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Serge Caparos

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Serge Caparos. Load and the spatial profile of visual selective attention. Psychology. University of London, 2010. English. NNT: . tel-00518229

**HAL Id: tel-00518229**

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*PhD Thesis*

**LOAD AND THE SPATIAL  
PROFILE OF VISUAL  
SELECTIVE ATTENTION**

**Serge Caparos**

**Goldsmiths College, University of London**

*I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning.*

***Date***

***Name***

***Signed***

## ABSTRACT

Selective attention has been hypothesised to operate at a perceptual level by focusing perceptual resources on the attended location (Lavie, 1995). This thesis examined (1) the shape of the *profile* of perceptual resources in space and (2) the effect of several factors on the *focus* of this profile.

The spatial profile of perceptual resources was indexed using different measures, namely, a range of measures of distractor interference in the flanker task (Eriksen & Hoffmann, 1972) and performance at detecting a probe in the cue/probe task (Posner, 1980). In all cases, the profile was found to describe a Mexican-hat pattern and this was true whether attention was directed at fixation or to the periphery. The effects of a number of factors on the focus of the Mexican-hat profile, namely, on the efficiency of the perceptual level of selective attention, were investigated. While increasing both perceptual load (i.e., the perceptual difficulty of extracting information) and trait anxiety caused the profile to *focus*, increasing cognitive load (i.e., the difficulty of a mental task performed in parallel to the selective-attention task) caused it to *defocus*.

These results have two important implications. First, variations in stimulus and task properties (e.g., load) or in individual characteristics (e.g., anxiety) across studies may explain why some studies have reported gradient rather than Mexican-hat patterns; in some studies, perceptual resources may have been defocused, causing the Mexican-hat profile to look like a gradient. Second, contrary to the load theory (Lavie, Hirst, de Fockert, & Viding, 2004), the focus of perceptual resources is controlled not only at

perceptual but also at cognitive levels. Cognitive load may therefore change what we *see*, whether it be an individuated object or the global properties of a scene.

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# ACKNOWLEDGEMENTS

First of all, I would like to express my very deep and sincere gratitude to my supervisor, Karina Linnell, who, in the first place, offered me the opportunity to work with her, who encouraged me and closely supervised me throughout the process of the PhD, who helped me to develop my critical thinking, who spent many hours discussing theories and data with me, who tirelessly taught me how to write in English, and who helped me in so many other ways that it would be incredibly long to enumerate them all. A warm thank you Karina!

I also need to thank Anne Giersch, without whom I would never have had the desire to engage into a PhD. She inspired me into doing research, she was a wonderful supervisor during my Master's degree and I hope to collaborate again with her in the future.

It would not have been possible to go through the difficult times inherent to the PhD experience without the support of Paul. He has helped me so much, especially in the weeks preceding submission, he has participated in my experiments countless times without complaining, encouraged me and believed in me. Thank you so much Paul, this PhD is dedicated to you! I also want to thank my parents, Nadoue and Silvere, my brothers, Matthieu and Thomas, my sisters in law, Aurore and Maite, and all the other members of my family. They have always been there to support me and, when I needed to pilot new experiments, they have always pretended to be eager to participate! At all times, their support was invaluable. As a whole, I need to thank all the participants who have given so much time for this research. Some of them (notably my good friends Thomas and Aurélie) have participated several times, thank you so much!

I would like to thank the Psychology Department of Goldsmiths, which has funded my bursary for three years, and all the staff who has helped me throughout the past four years. A special thanks to those who work (or have worked) in the office, namely, Val West, Sue Weston, Denise Barry, Ify Olabinjo, Margaret Ivin, Jenny Nansera. They are always there to help and are so efficient! Also, many thanks to Maurice Douglas, who has been of incredible help, and thanks to all the other technicians who are so competent and have always been there when I needed their help, namely, Rob Davis, Ian Hannent, Liz Elliott, Steven Yesson and Richard Billingham.

I want to thank everyone, at Goldsmiths and elsewhere, with whom I have had stimulating theoretical discussions or who have commented on my work and helped me to improve it, namely, Glyn Humphreys, Herman Müller, Alan Pickering, José van Velzen, Kyle Cave, Artem Belopolsky, Marisa Carrasco, Jules Davidoff, Andrew Cooper, Andrew Bremner, Pam Heaton, Tim Valentine, anonymous reviewers and others.

I must not forget to thank Kerry Kershaw and Helen Brinson, who have been fabulous office mates, collaborators, and friends. There are many other postgrads or postdocs whom it has been a pleasure to meet and spend time with, and who have helped me to go through the PhD, notably, Sharon Howard, Rob Slonje, Elisabeth Fonteneau, Lubna Ahmed, Steven Stagg, Nicky Malone, Angela Gosling, Saskia Sabelus, Rhiannon Jones, Gilly Nash, Helena Ribeiro, Jane Aspell, Saeideh, Ros Watling, Zara Bergstrom, Alex Marchant, Luke Mason, Ian Tharp, Mike Griffiths, Krissy Wilson and probably many others that I am forgetting. Beyond the limits of Goldsmiths, I have met many



wonderful people since coming to the UK for my PhD, who have become great friends and have helped me to release the pressure, notably, Hadleigh, Ian, Dean, Rafik, Jon, Ben, Mike, but also many others! A warm thank, as well, to my dear friend Sofie, who has provided me with a second home in Paris whenever I have felt a sudden need to cross the channel and to my other friends in Paris, notably Cécile, Mathieu, Etienne, Eric, Nicolas.

At last, but not least, I must thank the cleaners, whom unfortunately I have never met, but who have not once forgotten to empty my bin and tidy my office! I must also thank the porters for their patience during all these nights when Karina and I were the last people to leave the building and they were patiently waiting to close it behind us.

# CHAPTER 1 – GENERAL INTRODUCTION

To ensure efficient functioning, the brain must focus on goal-relevant information and exclude distracting information. In order to achieve this, the brain makes use of selective attention. This function has been the focus of much research in the field of cognitive psychology and is the subject of the present thesis. The experiments presented in this thesis addressed several questions that remain unresolved or controversial in the literature to date, namely, (1) what is the shape of the *profile* of selective attention around the attended location, (2) what are the *indices* that are best suited to study the shape of this profile, and (3) do perceptual load, cognitive load and a number of other factors affect the extent of *focus* of this profile?

In the present chapter, we summarize the literature that exists on these questions. We discuss some limitations of most previous studies that have addressed the effect of perceptual load, cognitive load and other factors on the focus of perceptual resources. These studies have examined only fixed separations from the attended location and have therefore not examined the profile of perceptual resources (available only by probing a range of separations). In the absence of a full profile, a change in focus can only be implied but not concluded (see Section 1.2 below). This is especially true given the controversy about the shape of the profile of perceptual resources; unless the shape of the profile is agreed upon, one cannot measure a change in the focus of perceptual resources. Some studies suggest that the profile describes a *gradient* pattern when others suggest that it describes a *Mexican-hat* pattern (see Section 1.3 below). Previous studies that have shown gradient or Mexican-hat profiles have used a variety of indices,

among which three have been most commonly used. These three indices are (1) performance at responding to a probe occurring at an uncued location, in the cue/probe paradigm (Posner, 1980; see Section 1.4 below), (2) response-related interference, namely, the interference generated by distractors drawn from the same set of letters as the target, in the flanker paradigm (Eriksen & Hoffmann, 1972; see Section 1.5 below), and (3) salience-related interference, namely, the interference generated by salient distractors, in the flanker paradigm (see Section 1.5 below). We examine whether or not these indices can be used interchangeably to measure the profile of perceptual resources.

In Chapters 2 to 5, we present the results of 12 new experiments that tested the above questions. Finally, in Chapter 6, we discuss the implications of the results of these experiments. This thesis will address only the *visual* modality of selective attention. While some of its conclusions may apply to other perceptual modalities, this possibility will not be discussed.

## **1.1 Selective attention**

Selective attention is the umbrella term given to the mechanisms thought to be involved in the exclusion of distracting information. It has been envisaged as a two-level process involving two independent mechanisms (e.g., Lavie, Hirst, de Fockert, & Viding, 2004; Pashler, 1999). According to this view, visual attention to a target location first involves a *perceptual* level of selection that blocks distractors from being perceptually processed. This level of selection is inherently spatial in nature; it is thought to involve a pool of perceptual resources that can be focused on a target location and removed from neighbouring distractor locations (e.g., Eriksen & St James, 1986; LaBerge, 1983;

Yantis & Johnston, 1990). Due to its spatial nature, this level of selection is often referred to as *spatial attention*. The second level of selection in the two-level process occurs *post-perceptually*. It allows distractor stimuli that have been perceptually processed (because they have not been efficiently blocked at the perceptual level) to be blocked from reaching the higher levels of processing that support awareness and response selection. This level of selection takes place at a post-perceptual level and is by definition independent of stimulus location; it is thought to rely on mechanisms that set and rehearse task priorities and that require the availability of working-memory resources (de Fockert, Rees, Frith, Lavie, 2001; Lavie et al., 2004; Lavie & de Fockert, 2005; 2006; Lavie & Fox, 2000).

The work presented in this thesis mainly focuses on the *perceptual level* of selective attention. It capitalizes on its spatial nature to isolate it from the (non-spatial) post-perceptual level of selective attention (note that the latter level of selection will nevertheless be addressed in Chapters 4 and 5). In Section 1.2 below, we summarize the dominant model of spatial attention.

## **1.2 The focus of perceptual resources**

Selective-attention theorists have classically referred to spatial attention, namely, the perceptual level of selective attention, by appealing to a *spotlight* metaphor (Posner, 1980). The stimuli present in the area receiving perceptual resources are perceptually processed, whereas the stimuli present in other areas are not (e.g., Briand & Klein, 1987; Broadbent, 1958; Egly & Homa, 1991; Hazlett & Woldorff, 2004; Remington & Pierce, 1984; Shulman, Remington, & McLean, 1979; Sperling & Weichselgartner, 1995; Tsal, 1983; Treisman, 1977; Treisman, 1988; Treisman & Gelade, 1980).

It has been suggested that the size of the area receiving perceptual resources varies as though controlled by a 'zoom lens' (Eriksen & St. James, 1986; LaBerge, 1983). When the size of this area decreases, perceptual resources are said to be spatially *focused*.

In this thesis, we are particularly interested in the effect of three factors that have previously been claimed either to cause a change in the focus of perceptual resources or not to do so. These factors are (1) the perceptual difficulty at processing a target stimulus (a higher perceptual difficulty, or perceptual load, is widely assumed to focus perceptual resources; e.g., Downing, 1988; Forster & Lavie, 2007; Handy, Kingstone & Mangun, 1996; LaBerge, Brown, Carter, Bash, & Hartley, 1991; Lavie, 1995; Lavie & Tsai, 1994; Lavie et al., 2004; MacDonald & Lavie, 2008; Williams, 1988), (2) the availability or successful deployment of cognitive resources (it has been concluded that *neither* the availability *nor* the deployment of cognitive resources affects the focus of perceptual resources; Forster & Lavie, 2007; Lavie et al., 2004), and, finally, (3) individual differences in trait anxiety (anxiety has been suggested *both* to focus *and* to defocus perceptual resources; Braunstein-Bercovitz, 2003; Dusek et al., 1975, 1976; Easterbrook, 1959; Janelle, Singer, & Williams, 1999; Shapiro & Johnson, 1987; Shapiro & Lim, 1989; Solso, Johnson, & Schatz, 1968; Weltman, Smith & Egstrom, 1971; Williams, Tonymon, & Anderson, 1990, 1991).

Remarkably, the evidence that exists on the effects of the above three factors on the focus of perceptual resources remains scarce despite the many studies on these effects. Classically, a given factor has been suggested to focus perceptual resources when it was found to cause (1) a decrease in the interference generated by a distractor stimulus

occurring away from the attended location (in the flanker paradigm; e.g., Braunstein-Bercovitz, 2003; Forster & Lavie, 2007; Kramer et al., 1994; LaBerge et al., 1991; Lavie, 1995; Lavie & Tsal, 1994; Lavie et al., 2004; MacDonald & Lavie, 2008; Martin & Jones, 1983; Scerif et al., 2006; Tipper & Baylis, 1987; see Section 1.5 below) *or* (2) a decrease in performance at responding to a probe stimulus occurring away from the attended location (in the cue/probe paradigm; e.g., Dusek et al., 1975, 1976; Downing, 1988; Easterbrook, 1959; Handy et al., 1996; Janelle et al., 1999; MacDonald & Lavie, 2008; Shapiro & Johnson, 1987; Shapiro & Lim, 1989; Solso, Johnson, & Schatz, 1968; Weltman et al., 1971; Williams, 1988; Williams et al., 1990, 1991; see Section 1.4 below).

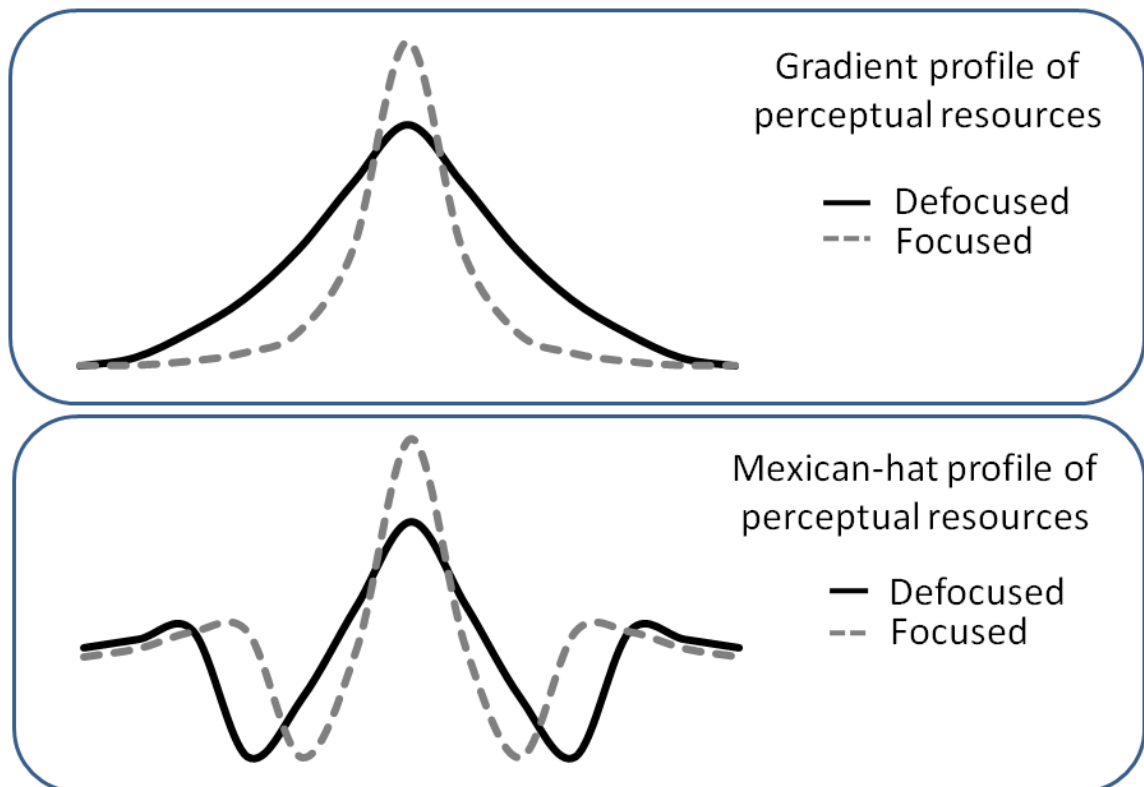
Neither of these two findings, however, provides firm evidence of a change in the focus of perceptual resources. Indeed, the first finding (a change in distractor interference) may reflect a change in the efficiency of *post-perceptual-selection* mechanisms (see Section 1.2 above) rather than a change in the focus of perceptual resources. Even where post-perceptual-selection mechanisms can be excluded, both the first and second findings would *only* unambiguously indicate a focusing of perceptual resources if the profile of perceptual resources (namely, the distribution of perceptual resources around the attended location) described a gradient pattern but *not* if it described a Mexican-hat pattern. The distinction between gradient and Mexican-hat profiles is discussed next.

