, Tshibanda LJ-F, Bruno M-A, Boveroux P, Schnakers C, Soddu A, Perlbarg V, Ledoux D, Brichant J-F, Moonen G, Maquet P, Greicius MD, Laureys S, Boly M (2010)

Default network connectivity reflects the level of consciousness in non-communicative brain-damaged patients. Brain 133:161–171.

Van Mourik R, Oosterlaan J, Heslenfeld DJ, Konig CE, Sergeant JA (2007) When distraction is not distracting: a behavioral and ERP study on distraction in ADHD. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 118:1855–1865.

Van Vugt M, Taatgen N, Sackur J, Bastian M (2015) Modeling mind-wandering: a tool to better understand distraction. Proc Int Conf Cogn Model 2015.

Vera L (1996) Echelle comportementale d'anxiété phobique (ECAP) : Construction, validation et intérêt en clinique enfant-adolescent. Neuropsychiatr Enfance Adolesc 44:429–438.

Vygotski L (1933) Pensée & Langage. La Dispute.

Ward AF, Wegner DM (2013) Mind-blanking: when the mind goes away. Front Psychol 4.

Watson JB (1913) Psychology as the behaviorist views it. Psychol Rev 20:158–177.

Wechsler D (2004) The Wechsler intelligence scale for children—fourth edition.

Weiss Y, Simoncelli EP, Adelson EH (2002) Motion illusions as optimal percepts. Nat Neurosci 5:598–604.

Westby CE, Cutler SK (1994) Language and ADHD: Understanding the bases and treatment of self-regulatory deficits. Top Lang Disord 14:58–76.

Whitmarsh S, Barendregt H, Schoffelen J-M, Jensen O (2014) Metacognitive awareness of covert somatosensory attention corresponds to contralateral alpha power. NeuroImage 85 Pt 2:803–809.

Willcutt EG (2012) The Prevalence of DSM-IV Attention-Deficit/Hyperactivity Disorder: A Meta-Analytic Review. Neurotherapeutics 9:490–499.

Winkielman P, Schooler JW (2011) Splitting consciousness: Unconscious, conscious, and metaconscious processes in social cognition. Eur Rev Soc Psychol 22:1–35.

Wittmann M (2013) The inner sense of time: how the brain creates a representation of duration. Nat Rev Neurosci 14:217–223.

Wyart V, Nobre AC, Summerfield C (2012) Dissociable prior influences of signal probability and relevance on visual contrast sensitivity. Proc Natl Acad Sci 109:3593–3598.

Yang Y-H, Yeh S-L (2011) Accessing the meaning of invisible words. Conscious Cogn 20:223–233.

Yeo BTT, Krienen FM, Sepulcre J, Sabuncu MR, Lashkari D, Hollinshead M, Roffman JL, Smoller JW, Zöllei L, Polimeni JR, Fischl B, Liu H, Buckner RL (2011) The organization of the human cerebral cortex estimated by intrinsic functional connectivity. J Neurophysiol 106:1125–1165.

Zhang Y, Song X, Ye Q, Wang Q (2015) Children with positive attitudes towards mind-wandering provide invalid subjective reports of mind-wandering during an experimental task. Conscious Cogn 35:136–142.