### **1.3 The profile of perceptual resources**

Up until recently, it has been widely held that the profile of perceptual resources describes a simple gradient, with perceptual resources decreasing steadily with increasing separation from the attended location (e.g., Cave & Bichot, 1999; Cohen &

Shoup, 1997; Connor, Preddie, Gallant, & Van Essen, 1997; Eimer, 1997; Eriksen & St. James, 1986; Handy et al., 1996; Henderson & Macquistan, 1993; Hommel, 2003; Kramer & Jacobson, 1991; LaBerge & Brown, 1989; Matchock & Mordkoff, 2007; Mattler, 2006; Miller, 1991; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Paquet, 2001; Pratt & Quilty, 2002; Rizzolatti, Riggio, Dascola, & Umiltà, 1987; Scharlau & Horstmann, 2006; Shepherd & Müller, 1989; Shulman, Wilson, & Sheehy, 1985; Starreveld, Theeuwes, & Mortier, 2004; Yantis & Johnston, 1990; see Figure 1). However, recent studies have suggested that the profile is more complex and best modelled by a Mexican-hat function, in which perceptual resources do indeed first decrease but then *increase*, before tailing off, with increasing separation (Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Downing, 1988; Hodgson, Müller, & O'Leary, 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Mounts 2000b; Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005; see Figure 1). The bottom of the Mexican hat (where perceptual resources stop decreasing and start increasing) represents the area of best exclusion and the stimuli occurring in this area are most efficiently ignored.

## GRADIENT VS. MEXICAN-HAT PROFILE OF PERCEPTUAL RESOURCES



**Figure 1**

*Schematic representation of a focused and defocused gradient profile of perceptual resources (top) and of a focused and defocused Mexican-hat profile of perceptual resources (bottom).*

The question of the pattern described by the profile of perceptual resources is important given that changes in the spatial focus of perceptual resources can only be properly indexed when the profile is well defined. According to the gradient model, the focusing of the profile of perceptual resources always causes perceptual resources to *decrease* except at the attended location and neighbouring locations (see Figure 1). On the other hand, according to the Mexican-hat model, the focusing of the profile causes perceptual resources to *decrease* at some separations from the attended location but it also causes them to *increase* at large separations (and not only at the attended location and



neighbouring locations; see Figure 1). As a result, if the profile of perceptual resources really describes a Mexican-hat pattern, findings of a decrease in distractor interference or in performance at responding to a probe (see Section 1.2) may indicate *either* a focusing *or* a defocusing of perceptual resources depending on the position at which the distractor, or the probe, occurred on the Mexican hat.

In sum, findings of a decrease in distractor interference, or in performance at responding to a probe, cannot be interpreted when only one distractor or probe location is sampled. The only way to ascertain that a given factor really causes a focusing (or defocusing) of perceptual resources is to measure the effect of this factor on the profile of perceptual resources. In other words, it is necessary to sample more than one separation from the attended location. To our knowledge, of all the studies which have tested the effect of perceptual load, the availability and deployment of cognitive resources, and trait anxiety (see Section 1.2), only four of them have examined the profile of perceptual resources and then only to measure the effect of perceptual load (Downing, 1988; Handy et al., 1996; Müller et al., 2005; Williams, 1988). These four studies generated contradictory findings, as only two of them showed a Mexican hat profile (Downing, 1988; Müller et al 2005), and one of them (Müller et al., 2005) did not replicate the finding of the other (Downing, 1988) that perceptual load focuses perceptual resources.

In the present thesis, we tested the effect of perceptual load, availability and deployment of cognitive resources, and trait anxiety on the profile of perceptual resources. Before testing these factors, we tested the possibility that the profile of perceptual resources describes a Mexican-hat pattern using Müller et al.'s (2005)

flanker paradigm and we attempted to bring the paradigm in question closer to other flanker paradigms which have revealed gradient profiles (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Pan and Eriksen, 1993; Yantis & Johnston, 1990; see Chapter 2). Moreover, we examined whether the same separation function is derived using different indices extracted in the flanker paradigm (McCarley & Mounts, 2008) and the cue/probe paradigm (e.g., Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Downing, 1988; Hodgson, Müller, & O'Leary, 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Mounts 2000b) with a view to deciding on the best index (or indices; see Chapter 3). Cue/probe and flanker paradigms are described below, in Sections 1.4 and 1.5 respectively.

## **1.4 The cue/probe paradigm**

### **1.4.1 Description of the paradigm**

The cue/probe paradigm has been commonly used to study selective attention (e.g., Briand & Klein, 1987; Berger, Dori, & Henik, 1999; Egly & Homa, 1991; Funes, Lupiañez, & Milliken, 2007; Haimson & Behrmann, 2001; Hazlett & Woldorff, 2004; Henderson & Macquistan, 1993; Jonides, 1983; Müller & Rabbit, 1989; Müller, Teder-Saelejaervi, & Hillyard, 1998; Murphy & Eriksen, 1987; Posner, 1980; Posner, Snyder, & Davidson, 1980; Prinzmetal, McCool, & Park, 2005; Remington & Pierce, 1984; Sheperd & Müller, 1989; Sperling & Weichselgartner, 1995; Tsal, 1983). In this paradigm, participants are asked to detect, or identify,<sup>1</sup> a *probe* that can occur at one of

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<sup>1</sup> In the cue/probe paradigm, the task requires participants either to decide whether a stimulus is present or absent (detection task) or what the identity of a stimulus is

several possible locations, the probe location, in the visual scene. Either before or simultaneously with the presentation of the probe, a *cue* is displayed to signal a spatial location (the cued location) and to orient to, and focus perceptual resources on, this location (thus making it the *attended location*). Cueing is said to be endogenous when it involves either an informative symbol or prior instructions that engage top-down mechanisms to orient perceptual resources to the cued location; it is said to be exogenous when it involves the presentation of a singleton stimulus at (or next to) the probe location that engages bottom-up mechanisms to orient perceptual resources to the cued location.<sup>2</sup> Critically, only in some trials does the probe location correspond to the cued location (i.e., the attended location). These trials are said to be *valid*. In other trials, when the probe occurs away from the attended location, the probe location corresponds to an uncued location. These trials are said to be *invalid*. It is typically found that performance at responding to the probe is better on valid than on invalid trials and it is concluded that the probe receives more perceptual resources on valid than on invalid trials. It is argued that the stronger the cueing effect is, the more efficient the cue is at orienting perceptual resources to, and/or focusing perceptual resources on, the cued location (e.g., Funes et al., 2007; Jonides, 1981; Juola, Koshino, & Warner, 1995; Shepherd & Müller, 1989).

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(identification task). In the following parts of Section 4, we will refer to participants' performance at *responding* to a probe, which can equally well refer to participants' performance at detecting or identifying a probe.

<sup>2</sup> Note that a particular stimulus can operate both as an endogenous and exogenous cue, namely, when a singleton stimulus is predictive of the location of the probe.

### 1.4.2 Measuring the profile of perceptual resources

Using the cue/probe paradigm, the profile of perceptual resources around the cued location can be extracted by looking at *invalid* trials (e.g., Handy et al., 1996; Henderson, 1991; Henderson & Macquistan, 1993). Participants' performance on these trials is measured as a function of the separation between the cued (attended) location and the probe location. Performance at responding to the probe at a given separation is assumed to reflect how many perceptual resources are present at this separation (e.g., Handy et al., 1996; Henderson, 1991; Henderson & Macquistan, 1993). Thus, *performance at responding to the probe as a function of separation* is used to index the spatial profile of perceptual resources around the cued location. Note that, in most studies, the cued and probe locations occur in the *periphery*, at a fixed eccentricity (e.g., Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Handy et al., 1996; Henderson & Macquistan, 1993; Hodgson et al., 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Mounts 2000b), to make sure that the effect of the separation between cued and probe locations really reflects the profile of perceptual resources rather than only an effect of cortical magnification (Anstis, 1998; Rovamo & Virsu, 1979; Virsu & Rovamo, 1979).

If performance at responding to the probe is found simply to decrease with increasing separation between the probe and the cued location, this would suggest that the profile of perceptual resources around the cued location describes a *gradient*. On the other hand, if performance at responding to the probe is found first to decrease and then to increase, before then tailing off, with increasing separation between the probe and the cued location, this would suggest that the profile of perceptual resources around the cued location describes a *Mexican hat*.

### **1.4.3 Limitation of the cue/probe paradigm**

The cue/probe paradigm might not be the best tool to index the profile of perceptual resources (Müller et al., 2005). This is mainly because, in this paradigm, the profile of perceptual resources is indexed using *invalid* trials, namely, those trials in which the probe (i.e., the stimulus that is central to the task) does *not* occur at the attended location. It is possible that, on those invalid trials, perceptual resources are *redistributed* from the cued to the probe location. The cue/probe paradigm would index mechanisms underlying this redistribution of resources rather than, or in addition to, the actual profile of perceptual resources around the cued location. Namely, performance at responding to the probe could index the strength of the redistribution of perceptual resources to the probe location (Müller et al., 2005). If this is true, it means that the effects on performance of cue-probe separation that are typically observed in the cue/probe paradigm (e.g., Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Handy et al., 1996; Henderson & Macquistan, 1993; Hodgson et al., 1999; Kristjansson & Nakayama, 2002; Mounts 2000b; Pan & Eriksen, 1993; see Section 1.4.2 above) index variations in the strength of the redistribution of resources due to separation rather than just the profile of perceptual resources.

This hypothesis was tested in Chapter 3 by directly comparing the performance function of separation measured using the cue/probe paradigm with that measured using the flanker paradigm which is thought not to be affected by the above limitation (Mueller et al., 2005; see below). Provided that the flanker paradigm measures the profile of perceptual resources, any qualitative difference observed between the functions of separation obtained with the cue/probe paradigm and the flanker paradigm would

suggest that the cue/probe paradigm does not purely index the profile of perceptual resources.

## **1.5 The flanker paradigm**

### **1.5.1 Description of the paradigm**

The flanker paradigm has also been widely used to study selective attention (e.g., Chastain & Cheal, 1997, 1999; Chen, 2005; Cohen & Shoup, 1997; Eriksen & Hoffman, 1972, 1973; Eriksen & St James, 1986; Eriksen & St. James, 1986; Facoetti, 2001; Flowers, 1990; Hommel, 2003; Jiang & Chun, 2001; Kramer & Jacobson, 1991; Matchock & Mordkoff, 2007; Mattler, 2006; Miller, 1991; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Müller et al., 2005; Paquet, 2001; Pan & Eriksen, 1993; Yantis & Johnston, 1990). In this paradigm, participants are asked to identify a *target* letter (typically through making a two-alternative-forced choice – 2-AFC – response) while ignoring a *distractor* letter that occurs in most (or all) trials. The target always occurs in a 100%-predictable location. In other words, unlike in the cue/probe paradigm, the stimulus that has to be responded to always occurs at the attended location. The distractor occurs at varying separations from the target (i.e., at different separations from the attended location). The distractor is completely irrelevant to the task and is typically not predictive of the response to the target. Despite the irrelevance of the distractor, its presence interferes with performance at identifying the target to the extent that it is allocated perceptual resources (and is therefore perceptually processed). As a result, it is typically argued that the amplitude of the interference is a function of how many perceptual resources are present at the location of the distractor (note

however that, as discussed in Section 1.2, the amplitude of distractor interference also reflects the efficiency of *post-perceptual selection* mechanisms).

In sum, in the cue/probe paradigm, perceptual resources are measured *at the probe location*, by measuring how well participants respond to the probe at a given separation from the attended location, whereas, in the flanker paradigm, perceptual resources are measured *at the distractor location*, by measuring how participants' performance is affected by the irrelevant distractor when it occurs at a given separation from the attended/target location.

### **1.5.2 Measuring the profile of perceptual resources**

In the flanker paradigm, the profile of perceptual resources around the target location can be extracted by looking at the interference of the distractor (which indexes perceptual resources at the location of the distractor) as a function of the target-distractor separation (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Müller et al., 2005; Pan & Eriksen, 1993; Yantis & Johnston, 1990). Thus, distractor interference as a function of separation is used to index the spatial profile of perceptual resources. Note that, in many flanker studies, as in cue/probe studies, the stimuli (target and distractor) are presented in the *periphery*, at a fixed eccentricity (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Müller et al., 2005; Pan & Eriksen, 1993; Yantis & Johnston, 1990), to make sure that the effect of target-distractor separation really reflects the profile of perceptual resources rather than only an effect of cortical magnification (Anstis, 1998; Rovamo & Virsu, 1979; Virsu & Rovamo, 1979).

By the same logic outlined in the previous section on the cue/probe paradigm, if the amplitude of distractor interference is found simply to decrease with increasing separation between the target and the distractor, this suggests that the profile of perceptual resources around the target location is shaped like a gradient (Yantis & Johnston, 1990). Similarly, if the amplitude of the distractor interference is found first to decrease and then to increase, before then tailing off, with increasing separation between the target and the distractor location, this suggests that the profile of perceptual resources around the target location is shaped like a Mexican hat (Müller et al., 2005).

### **1.5.3 Strength of the flanker paradigm**

The flanker task has been suggested not to be subject to the same limitation as the cue/probe paradigm (Müller et al., 2005; see Section 1.4.3 above). Namely, in the flanker task, the stimulus that is central to the task (the target) always occurs at the attended location and, therefore, there is (arguably) no incentive for a redistribution of perceptual resources.

### **1.5.4 Different categories of distractors**

In the flanker paradigm, the distractor can be (1) compatible, when its identity is mapped to the same response as the target, (2) incompatible, when its identity is mapped to the opposite response to the target, or (3) neutral, when its identity is not mapped to any response. To the extent that distractors are processed, it is possible for these three types of distractors to affect performance through one, or both, of two types of interference, namely, *response-related* interference and *salience-related* (singleton-type) interference. The former is assumed to reflect a competition for response selection (e.g., Anderson & Kramer, 1993; Debener, Ullsperger, Siegel, Fiehler, von Cramon, &



Engle, 2005; Eriksen & St. James, 1986; Forster & Lavie, 2007 ; Hommel, 2003; Iani, Ricci, Gherri, Rubichi, 2006; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Kramer & Jacobson, 1991; LaBerge et al., 1991; Lavie, 1995; Lavie & de Fockert, 2003; Lavie et al., 2004; Maruff, Danckert, Camplin, & Currie, 1999; Matchock & Mordkoff, 2007; Mattler, 2006; Müller et al., 2005; Murphy & Eriksen, 1987; Paquet, 2001; Pan & Eriksen, 1993; Yantis & Johnston, 1990) and the latter a competition for perceptual representation in the visual system (e.g., Björk & Murray, 1977; Forster & Lavie, 2008; McCarley et al., 2004, 2007; McCarley & Mounts, 2008; Mounts, 2005; Mounts & Tomaselli, 2005; Mounts & Gavett, 2004; van Veen, Cohen, Botvinick, Stenger and Carter, 2001; Verbruggen, Liefoghe, & Vandierendonck, 2006). It has been suggested that both response-related and salience-related interference can be used to index the allocation of perceptual resources at the location of the distractor (McCarley & Mounts, 2008).

#### *Response-related interference*

Compatible and incompatible (but not neutral) distractors can generate *response-related* interference. This effect relies on the fact that compatible and incompatible distractors are drawn from the same response set as the target. The direction of the response-related interference depends on whether the distractors are response-compatible or response-incompatible. Thus, incompatible distractors have been shown to *increase* latencies and errors for target-identification (e.g., Cohen & Shoup, 1997; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Miller, 1991; Müller et al., 2005; Ro, Cohen, Ivry, & Rafal, 1998; Yantis & Johnston, 1990). In such circumstances, it is generally concluded that incompatible distractors compete with the preparation of the response to the target because their identity is mapped to the opposite response to the

target; it can be concluded that incompatible distractors generate ‘positive’ *response-related interference* (i.e., competition). On the contrary, compatible distractors have sometimes been shown to *decrease* latencies and errors for target identification (e.g., Cohen & Shoup, 1997; Hazeltine, Poldrack, & Gabrieli, 2000; Miller, 1991; Müller et al., 2005; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990). In such circumstances, it is concluded that compatible distractors facilitate the response to the target because their identity is mapped to the same response as the target; it can be concluded that compatible distractors generate ‘negative’ *response-related interference* (i.e., facilitation). Note that neutral distractors cannot generate response-related interference as their identity is not mapped to any response.

Response-related interference has typically been isolated in two ways, either by comparing *compatible*-distractor performance with *incompatible*-distractor performance (e.g., Anderson & Kramer, 1993; Debener et al., 2005; Eriksen & St. James, 1986; Forster & Lavie, 2007; Hommel, 2003; Iani et al., 2006; Kramer & Jacobson, 1991; LaBerge et al., 1991; Lavie et al., 2004; Maruff et al., 1999; Matchock & Mordkoff, 2007; Mattler, 2006; McCarley & Mounts, 2008; Müller et al., 2005; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Paquet, 2001; Yantis & Johnston, 1990) or by comparing *neutral*-distractor performance with *incompatible*-distractor performance (e.g., Kramer, et al., 1994; Lavie, 1995; Lavie & de Fockert, 2003). These comparisons have been proposed to isolate *response-related* interference and to exclude *saliency-related* interference (see below). The first comparison (namely, incompatible- versus compatible-distractor performance) is proposed to isolate the *combination* of ‘negative’ and ‘positive’ response-related interference generated by, respectively, compatible and incompatible distractors. We refer to this first index as *combined response-related*

*interference*. The second comparison (namely, incompatible- versus neutral-distractor performance) is proposed to isolate the ‘positive’ response-related interference generated by incompatible distractors. We refer to this second index as *incompatible-distractor response-related interference*.

Both indices of response-related interference can be used to measure the allocation of perceptual resources at the location of the distractor and, therefore, can be used to reveal the spatial profile of perceptual resources. In this thesis, we used *both* these indices to measure the profile of perceptual resources (*combined response-related interference* was used in Experiments 1 to 6, Chapters 2 and 3, and *incompatible-distractor response-related interference* was used in Experiments 4, 5, 10 and 11, Chapters 3 and 4). The profiles extracted using the two types of measures were compared (see Experiments 4 and 5 in Chapter 3). A concern was to test whether the shapes and the foci of the two profiles agreed (see Chapter 3).

This concern emerges from the fact that one of the two measures, namely, the one obtained by comparing neutral-distractor performance with incompatible-distractor performance, may contain residual salience-related interference as, in certain circumstances, incompatible (and compatible) distractors can be predicted to be more salient than neutral distractors due to differences in their task-relatedness (Björk & Murray, 1977).<sup>3</sup> The possibility that salience-related interference differs between neutral and incompatible distractors can arguably be ignored when *stimulus*-driven salience is high given that *task*-driven differences in salience should then be

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<sup>3</sup> This form of saliency has been labelled ‘contingent’ to emphasize its dependence on the underlying task set (Corbetta & Shulman, 2002; Folk, Remington, & Johnston, 1992).

substantially reduced (this was supported by comparing the RTs generated by compatible and neutral distractors in Experiments 4 and 5, Chapter 3, where, respectively, stimulus-driven salience was low and high).

### *Saliency-related interference*

In any case, the presence of residual saliency-related interference in the index obtained by comparing neutral-distractor with incompatible-distractor performance is not problematical if saliency-related interference *also* measures the allocation of perceptual resources at the location of the distractor (as suggested by the results of some studies; Björk & Murray, 1977; Forster & Lavie, 2008; Lavie & de Fockert, 2005, 2006; McCarley et al., 2007; Mounts, 2000a, 2005; Mounts & Gavett, 2004; Mounts & Tomaselli, 2005). We tested whether the shape and the focus of the profile measured using saliency-related interference agreed with those measured using response-related interference. Experiment 5 (see Chapter 3) showed this to be the case and Experiments 8, 10, 11 and 12 (see Chapters 4 and 5) built upon this finding and used *saliency-related interference* to index the profile of perceptual resources.

*Saliency-related interference* was measured using neutral distractors by comparing target-identification performance in the presence and absence of a neutral distractor (Björk & Murray, 1977; Forster & Lavie, 2008; Lavie & de Fockert, 2005, 2006; McCarley et al., 2007; Mounts, 2000a, 2005; Mounts & Gavett, 2004; Mounts & Tomaselli, 2005).<sup>4</sup> Note that, unlike response-related interference, saliency-related interference can only operate in one direction (namely, to increase RTs and errors).

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<sup>4</sup> Response-compatible distractors also create saliency-related interference (Björk & Murray, 1977; Flowers, 1990; Grice, Borough, & Canham, 1984; Grice & Gwynne,

### *Total interference*

In four experiments (namely, in Experiments 6, 9, 10 and 11, Chapters 3 and 4), a measure that *combined* salience-related and response-related interference was also used. This measure was obtained by comparing no-distractor with incompatible-distractor performance and was therefore referred to as incompatible-distractor *total* interference. If both salience-related interference and response-related interference index the allocation of perceptual resources (as suggested in the literature and confirmed in Experiments 4 and 5, Chapter 3), incompatible-distractor *total* interference is a more sensitive index of the allocation of perceptual resources than either salience-related or response-related interference alone.

## **1.6 Plan of thesis**

In summary, the present thesis addressed the following issues. First, in Chapter 2, it was tested whether the profile of perceptual resources describes a gradient or a Mexican-hat pattern, as measured using *combined response-related interference* in the flanker paradigm. Second, in Chapter 3, three types of measures other than *combined response-related interference* that have been used to index the profile of perceptual resources were tested, two from the flanker paradigm and one from the also widely used cue/probe paradigm. These measures are *incompatible-distractor response-related interference* (in the flanker task), *salience-related interference* (in the flanker task), and *performance at responding to a probe* (in the cue/probe task). Third, in Chapter 4, the

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1985; Lavie, 1995; Madden & Langley, 2003; McCarley & Mounts, 2008; Miller, 1991; Yeh & Eriksen, 1984). However, compatible distractors cannot be used to measure this interference as their effect is a combination of ‘positive’ salience-related interference and ‘negative’ response-related interference.

effects of perceptual load, working-memory span and cognitive load on the extent of focus of perceptual resources were tested. Fourth, in Chapter 5, the effects of individual differences in trait anxiety and cognitive failure on the extent of focus of perceptual resources were tested. Finally, in Chapter 6, we discussed the implications of the findings presented in Chapters 2 to 5.

# CHAPTER 2 – THE PROFILE OF PERCEPTUAL RESOURCES

## 2.1 Introduction: Gradient or Mexican hat?

This Chapter focuses on mapping the profile of perceptual resources and testing whether it is shaped like a gradient or a Mexican hat (see Chapter 1, Section 1.3). Note that studies have attempted to map this profile using the flanker paradigm (e.g., Eriksen & St. James, 1986) and the cue/probe paradigm (e.g., Posner, 1980) but, because of reservations with regard to the cue/probe paradigm (see Chapter 1; Müller et al., 2005), in this chapter we confine ourselves to the flanker paradigm; we return to the cue/probe paradigm in Chapter 3.

Flanker studies have measured the effect on performance of distractors as a function of the separation between the attended location and the distractor location (see Chapter 1, Section 1.5). It has been widely reported that compatible and incompatible distractors generate *response-related interference* to an extent that decreases with increasing separation from the attended location (e.g., Eriksen & St. James, 1986; Yantis & Johnston, 1990). Such findings have stimulated much work that has generated widespread support for a ‘gradient’ profile of perceptual resources (e.g., Cohen & Shoup, 1997; Eriksen & St. James, 1986; Hommel, 2003; Kramer & Jacobson, 1991; Matchock & Mordkoff, 2007; Mattler, 2006; Miller, 1991; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Paquet, 2001; Pan & Eriksen, 1993; Yantis & Johnston, 1990). A recent study using the flanker task by Müller et al. (2005), however, has

suggested that the profile of perceptual resources is more complex and describes a ‘Mexican-hat’ function. Thus, Müller et al. (2005) showed that distractor interference was higher at 1.3 than 2.5 deg from the attended location, but *lower* at 2.5 than 4.7 deg from the attended location.

It is possible that the profile of perceptual resources is really shaped like a Mexican hat, in which case sampling only *part* of the profile would have made it look like a gradient; it is more difficult to see how a gradient profile could present as a Mexican hat. One reason why previous flanker studies might have mistaken a Mexican hat for a gradient may be that, in these studies, some factors have caused changes in the focus of perceptual resources, causing the bottom of the Mexican hat to occur so close to, or so far from, the attended location as to make it impossible (or very difficult) to index a Mexican-hat profile of perceptual resources. Factors that could have had such an effect are, for instance, perceptual load, the availability (and deployment) of cognitive resources, and trait anxiety (see Chapter 1).

In this chapter, we did *not* address these factors (they were addressed in Chapters 4 and 5). We reasoned that, in order to be in a good position to test the effects of these factors on the focus of perceptual resources, we first needed to know whether the profile describes a gradient or a Mexican-hat pattern. If it *does* describe a Mexican hat, arguably the best place to find such a profile is to use a methodology as close as possible to that used by Müller et al. (2005) as their study is the only flanker study that showed a Mexican hat. In sum, in this chapter, we tested whether the profile of



perceptual resources describes a Mexican hat or a gradient pattern using the methodology closely related to that of Müller et al. (2005).<sup>5</sup>

In addition, we attempted to bring Müller et al.'s (2005) paradigm closer to the flanker paradigms previously used to measure the profile of perceptual resources. This was motivated by the fact that Müller et al.'s (2005) paradigm is different from other flanker paradigms on (at least) three important aspects: (1) it used a considerably higher number of trials; (2) it used a unique target location and sampled only within the right hemifield; and (3) it used a target location that was endogenously defined. These three aspects are developed below.

First, Müller et al.'s (2005) study used a significantly higher number of trials than other flanker studies (that have measured the profile of perceptual resources<sup>6</sup>). Specifically, in Müller et al. (2005), there were 4096 trials as opposed to 'only' 432 in McCarley and

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<sup>5</sup> Using Müller et al.'s (2005) methodology arguably allowed us to control for the effect of perceptual load and of the availability (and deployment) of cognitive resources; if these factors do affect the focus of perceptual resources, they should do so in the same manner in the experiments of this chapter as in Müller et al.'s experiment because we use a closely related methodology.

<sup>6</sup> In many flanker studies, only two separations from the attended location were sampled and it has been argued that the profile of perceptual resources describes a gradient pattern from the finding that distractors interfered more at small than at large separations (e.g., Cohen & Shoup, 1997; Hommel, 2003; Kramer & Jacobson, 1991; Matchock & Mordkoff, 2007; Mattler, 2006; Miller, 1991; Paquet, 2001). However, the shape of the profile of perceptual resources cannot be derived from just two sample points if it is not a gradient. Therefore, only studies that have sampled more than two separations are considered here.

Mounts (2008), 512 in Yantis and Johnston (1990), 990 in Murphy and Eriksen (1987), 936 in Pan and Eriksen (1993) and 2700 in Eriksen and St. James (1986). We tested whether the high number of trials used in Müller et al. (2005) is a critical aspect of their paradigm (see Experiments 1 and 2).

Second, Müller et al. (2005) used a single target location and always sampled within the right hemifield where most other flanker studies (that measured the profile of perceptual resources) used multiple target locations and sampled in both hemifields (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Yantis & Johnston, 1990). This meant that, in Müller et al. (2005), target-distractor separation was confounded with distractor location. Because of this, it is possible that the Mexican-hat finding of Müller et al. resulted from field effects rather than from the profile of perceptual resources. This possibility was tested by testing the effect of target location and hemifield of distractor presentation (see Experiments 2 and 3).

Third, Müller et al. (2005) used a target location that was endogenously defined where most other flanker studies (that measured the profile of perceptual resources) used target locations that were exogenously defined (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Yantis & Johnston, 1990). The use of an endogenously defined target location meant that it was necessary to monitor eye movements. We tested whether using an endogenously defined target location was a critical aspect of Müller et al.'s (2005) paradigm (see Experiment 3).

In the present experiments, the method was closely modelled on that of Müller et al. (2005). The participants had to identify a target letter ('E' or 'F') – by making a two-

alternative forced-choice (2-AFC) response – while ignoring a distractor letter (‘E’ or ‘F’) occurring at *varying separations* from the target location (i.e., from the attended location). Both target and distractor letters occurred in the periphery at the same fixed eccentricity (in order to control for cortical-magnification factors; Anstis, 1998; Rovamo & Virsu, 1979; Virsu & Rovamo, 1979) amongst irrelevant filler letters (‘X’s and ‘O’s). In Experiments 1 and 2, the target location was always the same (and therefore endogenously defined). In Experiment 3, the target location varied from trial to trial and was indicated by a 100%-valid exogenous cue.

In all three experiments, *combined response-related interference* of the distractors (i.e., the combination of response facilitation for compatible distractors and response competition for incompatible distractors) was measured by comparing compatible- with incompatible-distractor performance (see Chapter 1, Section 1.5.4) and the spatial profile of perceptual resources was indexed by measuring this interference as a function of target-distractor separation (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Müller et al., 2005; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990).

## **2.2 EXPERIMENT 1: Replication of Müller et al. (2005) and effect of number of trials**

In Experiment 1, as in Müller et al., the target always occurred at the same (‘North-East’) location and the stimuli (target, distractor and filler letters) were presented at fixed eccentricity (4.0 deg away from fixation) around an imaginary arc of a circle. In this experiment, in addition to measuring the profile of perceptual resources, we tested

the importance of using a high number of trials to sample this profile. In order to do this, we compared the profile of perceptual resources obtained in the first and last 20% of trials of the experiment; we referred to this factor as *experimental practice* since, arguably, the number of trials equates to the degree of practice.

## **2.2.1 Method**

### **2.2.1.1 Design**

The response-compatibility of the distractor (compatible or incompatible) and the target-distractor separation (1.6, 2.9, 4.4 or 5.6 deg) were manipulated at fixed stimulus eccentricity in a repeated-measures design.

### **2.2.1.2 Participants**

10 participants (7 females; all right-handed; mean age 28.6 yr; age range 18 to 55 yr; see Appendix 2), with reported normal or corrected-to-normal vision, participated in the experiment. Six of them were postgraduates and the other four were the experimenter, his supervisor and two relatives. Participation was voluntary and was not remunerated. Participants were all naïve as to the aim of the study apart from two of them (the experimenter and his supervisor).

### **2.2.1.3 Apparatus**

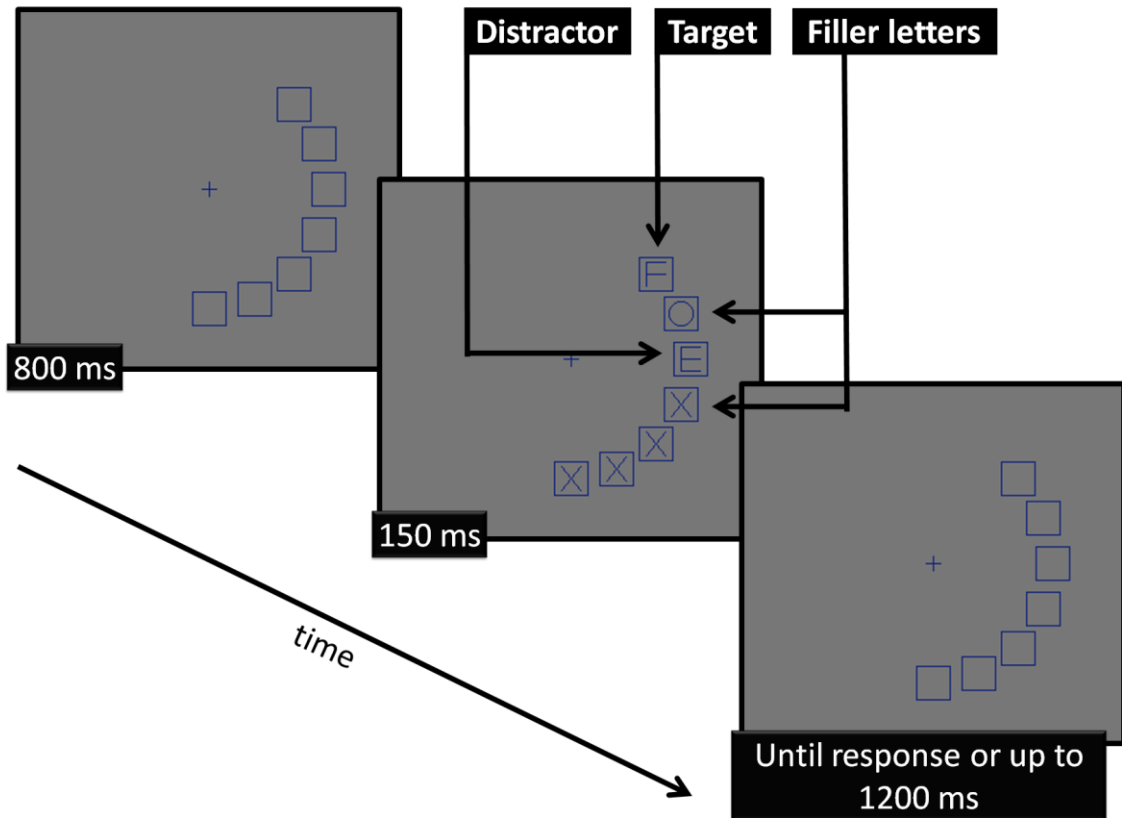
The testing room was sound insulated and dimly lit. Stimuli were presented on a 20-in monitor, operating at a resolution of 800 x 600 pixels with a vertical refresh rate of 100 Hz. A chin rest was used to maintain a viewing distance of 70 cm. The program used to generate the stimuli and run the experiment was Turbo Pascal 7.0.

#### **2.2.1.4 Stimuli and Procedure**

The stimuli are illustrated in Figure 2. Participants were instructed to make a two-alternative forced-choice (2-AFC) identification of a target letter while ignoring a distractor letter and five filler letters, or no distractor and six filler letters. The target was always the letter ‘E’ or ‘F’, the distractor (when present) was always the letter ‘E’ or ‘F’, and the filler letters were always the letters ‘O’ and ‘X’. The stimulus letters (target, distractor and filler letters) were all of the same dark blue (CIE  $x = 0.147$ ,  $y = 0.074$  and  $L = 0.44 \text{ cd/m}^2$ ) and subtended 0.7 by 0.8 deg.

A cross (subtending 0.5 deg square; the fixation cross) and seven outline boxes (subtending 1.1 deg square; the placeholders) were present on the screen throughout the experiment (see Figure 2). They were dark blue (the same dark blue as the stimulus letters) against a light grey background (CIE  $x = 0.289$ ,  $y = 0.320$  and  $L = 3.71 \text{ cd/m}^2$ ). (Note that Müller et al. did not report the precise colour and luminance of the stimuli and background they used.) The fixation cross indicated where participants had to fixate. The seven placeholders were arranged around an arc of an imaginary circle of radius 4.0 deg in the right hemifield and circumscribed the locations of the 7 stimulus letters (target, distractor and filler letters). The centre of each placeholder was separated from that of its neighbours by a distance of 1.6 deg (centre to centre). The box located in the North-East location (45° clockwise from the vertical) defined the top edge of the row of seven placeholders. The six other placeholders were displayed underneath it.

## EXPERIMENT 1: METHOD



**Figure 2**

*Experiment 1 – Method. A schematic representation of an experimental trial. In each trial, a target letter ('E' or 'F') occurred in the top placeholder. Participants signalled target identity (with a two-alternative forced choice; 2-AFC) while ignoring distractor ('E' or 'F') and filler ('X's and 'O's) letters. The distractor could occur at one of four possible target-distractor separations (1.6, 2.9, 4.4 and 5.6 deg, corresponding respectively to the first, second, third and fourth placeholder removed from the target placeholder) and could be compatible with the response to the target (e.g., 'F' if the target was 'F') or incompatible with the response to the target (e.g., 'E' if the target was 'F'). The figure illustrates an 'F' target with a response-incompatible 'E' distractor occurring at a target-distractor separation of 2.9 deg.*

The letter that appeared in the top placeholder was defined as the target to be identified. It was always the letter ‘E’ or ‘F’. Five filler letters (‘X’s and ‘O’s) and one distractor (‘E’ or ‘F’), or six filler letters and no distractor, appeared inside the six placeholders displayed underneath the target placeholder. When a distractor was presented, it was either response-compatible with the target (e.g., the letter ‘E’ if the target was ‘E’) or response-incompatible with the target (e.g., the letter ‘F’ if the target was ‘E’). The distractor always appeared inside a placeholder separated from the target placeholder (centre to centre) by 1.6, 2.9, 4.4 or 5.6 deg (the four levels of target-distractor separation) in a clockwise direction. These separations corresponded to presenting the distractor in the placeholders that were respectively one, two, three, and four placeholders removed from the target placeholder (see Figure 2). Note that these separations are not exactly the same as those used by Müller et al. (namely, 1.3, 2.5, 4.7 and 6.5 deg). We found it hard to replicate the design they reported with placeholders that did not touch each other or letters that remained distinguishable inside the placeholders. We therefore adapted the sizes slightly.

Each trial started with a screen containing the fixation cross and 7 empty placeholders (for 800 ms). This was followed by the presentation of the stimulus letters (target, distractor and filler letters) in their respective placeholders for 150 ms. Participants were asked to respond to the target letter (‘E’ or ‘F’) with a two-alternative forced choice (2-AFC) as *quickly but accurately* as possible while ignoring the distractor letter (the participants had to give an answer within 1000 ms). Half the participants used their left forefinger to answer ‘E’ (with the ‘z’ key of an English keyboard) and their right forefinger to answer ‘F’ (with the ‘m’ key of the keyboard). The other half responded ‘E’ with their right forefinger and ‘F’ with their left forefinger. Feedback was given for

incorrect answers. The next trial started 200 ms after the participants had pressed a response key.

The whole experiment lasted 2.5 hours and was performed in two sessions (over two different days). Each participant run a total of 4160 trials, of which 10% were no-distractor (control) trials. Each of the four target-distractor separations was tested 936 times (with equal proportions of response-incompatible and -compatible distractors). Participants were given short (participant-terminated) breaks every 70 trials (about every two minutes). The experimental conditions (combinations of distractor compatibility and target-distractor separation) were presented in a randomised order in each block.

#### ***2.2.1.5 Fixation control***

In order to monitor the steadiness of the participants' fixation, the participants' gaze was monitored using the Eyelink 2 eyetracker and software (SR Research). Eye movements were calculated for each trial by subtracting the average coordinates of the eyes during the first 400 ms of each trial (with the eyes fixating the fixation cross) and the average coordinates of the eyes during the subsequent 150 ms display of the target. The computer used for experimental testing sent trigger signals to the eyetracker machine in order to define the start of each trial and each phase within a trial.

#### **2.2.2 Results**

We discarded trials with eye movements beyond 1.0 deg from fixation (this meant excluding an average of 7.6% of trials). For the remaining trials, we analysed both the speed and accuracy of forced-choice target-identification ('E' vs. 'F') responses.



Latencies were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented an average of 90.5% of the latencies.

For each participant, mean RTs (and error percentages) were calculated for incompatible-distractor and compatible-distractor (distractor-present) trials at each of the four levels of target-distractor separation (1.6, 2.9, 4.4 and 5.6 deg; see Figures 3 and 4). No-distractor (i.e. filler-letters-only) RTs (and errors) were not analysed but were plotted on the graphs to provide a visual baseline (see Figures 3 and 4).

Two analyses were performed on mean RTs (and error percentages) using repeated-measures ANOVAs.<sup>7</sup> The first one was performed on the trials from the whole experiment and the second one was performed on a subset of trials and tested for the effect of *experimental practice* by comparing the first and last 20% of trials from the experiment.

The first analysis tested for the effects of two factors, namely, Compatibility (Incompatible vs. Compatible distractor, or I. vs. C.) and Separation (between target and distractor; 1.6, 2.9, 4.4 and 5.6 deg of separation) on target-identification RTs (and error percentages). In this analysis, we were particularly interested to see (1) whether the main effect of Compatibility (I. vs. C.) was significant, which would indicate that

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<sup>7</sup> The level of significance was set at 0.05 and a level of marginal significance at 0.10. The  $p$  values were Greenhouse-Geisser corrected when the test of sphericity was significant at  $p = 0.05$ , leading to non-integer values of degrees of freedom (d.f.) where  $d.f. > 1$ . Non-integer d.f. were written with one decimal place,  $F$  statistics with two decimal places and  $p$  and  $\eta_p^2$  values with three decimal places.

distractors generated significant *combined response-related interference* (and therefore that distractor locations were allocated significant perceptual resources; see Chapter 1), and (2) whether the interaction between the effects of Compatibility (I. vs. C.) and Separation was significant, which would indicate that *combined response-related interference* varied with separation. If the interaction between the effects of Compatibility (I. vs. C.) and Separation was found to be significant (in other words, if the interference function of separation was found *not to be flat*), the shape of the interference function of separation would be examined using polynomial trends, thus indexing the spatial profile of perceptual resources.<sup>8</sup> A function explained by a linear trend would be consistent with a gradient profile of perceptual resources. On the other hand, a function explained by a quadratic or a cubic trend (or a combination of both of these trends) would be consistent with a Mexican-hat profile of perceptual resources (as a quadratic and/or a cubic trend can only be explained by the presence of an increasing arm in the profile).

In the second analysis, the same comparisons were performed as in the first analysis, except that an additional factor, namely, Experimental Practice, was also tested. This analysis tested whether Experimental Practice affected *combined response-related interference* pooled across separations, and whether it affected *combined response-related interference* as a function of separation. If the latter was found to be the case (i.e., if there was a significant interaction between the effects of Compatibility, Separation and Experimental Practice), this would indicate that the functions of

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<sup>8</sup> The interference functions of separation are not explicitly illustrated in this thesis (except in one condition of Experiment 8) but they can be derived from differencing the absolute RTs as a function of separation in the relevant distractor conditions (see Figure 2).

separation described by *combined response-related interference* were different in the two conditions of Experimental Practice. If such difference was found, it would be investigated with additional analyses.

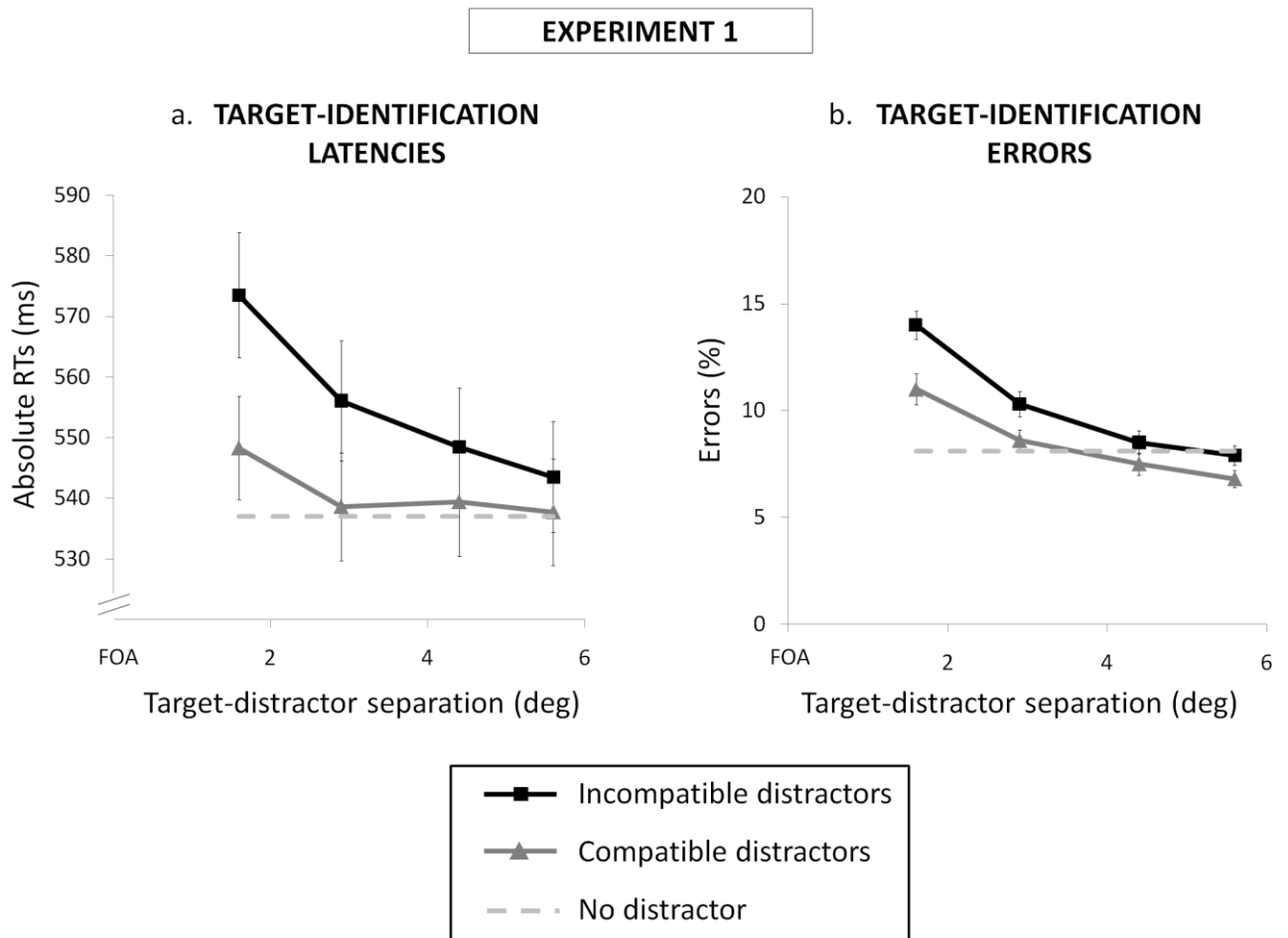
### ***2.2.2.1 Analyses on the trials from the whole experiment: comparison of incompatible- with compatible-distractor RTs as a function of separation***

#### **Reaction times**

This analysis tested for the effects of Compatibility (I. vs. C.) and Separation on target-identification RTs from the whole experiment. The results of the ANOVA showed a highly significant effect of Compatibility (I. vs. C.;  $F(1,9) = 67.46$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.882$ ): incompatible-distractor RTs were higher than compatible-distractor RTs. This finding shows that, consistent with the findings of numerous flanker studies (e.g., Eriksen & St. James, 1986; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990), *combined response-related interference* was significant. It can therefore be concluded that the distractor locations received significant perceptual resources.

The analysis also revealed a significant main effect of Separation ( $F(1.4,13.0) = 11.24$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.555$ ), showing that RTs (pooled across incompatible- and compatible-distractor conditions) varied with target-distractor separation. Most importantly, the analysis produced a significant interaction between Compatibility (I. vs. C.) and Separation ( $F(3,27) = 9.30$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.508$ ), showing that *combined response-related interference* varied with separation. Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was

best explained by a linear trend ( $F(1,9) = 17.36, p = 0.002, \eta_p^2 = 0.659$ ; the  $p$  values for quadratic and cubic trends were  $> 0.100$ ): *combined response-related interference* just decreased with increasing target-distractor separation, suggesting that the spatial profile of perceptual resources described a gradient pattern in this experiment (see Figure 3).



**Figure 3**

*Experiment 1 – Latencies and errors. The figure shows: (1) distractor-present mean latencies (in ms) and error percentages (in %) as a function of target-distractor separation (in deg) and target-distractor compatibility (compatible or incompatible) – see solid lines; and (2) no-distractor mean latencies (in ms) and error percentages (in %) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (FOA) = attended location.*

## **Errors**

The results of the repeated-measures ANOVA showed a significant effect of Compatibility (I. vs. C.;  $F(1,9) = 19.65$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.686$ ): incompatible-distractor errors were higher than compatible-distractor ones. This finding showed that, consistent with the findings observed in the RT data, the distractors generated significant *combined response-related interference* (see Figure 3).

The analysis also showed a significant main effect of Separation ( $F(1.6,14.2) = 21.27$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.703$ ), indicating that errors (pooled across compatible and incompatible conditions) varied with separation. On the other hand, unlike in the RT data, there was no significant interaction between Compatibility (I. vs. C.) and Separation ( $F(1.4,13.1) = 1.34$ ,  $p = 0.283$ ,  $\eta_p^2 = 0.129$ ). The absence of a significant interaction showed that, in this experiment, errors were not as sensitive an index as RTs of *combined response-related interference* as a function of separation.

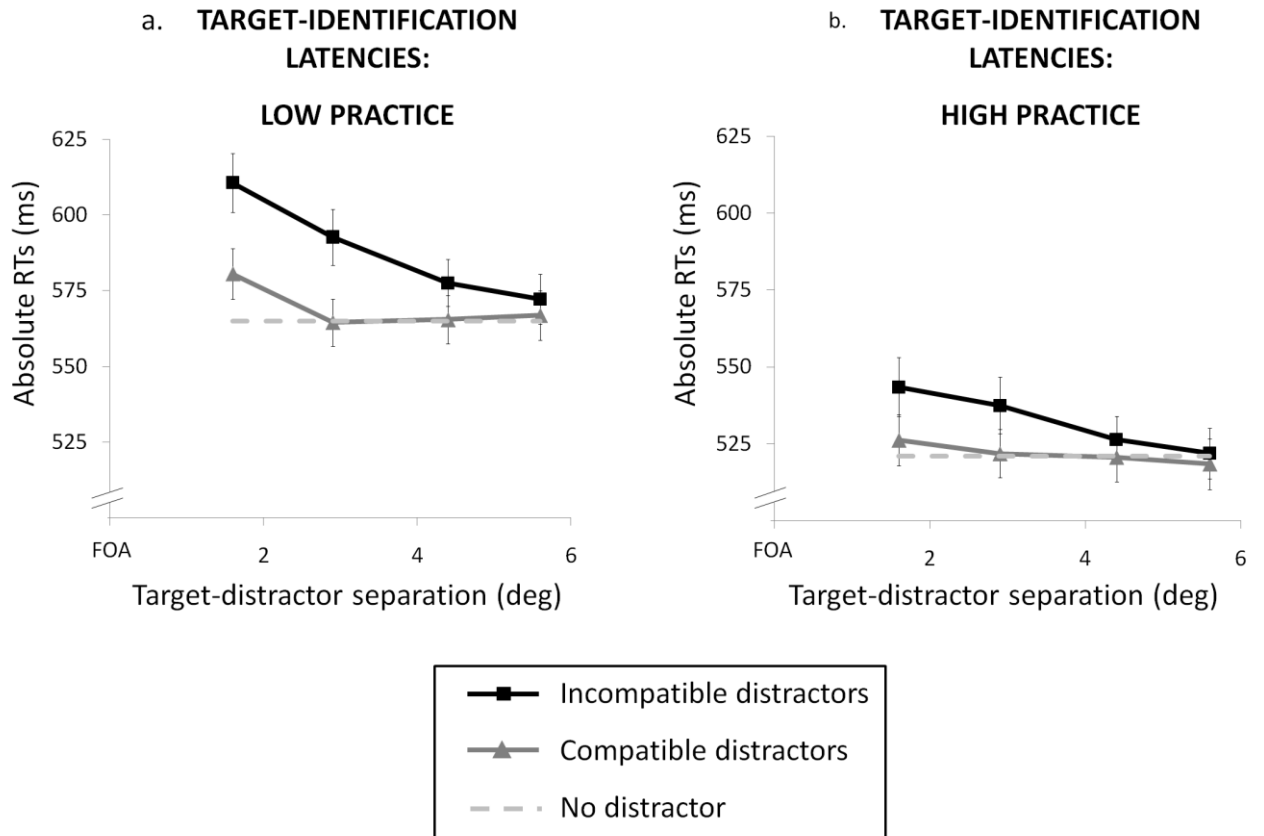
### ***2.2.2.2 Analysis of the effect of Experimental Practice: comparison of incompatible- with compatible-distractor RTs as a function of separation in the first and last 20% of the trials from the experiment***

## **Reaction times**

We selected the trials obtained from the first 20% and the last 20% of the experiment and compared them to test for an effect of Experimental Practice. In order to do so, we performed the same repeated-measures ANOVA as in Section 2.2.2.1 except that the factor Experimental Practice was added to the analysis.

This analysis replicated the main effects and interaction reported above and showed a significant main effect for Experimental Practice ( $F(1,9) = 27.31, p = 0.001, \eta_p^2 = 0.752$ ): participants were overall faster by the end of the experiment (by 51 ms). This analysis also showed that the interaction between Experimental Practice and Compatibility (I. vs. C.) was significant ( $F(1,9) = 5.77, p = 0.040, \eta_p^2 = 0.391$ ), indicating that increasing experimental practice significantly decreased *combined response-related interference* across separations (see Figure 4). This decrease was not the result of a spatial focusing of perceptual resources: the three-way interaction between Experimental Practice, Compatibility (I. vs. C.) and Separation was not significant ( $F(3,27) = 0.75, p = 0.534, \eta_p^2 = 0.077$ ), showing that *combined response-related interference* as a function of separation described a similar pattern at the beginning and the end of the experiment (see Figure 4). This suggests that the profile of perceptual resources did *not* focus with increasing experimental practice.

**EXPERIMENT 1: EFFECT OF EXPERIMENTAL PRACTICE**



**Figure 4**

*Experiment 1 – Effect of Experimental Practice on latencies. The figure shows: (1) distractor-present mean latencies (in ms) as a function of target-distractor separation (in deg), target-distractor compatibility (compatible or incompatible) and experimental practice (low or high) – see solid lines; and (2) no-distractor mean latencies (in ms) as a function of experimental practice (low or high) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (FOA) = attended location.*

**Errors**

None of the effects of Experimental Practice were significant in the error data (all  $p$  values > 0.100).

### 2.2.3 Discussion

The first important finding of Experiment 1 was that incompatible distractors increased latencies and errors compared to compatible distractors: *combined response-related interference* was significant, consistent with numerous previous findings (e.g., Cohen & Shoup, 1997; Eriksen & St. James, 1986; Hommel, 2003; Kramer & Jacobson, 1991; Matchock & Mordkoff, 2007; Mattler, 2006; Miller, 1991; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Paquet, 2001; Yantis & Johnston, 1990).

The second important finding of Experiment 1 was that *combined response-related interference* steadily decreased with increasing separation. This finding was consistent with a gradient profile of perceptual resources (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990) and not with a Mexican-hat profile (Müller et al., 2005).

The factor ‘experimental practice’ could not explain the failure to replicate the Mexican-hat finding of Müller et al. (2005) as it did not affect *combined response-related interference as a function of separation*. On the other hand, it *did* affect overall *combined response-related interference* (i.e., interference pooled across separations). Indeed, the latter was shown to be significantly lower at the *end* of the experiment. This might reflect an improvement of selection at post-perceptual rather than perceptual levels (since the decrease in distractor interference was not accompanied by a focusing of perceptual resources; see Chapters 1 and 4). Alternatively, it is possible that the decrease in distractor interference with experimental practice resulted, not from improved post-perceptual levels of selection, but from the speeding of reaction times



(by approximately 40 ms). According to this logic, the distractor was not given an opportunity to compete as much with the target when responses were speeded (Miller, 1991). In any case, increasing experimental practice made it harder to observe a Mexican-hat profile of perceptual resources as it reduced the effect of distractors and therefore the sensitivity of the paradigm. For the latter reason, in subsequent experiments, we did not use as many trials per condition as in Experiment 1.

A last observation on Experiment 1 that deserves to be noted is that compatible distractors appeared to have *increased* latencies and errors compared to the no-distractor baseline (rather than decreasing them; see Figures 3 and 4). This finding is compatible with several previous findings of the literature (e.g., Björk & Murray, 1977; Flowers, 1990; Grice, Borough, & Canham, 1984; Grice & Gwynne, 1985; Lavie, 1995; Madden & Langley, 2003; McCarley & Mounts, 2007; Miller, 1991; Yeh & Eriksen, 1984) showing that compatible distractors can generate *saliency-related interference* (see Chapter 1). It must be noted that the interference effect of compatible distractors was not tested as it cannot easily be interpreted, combining as it does influences that go in opposite directions (compatible distractors can improve performance through response-related facilitation but impair it through *saliency-related interference*; *saliency-related interference* was tested using neutral distractors in Chapter 3).

In conclusion, Experiment 1 did not replicate Müller et al.'s (2005) Mexican-hat finding despite having used a very similar methodology. It is possible that this discrepancy arose because of participant differences (e.g., an effect of trait anxiety; see Chapter 5). In our experiments and with our participants, the bottom of the putative Mexican hat may have occurred at or above 5.0 deg, further out than in Müller et al. (2005). This

being the case, since we only sampled separations from 1.6 to 5.6 deg in Experiment 1, we would have missed the bottom. This hypothesis was tested in Experiment 2 where we sampled the additional separations of 7.2 and 8.0 deg. Doing this meant that the largest separation would have occurred in the opposite hemifield and the second largest separation would have occurred on the boundary between hemifields. We therefore moved the target location from the fixed North-East location used in Experiment 1 to a mixture of North and South locations so that the target and distractor always occurred in the same hemifield. This made it possible for us also to test the effect of target location and hemisphere of distractor presentation in Experiment 2 (see Introduction of this chapter).

## **2.3 EXPERIMENT 2: Range of separation sampling, target location and hemifield of distractor presentation**

This experiment used a method similar to that used in Experiment 1 except that it tested larger separations and it extracted the profile of perceptual resources with North and South targets and in both visual hemifields.

### **2.3.1 Method**

#### ***2.3.1.1 Design***

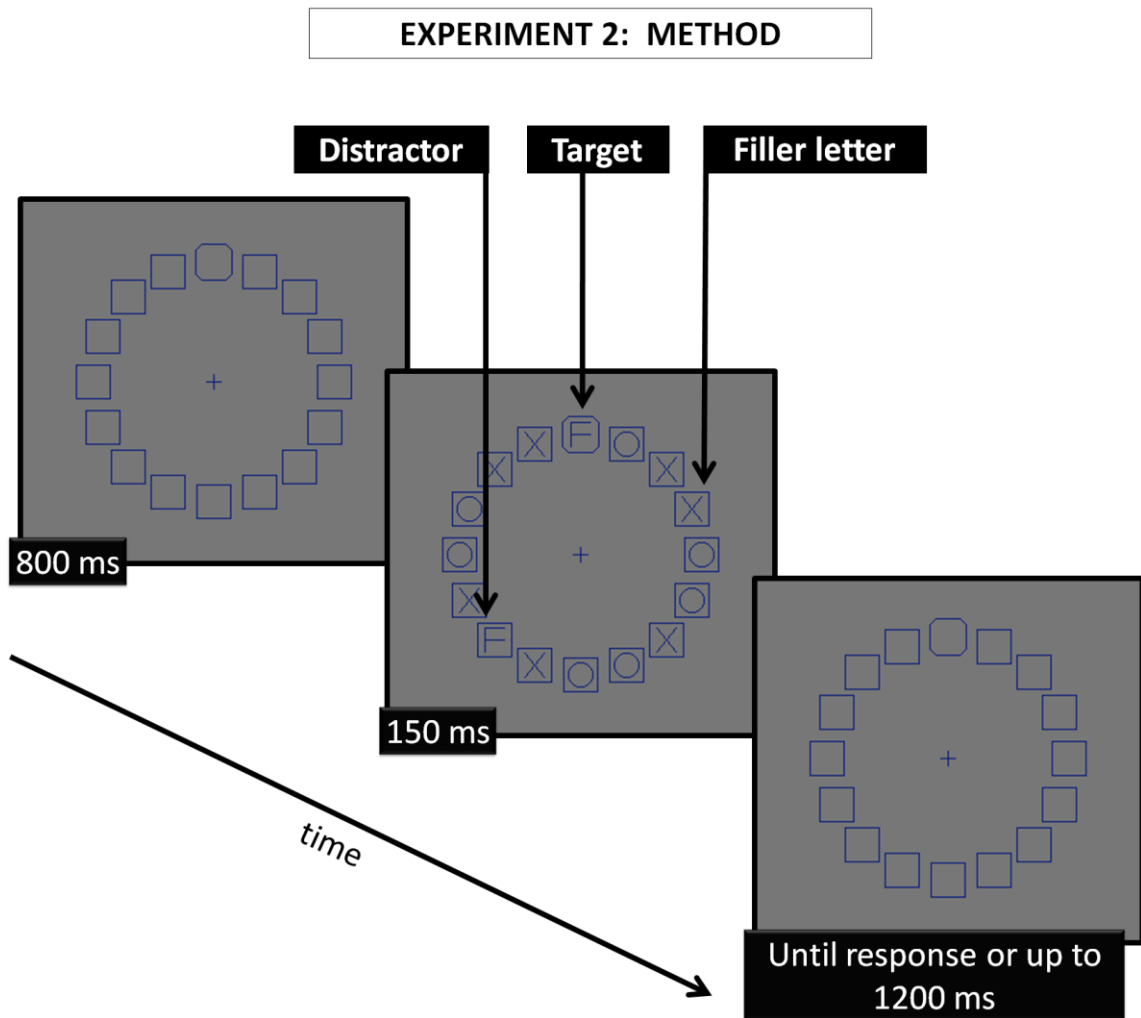
The compatibility of the distractor (compatible or incompatible), the target-distractor separation (1.6, 2.9, 5.6, 7.2 or 8.0 deg), the hemifield of distractor presentation (left or right) and the target location (North or South) were manipulated at fixed stimulus eccentricity in a repeated-measures design.

### ***2.3.1.2 Participants***

18 participants (16 females; 3 left-handed; mean age 20.6 yr; age range 17 to 36 yr; see Appendix 3), with reported normal or corrected-to-normal vision, participated in the experiment. They were all undergraduates and received course credits for their participation. Participants were all naïve as to the aim of the study.

### ***2.3.1.3 Stimuli and Procedure***

As in Experiments 1 and 2, participants were instructed to make a two-alternative forced-choice (2-AFC) identification of a target letter by pressing one of two keyboard keys (using the forefinger of each hand) as quickly but as accurately as possible while ignoring a distractor and filler letters. The target was always the letter ‘E’ or ‘F’, the distractor (when present) was always the letter ‘E’ or ‘F’, and the filler letters were always the letters ‘O’ and ‘X’. The stimuli were the same as those used in Experiment 1, except for the following difference. In this experiment, there were sixteen instead of seven placeholders. The sixteen placeholders were arranged around a whole imaginary circle of radius 4.0 deg. Fifteen of them subtended 1.1 deg square and one of them, the placeholder located North (in one set of trials) or South (in another set of trials), subtended 1.2 deg square and had chipped-off corners (see Figure 5).



**Figure 5**

*Experiment 2 – Method. A schematic representation of an experimental trial. In each trial, a target letter ('E' or 'F') occurred in the top placeholder (North Target) in one set of trials, or in the bottom placeholder (South Target) in another set of trials. Participants signalled target identity (with a 2-AFC) while ignoring distractor ('E' or 'F') and filler ('X's and 'O's) letters. The distractor occurred equally often in the left and right visual hemifields, at one of four possible target-distractor separations (1.6, 2.9, 5.6, 7.2), corresponding respectively to the first, second, fourth and sixth placeholder removed from the target placeholder (note that the 8.0-deg separation was also tested but it was not included in the analysis; see Results section). The distractor could be compatible with the response to the target (e.g., 'F' if the target was 'F') or incompatible with the response to the target (e.g., 'E' if the target was 'F'). The figure illustrates a North 'F' target with a compatible 'F' distractor occurring in the left hemifield at a target-distractor separation of 7.2 deg.*

Each placeholder was separated from its nearest neighbours by 1.6 deg (centre to centre). They circumscribed the locations of the 16 stimulus letters (target, distractor and filler letters). The placeholder with chipped-off corners located in the North location (in one set of trials) or in the South location (in another set of trials) defined the target location: the letter that appeared in this placeholder was defined as the letter to be discriminated.

Fourteen filler letters and one distractor, or fifteen filler letters and no distractor, appeared inside the remaining placeholders. When a distractor was presented, it was always response-compatible or -incompatible and it always appeared inside a placeholder separated from the target placeholder (centre to centre) by 1.6, 2.9, 5.6, 7.2 or 8.0 deg (the five levels of target-distractor separation) in both clockwise and anticlockwise directions. These separations corresponded to presenting the distractor in the placeholders that were respectively one, two, four, six and eight placeholders removed from the target placeholder (see Figure 5). Within each set of trials, 10% of trials were no-distractor (baseline) trials. In the remaining 90% of trials, a distractor, that was equally often response compatible and response incompatible with the target, occurred equally often at each of the nine possible distractor locations.

The whole experiment lasted 1 hour. Four sets of 500 trials were run for each participant. In two consecutive ones, the target was always at the North location and, in the two consecutive others, it was always at the South location. The order in which the participants performed North- and South-target locations was counterbalanced. At the beginning of the experiment, participants performed a training block of 60 trials. During

the experiment, participants were given short (participant-terminated) breaks every 75 trials (about every two minutes). Three of the experimental conditions (distractor compatibility, target-distractor separation and hemisphere of distractor presentation) were presented in a randomised order in each set of trials. The remaining one (target location) was presented in different sets of trials. Fixation was controlled using Eyelink 2 (see Method of Experiment 1).

### 2.3.2 Results

We discarded trials with eye movements beyond 1.0 deg from fixation (this meant excluding an average of 8.0% of trials). For the remaining trials, we analyzed both the speed and accuracy of forced-choice target-identification ('E' vs. 'F') responses. Latencies were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented an average of 89.1% of the latencies.

For each participant, mean RTs (and error percentages) were calculated for incompatible-distractor and compatible-distractor (distractor-present) trials at each of the two levels of target location (North and South), at each of the two levels of hemifield of distractor presentation (Left and Right) and at each of the four levels of target-distractor separation (1.6, 2.9, 5.6 and 7.2 deg; see Figures 6 and 7).<sup>9</sup> No-distractor (i.e. filler-letters-only) RTs (and errors) were not analysed but were plotted on the graphs to provide a visual baseline (see Figures 6 and 7).

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<sup>9</sup> RTs and errors were also calculated for the fifth target-distractor separation (8.0 deg) but this separation was not included in the analysis as it would have had to be attributed to *both* 'right' and 'left' levels of the factor Hemifield of Distractor Presentation.

RTs (and error percentages) were analysed using a repeated-measures ANOVA. The ANOVA tested for the effects of four factors, namely, Compatibility (I. vs. C.), Separation (1.6, 2.9, 5.6 and 7.2 deg of separation), Target Location (North and South), and Hemifield of Distractor Presentation (Left and Right) on target-identification RTs (and error percentages). In this analysis, we were particularly interested to see: (1) whether the main effect of Compatibility (I. vs. C.) was significant, which would indicate that distractors generated significant *combined response-related interference*, (2) whether the interaction between the effects of Compatibility (I. vs. C.) and Separation was significant, which would indicate that *combined response-related interference* varied with separation, (3) whether the three-way interaction between the effects of Compatibility (I. vs. C.), Separation and Hemifield of Distractor Presentation was significant, which would indicate that the shape of *combined response-related interference* as a function of separation was different in the two hemifields, and (4) whether the three-way interaction between the effects of Compatibility (I. vs. C.), Separation and Target Location was significant, which would indicate that the shape of *combined response-related interference* as a function of separation was different with North and South targets. If point 3 and/or 4 were found to be true, the effect of Hemifield of Distractor Presentation and/or Target Location on the shape of the function of separation would be investigated with additional ANOVAs and interpolation analyses.

### ***2.3.2.1 Comparison of incompatible-distractor with compatible-distractor RTs as a function of separation, target location and hemifield of distractor presentation***

## **Reaction times**

### *Effects of Compatibility (I. vs. C.) and Separation*

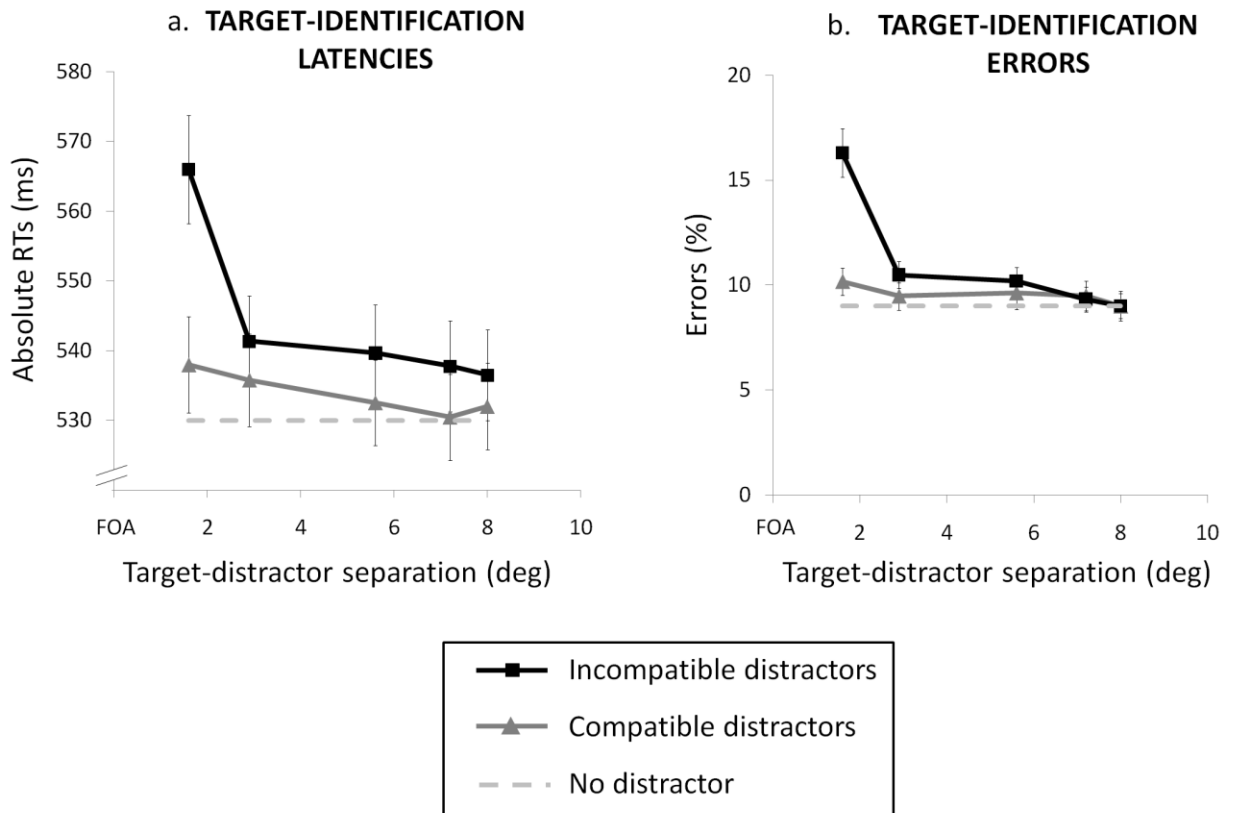
The results of the ANOVA showed that: (1) the effect of Compatibility (I. vs. C.) was significant ( $F(1,17) = 69.69, p < 0.001, \eta_p^2 = 0.804$ ), showing that *combined response-related interference* was significant; (2) the effect of Separation was significant ( $F(3,51) = 29.05, p < 0.001, \eta_p^2 = 0.631$ ), showing that RTs (pooled across compatible- and incompatible-distractor conditions) varied with separation; and (3) the interaction between Compatibility (I. vs. C.) and Separation was significant ( $F(3,51) = 15.07, p < 0.001, \eta_p^2 = 0.470$ ), showing that *combined response-related interference* varied with separation.

Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was best explained by a combination of linear and quadratic trends (respectively  $F(1,17) = 21.83, p < 0.001, \eta_p^2 = 0.562$  and  $F(1,17) = 54.38, p < 0.001, \eta_p^2 = 0.762$ ; the cubic trend was not significant with a  $p$  value  $> 0.100$ ). This finding suggests that *combined response-related interference* pooled across the different conditions of Target Location and Hemifield of Distractor Presentation decreased and then increased with increasing target-distractor separation, consistent with a Mexican-hat profile (Müller et al., 2005). Nevertheless, the increase in *combined response-related interference* with increasing separation was very small (of 1.8 ms, from separation 2.9 to separation 5.6 deg; see Figure 6). Moreover, this increase in interference was only due to the fact that incompatible-distractor RTs decreased *more slowly* than compatible-distractor RTs with increasing separation (see Figure 6). In



sum, the evidence for a Mexican-hat profile was scarce when the data was pooled across target-location and hemifield conditions.

## EXPERIMENT 2



**Figure 6**

*Experiment 2 – Latencies and errors. The figure shows: (1) distractor-present mean latencies (in ms) and error percentages (in %) as a function of target-distractor separation (in deg) and target-distractor compatibility (compatible or incompatible) – see solid lines; and (2) no-distractor mean latencies (in ms) and error percentages (in %) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (FOA) = attended location.*

### *Effect of Target Location*

The main effect of Target Location was significant ( $F(1,17) = 13.02, p = 0.002, \eta_p^2 = 0.434$ ): participants were slower (by 28 ms) to give their response when the target occurred at the North location. Moreover, Target Location significantly interacted with Compatibility (I. vs. C.;  $F(1,17) = 4.83, p = 0.042, \eta_p^2 = 0.221$ ): *combined response-*

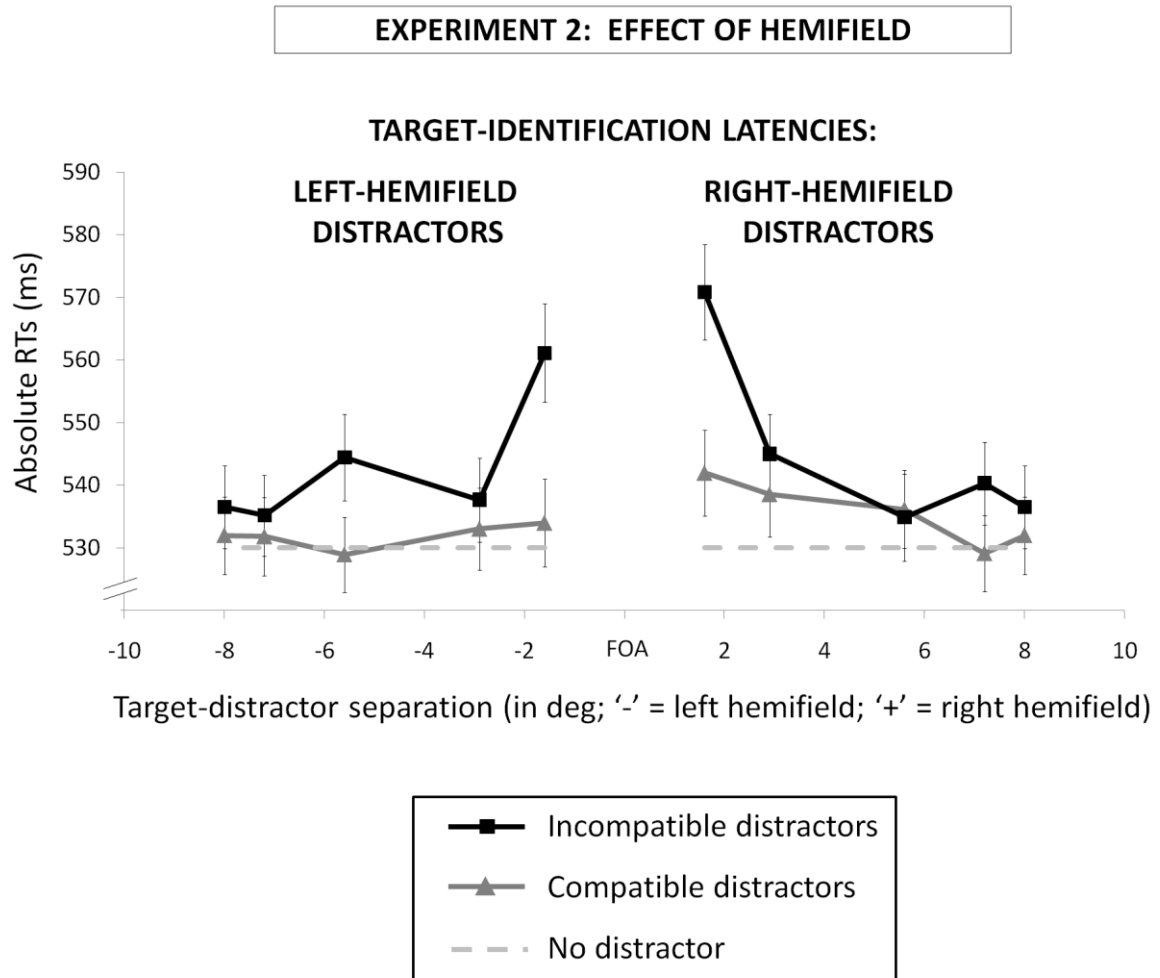
*related interference* was larger when the target occurred at the North than at the South location. The interaction between Target Location and Separation, and that between Target Location, Compatibility (I. vs. C.) and Separation, were not significant (respectively,  $F(3,51) = 1.05$ ,  $p = 0.380$ ,  $\eta_p^2 = 0.058$  and  $F(3,51) = 0.48$ ,  $p = 0.698$ ,  $\eta_p^2 = 0.027$ ).

#### *Effect of Hemifield of Distractor Presentation*

Stronger evidence for a Mexican-hat profile of perceptual resources emerged when considering Hemifield of Distractor Presentation. This factor had a significant main effect ( $F(1,17) = 7.60$ ,  $p = 0.013$ ,  $\eta_p^2 = 0.309$ ), as RTs were overall faster (of 4 ms) when a distractor occurred in the left than in the right hemifield (see Figure 7). Moreover, while neither the two-way interaction between Hemifield of Distractor Presentation, and Compatibility (I. vs. C.), nor that between Hemifield of Distractor Presentation, and Separation, were significant (respectively,  $F(1,17) = 0.67$ ,  $p = 0.425$ ,  $\eta_p^2 = 0.038$ , and  $F(3,51) = 2.21$ ,  $p = 0.099$ ,  $\eta_p^2 = 0.115$ ), the three-way interaction between Hemifield of Distractor Presentation, Compatibility (I. vs. C.) and Separation was significant ( $F(3,51) = 3.07$ ,  $p = 0.036$ ,  $\eta_p^2 = 0.153$ ). The significance of the three-way interaction showed that *combined response-related interference* as a function of separation described a *different* pattern in the left and right hemifields (see analyses below and Figure 7).

None of the interactions involving Target Location was significant (Target Location x Hemifield of Distractor Presentation:  $F(1,17) = 0.35$ ,  $p = 0.561$ ,  $\eta_p^2 = 0.020$ ; Target Location x Hemifield of Distractor Presentation x Separation:  $F(3,51) = 2.28$ ,  $p = 0.090$ ,  $\eta_p^2 = 0.118$ ; Target Location x Hemifield of Distractor Presentation x Compatibility:

$F(1,17) = 2.51, p = 0.131, \eta_p^2 = 0.129$ ; Target Location x Hemifield of Distractor Presentation x Compatibility x Separation:  $F(3,51) = 0.98, p = 0.409, \eta_p^2 = 0.055$ ).



**Figure 7**

*Experiment 2 – Effect of Hemifield on latencies. The figure shows: (1) distractor-present mean latencies (in ms) as a function of target-distractor separation (in deg), target-distractor compatibility (compatible or incompatible) and hemifield of distractor presentation (left or right) – see solid lines; and (2) no-distractor mean latencies (in ms) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (FOA) = attended location.*

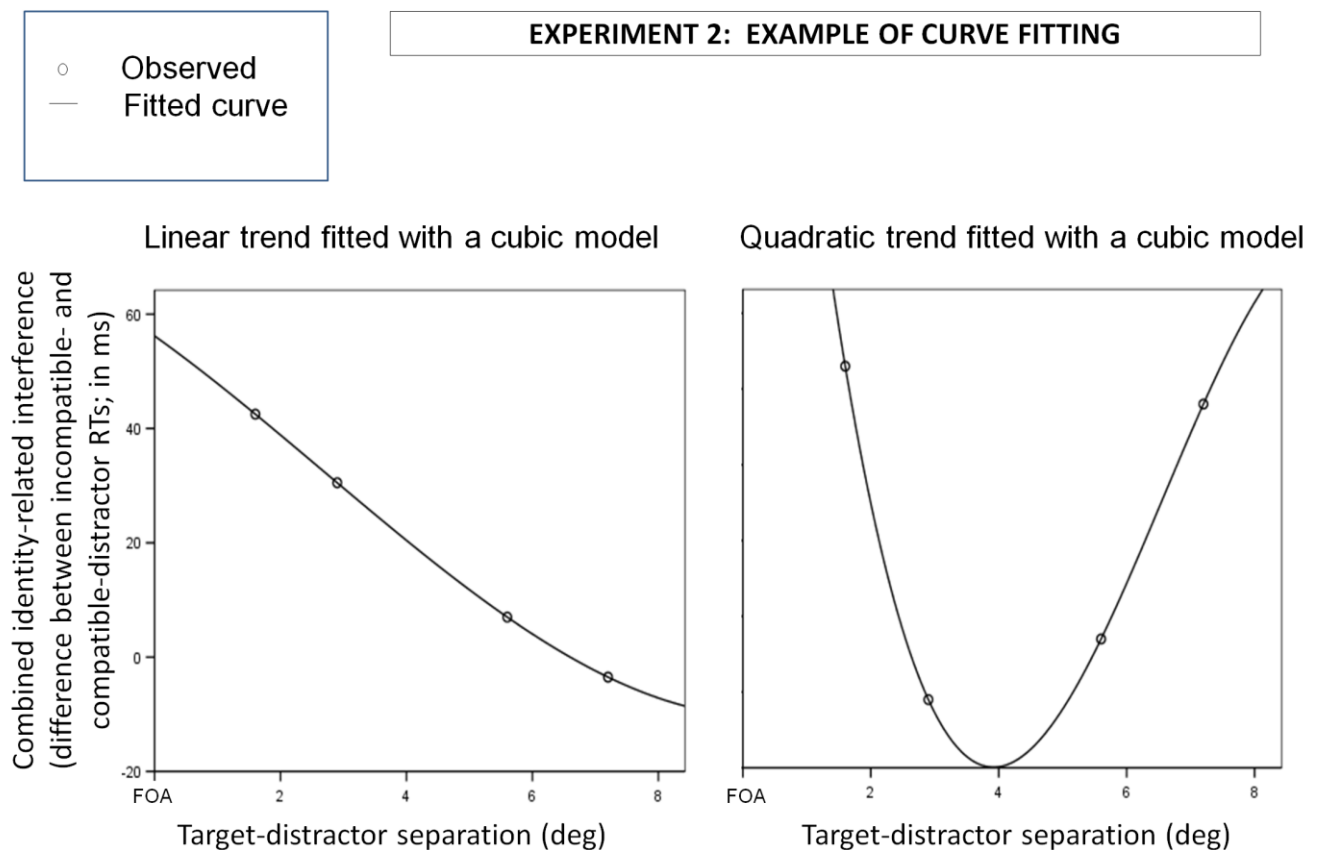
Given the significance of the three-way interaction between Hemifield of Distractor Presentation, Compatibility (I. vs. C.) and Separation, the effects of Compatibility (I.

vs. C.) and Separation were tested separately for each level of Hemifield of Distractor Presentation. Significant interactions between Compatibility (I. vs. C.) and Separation were revealed in both left and right hemifields (respectively,  $F(3,51) = 8.44$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.332$  and  $F(3,51) = 8.49$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.333$ ). Polynomial trends for the interactions showed that, in the left hemifield, *combined response-related interference* as a function of separation was best explained by a combination of cubic and linear trends (respectively  $F(1,17) = 12.24$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.419$  and  $F(1,17) = 10.67$ ,  $p = 0.005$ ,  $\eta_p^2 = 0.386$ ) and, in the right hemifield, *combined response-related interference* as a function of separation was best explained by a combination of quadratic and linear trends (respectively  $F(1,17) = 22.14$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.566$  and  $F(1,17) = 16.63$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.494$ ). In both hemifields, *combined response-related interference* first decreased and then increased (before tailing off) with increasing separation (see Figure 7); thus, in both hemifields, the interference function of separation described a pattern compatible with a Mexican-hat profile of perceptual resources (Müller et al., 2005). Nevertheless, the bottom of this Mexican-hat function seemed to have occurred *closer to the attended location* in the left than in the right hemifield. This suggestion was tested using interpolation analyses that isolated the separation at which each participant's interference function occurred in each hemifield condition. It was then tested whether these separations were different in the two hemifield conditions.

#### *Comparison of the locations of the bottoms of the functions of separation*

A cubic model was used for these interpolation analyses (see Figure 8 for an example of interpolation). Such a cubic model was used because the Mexican-hat pattern consists: (1) first in a decrease, (2) then in an increase, and (3) finally in a tailing off of perceptual resources with increasing separation (Müller et al., 2005). It is important to

note that, even when the data are best explained by a linear trend (see left of Figure 8), the function obtained by fitting a cubic model closely mirrors that obtained by fitting a linear model (because the cubic and quadratic coefficients in the cubic model approach zero, bringing the model close to a linear model). The same is true when the data are best explained by a quadratic trend (see right of Figure 8), in which case the function obtained by fitting a cubic model closely mirrors that obtained by fitting a quadratic model (because the cubic coefficients in the cubic model approach zero, bringing the model close to a quadratic model).



**Figure 8**

*Experiment 2 – Example of curve fitting. Combined response-related interference as a function of target-distractor separation (in deg) describing a linear trend (left) and a quadratic trend (right). The local minima in this example were at 7.2 deg and 3.9 deg*

for the left and right examples respectively. (○) = observed data points; (-) = curve fitted with a cubic model.

For each hemifield condition and for each participant, the separation at which the ‘local minimum’ or bottom of the interference function occurred (i.e., the point where the function stopped decreasing and started increasing) was estimated by calculating the derivative of the fitted function. When the local minimum occurred outside the boundaries of the sampled interval (namely, at a smaller separation than 1.6 deg or a larger separation than 7.2 deg), the boundary closest to the local minimum was coded as the local minimum: for instance, if the local minimum occurred at 9.0 deg, the bottom was coded as 7.2 deg. When there was no derivative in the domain of real numbers (i.e., when there was no local minimum in the function), the function described a linear trend, and the local minimum was therefore defined as the lowest point of the function within the sampled interval (i.e., either 1.6 or 7.2 deg, for linearly increasing and decreasing functions respectively).

The local minima so derived were compared across the two hemifield conditions for all participants. The group-mean local minimum occurred at 3.4 deg (SEM = 0.30) in the left hemifield and at 4.5 deg (SEM = 0.30) in the right hemifield. This difference was significant ( $t(17) = 2.36, p = 0.030, d = 0.712$ ). In other words, the profile of perceptual resources presented as being *more focused* in the left than the right hemifield.

## **Errors**

### *Effects of Compatibility (I. vs. C.) and Separation*

The results of the ANOVA showed that: (1) the effect of Compatibility (I. vs. C.) was significant ( $F(1,17) = 11.65, p = 0.003, \eta_p^2 = 0.407$ ): the distractors generated significant *combined response-related interference*; (2) the effect of Separation was significant ( $F(3,51) = 20.73, p < 0.001, \eta_p^2 = 0.549$ ): errors (pooled across compatible- and incompatible-distractor conditions) varied with separation; and (3) the interaction between Compatibility (I. vs. C.) and Separation was significant ( $F(3,51) = 12.10, p < 0.001, \eta_p^2 = 0.416$ ): *combined response-related interference* varied with separation.

Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was best explained by a linear trend ( $F(1,17) = 26.46, p < 0.001, \eta_p^2 = 0.609$ ; the quadratic and cubic trends were not significant with  $p$  values  $> 0.100$ ). This shows that, in the error data, *combined response-related interference* pooled across conditions of Target Location and Hemifield of Distractor Presentation tended just to decrease with increasing target-distractor separation (see Figure 6).

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(1,17) = 24.02, p < 0.001, \eta_p^2 = 0.586$ ): participants made more errors (i.e., 4.6% more) for North- than for South-located targets. Moreover, Target Location significantly interacted with Compatibility (I. vs. C.;  $F(1,17) = 4.96, p = 0.040, \eta_p^2 = 0.226$ ): the compatibility effect was larger (by 2.0%) when the target occurred at the North than at the South location. The interaction between Target Location and Separation, and that between Target Location, Compatibility (I. vs. C.) and Separation, were not significant (respectively,  $F(3,51) = 0.69, p = 0.561, \eta_p^2 = 0.039$  and  $F(3,51) = 1.35, p = 0.267, \eta_p^2 = 0.074$ ).



### *Effect of Hemifield of Distractor presentation*

The main effect of Hemifield of Distractor Presentation was not significant ( $F(1,17) = 2.35, p = 0.144, \eta_p^2 = 0.122$ ). Moreover, Hemifield of Distractor Presentation did not interact significantly either with Compatibility (I. vs. C.), Separation or Target Location (Hemifield of Distractor Presentation x Compatibility:  $F(1,17) = 0.74, p = 0.401, \eta_p^2 = 0.042$ ; Hemifield of Distractor Presentation x Separation:  $F(3,51) = 1.07, p = 0.369, \eta_p^2 = 0.059$ ; Hemifield of Distractor Presentation x Target Location:  $F(1,17) = 0.27, p = 0.610, \eta_p^2 = 0.016$ ; Hemifield of Distractor Presentation x Compatibility x Separation:  $F(3,51) = 0.41, p = 0.746, \eta_p^2 = 0.024$ ; Target Location x Hemifield of Distractor Presentation x Separation:  $F(3,51) = 1.24, p = 0.304, \eta_p^2 = 0.068$ ; Target Location x Hemifield of Distractor Presentation x Compatibility:  $F(1,17) = 0.00, p = 0.982, \eta_p^2 = 0.000$ ; Target Location x Hemifield of Distractor Presentation x Compatibility x Separation:  $F(3,51) = 1.61, p = 0.198, \eta_p^2 = 0.087$ ). The effect of Hemifield of Distractor Presentation observed in the RT data (see above) was therefore not replicated in the error data.

### **2.3.3 Discussion**

Once again, the distractors generated significant *combined response-related interference* which varied with separation. In this experiment, where we sampled separations up to 8.0 deg<sup>10</sup> and measured the effect of hemifield, the profile of perceptual resources was found to describe a Mexican-hat pattern. Importantly, the Mexican-hat profile presented as being less focused in the right than in the left field. As

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<sup>10</sup> Only separations up to 7.2 deg were included in the analysis (see Results section of this experiment).

a result of the latter, when left- and right-field profiles were averaged, the Mexican hat almost disappeared (compare Figures 6 and 7). If this difference in focus in the two hemifields had occurred in previous studies that probed both hemifields but did not analyse the effect of hemifield (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Yantis & Johnston, 1990), this could explain why they revealed a gradient profile. Thus, it is important to take into account the hemifield of distractor presentation when studying the profile of perceptual resources. Assuming that the effect of hemifield observed in Experiment 2 can be extrapolated to Experiment 1, we might, in Experiment 1, have revealed a Mexican-hat profile with a range of separations extending only up to 5.6 deg, if we had sampled the left hemifield. Because we sampled the right hemifield, where the profile was potentially less focused, we could only reveal a Mexican-hat profile with a range extending up to 7.2 deg. We suggest that the profile was really shaped like a Mexican hat in Experiment 1 but we mistook it for a gradient.

This experiment also showed that, while the hemifield of distractor presentation affected the focus of the profile of perceptual resources, target location did not have such effects. This null effect argues against the possibility that the Mexican-hat profile obtained in this experiment (and, by extension, in Müller et al., 2005) resulted from a complex interaction between a gradient profile of perceptual resources and irregularities in the visual field (see Introduction of this chapter). Nevertheless, because this finding is based on the comparison of profiles obtained with a limited number of target and distractor locations, there arguably remains a possibility that the Mexican-hat findings of this experiment resulted from irregularities in the visual field. The effect of the latter factor was therefore investigated further in Chapter 3 (see Experiment 7).

In this experiment, the null effect of target location on the profile of perceptual resources was found despite target location exerting an overall effect on absolute reaction times and on overall *combined response-related interference* (pooled across separations). Participants were slower to respond to North than to South targets; this is consistent with previous findings showing that visual resolution is better in the lower than in the upper visual field (e.g., Carrasco, Giordano, & McElree, 2004; Kristjansson & Sigurdardottir, 2008; Lakha & Humphreys, 2005). Moreover, *combined response-related interference* was overall larger with North than with South targets. The origins of this effect are not clear; it may be that, when a target takes longer to be processed, this leaves overall more ‘space’ for distractors to generate interference.

The results of these experiment also bear on the issue of practice addressed in the previous experiment. In the present experiment, we succeeded in replicating Müller et al.’s (2005) Mexican-hat profile of perceptual resources despite using ‘only’ 1000 trials. Therefore, the results of this experiment confirm that it is not necessary to use an excessive number of trials to index the profile of perceptual resources.

In conclusion, this experiment replicated the Mexican-hat finding of Müller et al. (2005). In the next experiment, we tested whether this finding can also be obtained with exogenous cueing of the target location as most previous flanker studies have used exogenous cueing and doing so obviates the need to monitor eye movements. Experiment 3 also further investigated the effect of target location and hemifield of distractor presentation.

## **2.4 EXPERIMENT 3: Exogenous cueing of target location**

Experiment 3 used a method similar to that used in Experiment 2 except that the target location was exogenously cued and that the target could occur at eight possible locations (North, North-East, East, South-East, South, South-West, West and North-West) rather than only at two locations as in Experiment 2 (North and South). In addition, to limit the number of trials, the distractor always occurred removed from the target location in a clockwise direction.

### **2.4.1 Method**

#### ***2.4.1.1 Design***

The response-compatibility of the distractor (compatible or incompatible), the target-distractor separation (1.6, 2.9, 5.6, 7.2 and 8.0 deg) and the target location (North, North-East, East, South-East, South, South-West, West or North-West) were manipulated at fixed stimulus eccentricity in a repeated-measures design.

#### ***2.4.1.2 Participants***

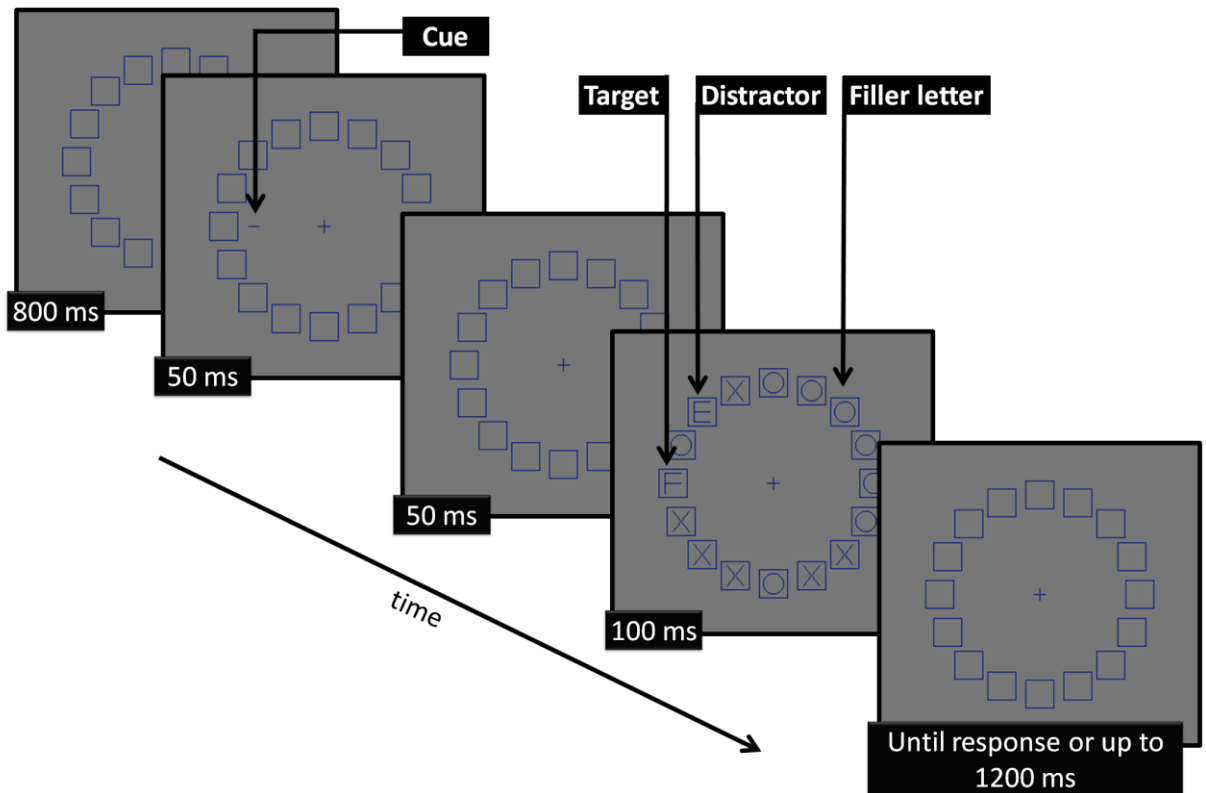
16 participants (11 females; 1 left-handed; mean age 23.6 yr; age range 16 to 39 yr; see Appendix 4), with reported normal or corrected-to-normal vision, participated in the experiment. Their participation was remunerated and they were all naïve as to the aim of the study.

### ***2.4.1.3 Stimuli and Procedure***

As in Experiments 1 and 2, participants were instructed to make a two-alternative forced-choice (2-AFC) identification of a target letter by pressing one of two keyboard keys (using the forefinger of each hand) as quickly but as accurately as possible while ignoring a distractor and filler letters. The target was always the letter 'E' or 'F', the distractor (when present) was always the letter 'E' or 'F', and the filler letters were always the letters 'O' and 'X'. The stimuli were the same as those used in Experiment 1, except for the following difference.

In this experiment, like in Experiment 2, there were sixteen instead of seven placeholders (see Figure 9). The placeholders were arranged around an imaginary circle of radius 4.0 deg and circumscribed the locations of the 16 stimulus letters (target, distractor and filler letters). Each of them was separated from its nearest neighbours by 1.6 deg (centre to centre). In this experiment, a cue was used to indicate the target location. It was a bar, 0.4 deg long, of the same dark blue as stimulus letters, fixation cross and placeholders.

### EXPERIMENT 3: METHOD



**Figure 9**

*Experiment 3 - Method. A schematic representation of an experimental trial. In each trial, a target letter ('E' or 'F') occurred in the placeholder indicated by a 100%-valid exogenous cue. Participants signalled target identity (with a 2-AFC) while ignoring distractor ('E' or 'F') and filler ('X's and 'O's) letters. The distractor could occur at one of five possible target-distractor separations (1.6, 2.9, 5.6, 7.2 and 8.0 deg) corresponding respectively to the first, second, fourth, sixth and eighth placeholder removed from the target placeholder in a clockwise direction, and could be compatible with the response to the target (e.g., 'F' if the target was 'F') or incompatible with the response to the target (e.g., 'E' if the target was 'F'). The figure illustrates a West 'F' target with an incompatible 'E' distractor occurring at a target-distractor separation of 2.9 deg.*

Each trial proceeded as follows. 800 ms after the beginning of the trial, the cue bar was displayed collinearly with one of the four cardinals (North, South, East or West) or one of the four diagonals (North-East, North-West, South-East or South-West) for 50 ms, 1

deg away from the centre of the placeholder it indicated. After the offset of the cue and a delay of 50 ms, the target appeared in the placeholder indicated by the cue and the distractor and/or filler letters appeared in the remaining placeholders. The stimulus letters stayed on the screen for 100 ms. The next trial started 200 ms after the participants responded or after 1200 ms had elapsed.

When a distractor was presented, it always appeared inside a placeholder separated from the target placeholder (centre to centre) by 1.6, 2.9, 5.6, 7.2 or 8.0 deg (the five levels of target-distractor separation) in the clockwise direction. These separations corresponded to presenting the distractor in the placeholders that were respectively one, two, four, six and eight placeholders removed from the target placeholder (see Figure 9).

The whole experiment lasted 2.5 hours and was performed in two sessions (over two different days). Each participant ran a total of 3872 trials (in six blocks). All the experimental conditions (distractor compatibility, target-distractor separation and target location) were presented in a randomised order in each block. The target occurred equally often at each of the eight possible target locations. 5% of trials were no-distractor (baseline) trials and, in the remaining 95% of trials, a distractor, that was equally often response compatible and response incompatible with the target, occurred equally often at each of the five possible target-distractor separations.

At the beginning of the experiment, the participants performed a training block of 60 trials. Within each block, participants were given short (participant-terminated) breaks every 72 trials (8 breaks per block, about every two minutes).

#### **2.4.1.4 Fixation control**

Participants were instructed to keep their eyes fixated on the fixation cross at all times. Their gaze was not monitored with an eye tracker since only 200 ms separated the onset of the cue from the offset of the target and it is generally accepted that the planning and execution of eye movements requires approximately 250 ms (Darrien, Herd, Starling, Rosenberg & Morrison, 2001; Henderson, Pollatsek & Rayner, 1987). Moreover, all participants kept their eyes fixated on the central cross during the practice session (as monitored by the experimenter) and reported having done so throughout the experiment.

#### **2.4.2 Results**

We analyzed both the speed and accuracy of forced-choice target-identification ('E' vs. 'F') responses. Latencies were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented an average of 89.5% of the latencies.

For each participant, mean RTs (and error percentages) were calculated for incompatible-distractor and compatible-distractor (distractor-present) trials at each of the eight levels of target location (North, North-East, East, South-East, South, South-West, West and North-West), and at each of the five levels of target-distractor separation (1.6, 2.9, 5.6, 7.2 and 8.0 deg; see Figures 10 and 12). No-distractor (i.e. filler-letters-only) RTs (and errors) were not analysed but were plotted on the graphs to provide a visual baseline (see Figures 10 and 12).

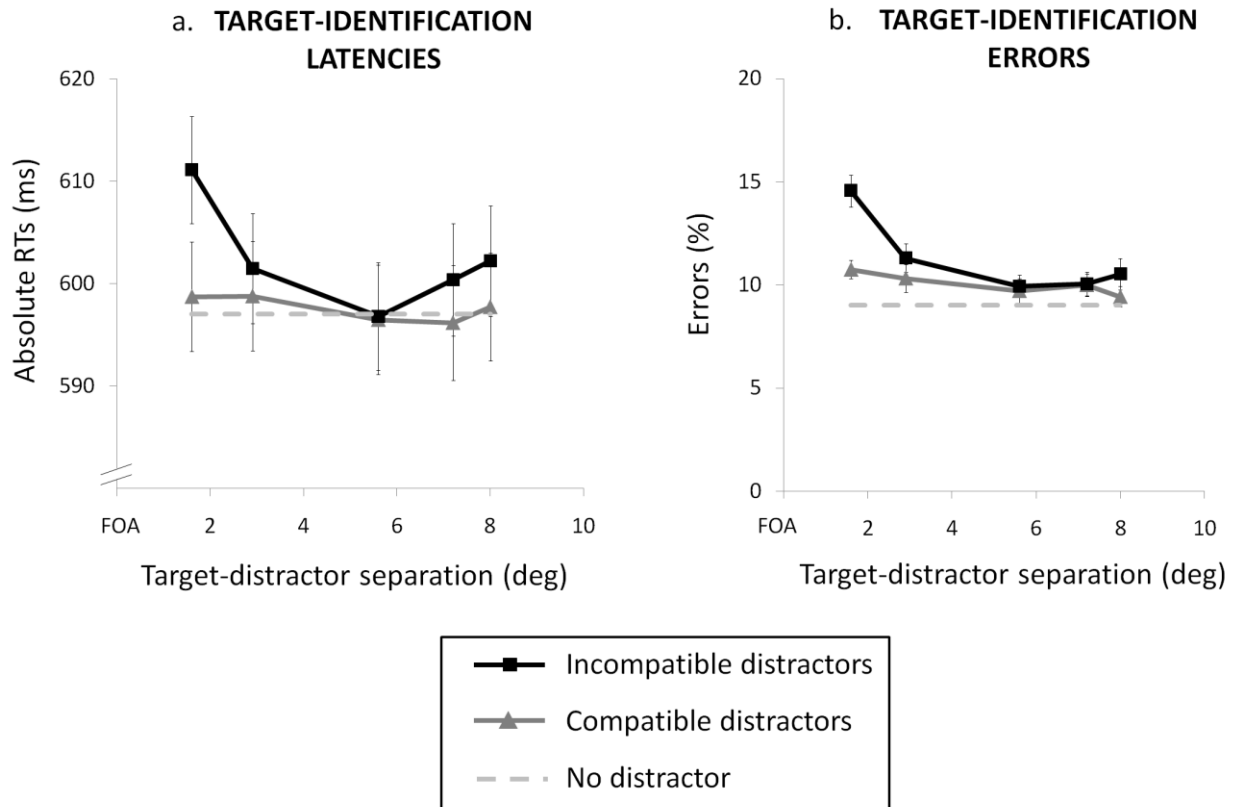


RTs (and error percentages) were analysed using two different repeated-measures ANOVAs. In the first analysis, the data from all conditions was tested. The ANOVA tested for the effects of three factors, namely, Compatibility (I. vs. C.), Separation (1.6, 2.9, 5.6 and 7.2 deg) and Target Location (North, North-East, East, South-East, South, South-West, West or North-West) on target-identification RTs (and error percentages). In this analysis, we were particularly interested to see: (1) whether the main effect of Compatibility (I. vs. C.) was significant, which would indicate that distractors generated significant *combined response-related interference*, (2) whether the interaction between the effects of Compatibility (I. vs. C.) and Separation was significant, which would indicate that *combined response-related interference* varied with separation, and (3) whether the interaction between the effects of Compatibility (I. vs. C.), Separation and Target Location was significant, which would indicate that *combined response-related interference* as a function of separation had a different shape for different target locations. If the latter was found to be the case, the effect of Target Location on the shape of the function of separation would be investigated with additional ANOVAs and interpolation analyses.

In the second analysis, only a subset of the data was tested. The analysis was performed on the data obtained with North and South targets only. The effect of Target Location was thus confounded with an effect of Hemifield of Distractor Presentation in this analysis. Indeed, when the target appeared at the North location, the distractor always occurred in the *right* hemifield and, when the target appeared at the South location, the distractor always occurred in the *left* hemifield (see Method section). Since Target Location has not been found to affect the shape of the profile of perceptual resources (see Experiment 2), we predicted that an effect of Target Location would in fact reflect

an effect of Hemifield of Distractor Presentation in this analysis. In sum, the ANOVA tested for the effects of three factors, namely, Compatibility (I. vs. C.), Separation (1.6, 2.9, 5.6, 7.2 and 8.0 deg) and Hemifield of Distractor Presentation (left and right), on target-identification RTs (and error percentages). In this analysis, we were particularly interested to see whether the interaction between the effects of Compatibility (I. vs. C.), Separation and Hemifield of Distractor Presentation was significant, which would indicate that the shape of *combined response-related interference* as a function of separation was different in the two hemifields (as was shown in Experiment 2). If the latter was found to be the case, the effect of Hemifield of Distractor Presentation on the shape of the function of separation would be investigated using additional ANOVAs and interpolation analyses.

### EXPERIMENT 3



**Figure 10**

*Experiment 3 - Latencies and errors. The figure shows: (1) distractor-present mean latencies (in ms) and error percentages (in %) as a function of target-distractor separation (in deg) and target-distractor compatibility (compatible or incompatible) – see solid lines; and (2) no-distractor mean latencies (in ms) and error percentages (in %) – see dashed lines. Error bars depict  $\pm 0.5$  SEM. ( $\blacktriangle$ ) = compatible distractor; ( $\blacksquare$ ) = incompatible distractor; (FOA) = attended location.*

### ***2.4.2.1 Comparison of incompatible-distractor with compatible-distractor RTs as a function of separation and target location***

#### **Reaction times**

##### *Effects of Compatibility (I. vs. C.) and Separation*

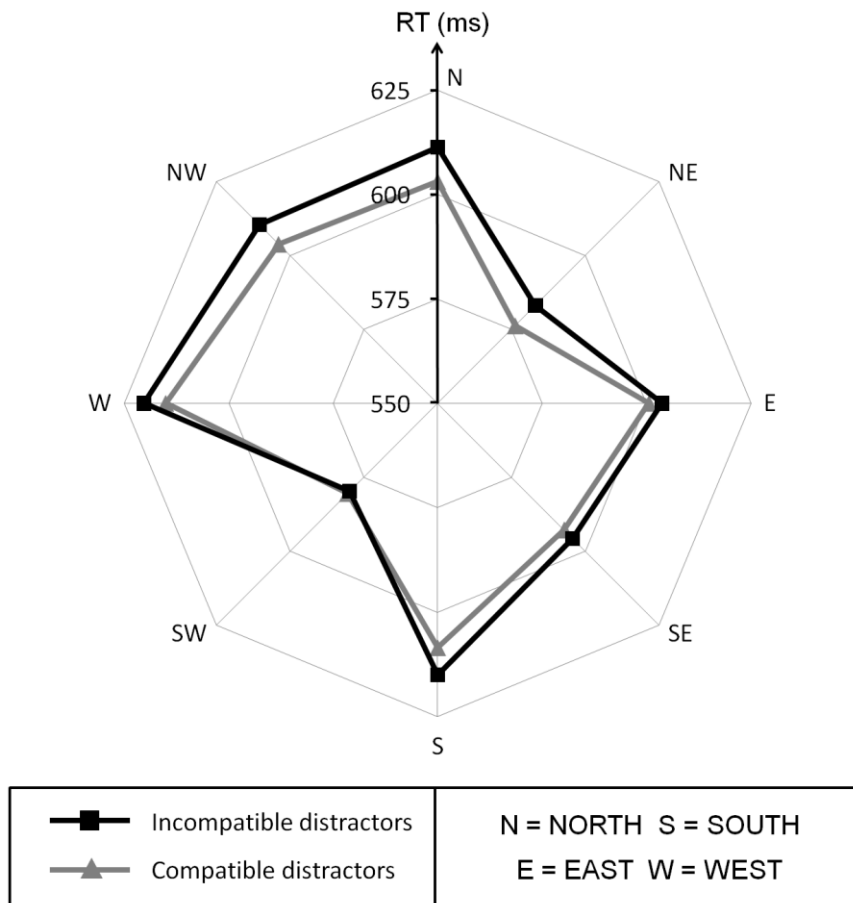
The results of this repeated-measures ANOVA showed that: (1) the effect of Compatibility (I. vs. C.) was significant ( $F(1,15) = 14.00, p = 0.002, \eta_p^2 = 0.483$ ), showing that the distractors generated significant *combined response-related interference*; (2) the effect of Separation was significant ( $F(1.9,28.6) = 4.59, p = 0.020, \eta_p^2 = 0.234$ ), showing that RTs (pooled across compatible- and incompatible-distractor conditions) varied with separation; and (3) the interaction between Compatibility (I. vs. C.) and Separation was significant ( $F(4,60) = 6.24, p < 0.001, \eta_p^2 = 0.294$ ), showing that *combined response-related interference* varied with separation.

Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was best explained by a combination of linear and quadratic trends (respectively  $F(1,15) = 11.13, p = 0.005, \eta_p^2 = 0.426$  and  $F(1,15) = 10.93, p = 0.005, \eta_p^2 = 0.421$ ; the cubic and quadratic trends had  $p$  values  $> 0.100$ ): *combined response-related interference* first decreased but then increased with increasing target-distractor separation (see Figure 10), consistent with a Mexican-hat profile of perceptual resources (Müller et al., 2005).

### *Effect of Target Location*

The main effect of Target Location was significant ( $F(7,105) = 16.74, p < 0.001, \eta_p^2 = 0.527$ ). Bonferroni-corrected pairwise comparisons showed that participants were significantly faster (at the 0.05 level) to respond to a North-East or a South-West target than to a North, East, South, West or North-West target (see Figure 11 for a representation of RTs at each target location). Target location did not interact with any other factor (Target Location x Compatibility (I. vs. C.):  $F(7,105) = 1.09, p = 0.374, \eta_p^2 = 0.068$ ; Target Location x Separation:  $F(7.8,116.3) = 1.53, p = 0.157, \eta_p^2 = 0.092$ ; Target Location x Compatibility (I. vs. C.) x Separation:  $F(28,420) = 0.72, p = 0.854, \eta_p^2 = 0.046$ ), suggesting that *incompatible-distractor response-related interference* as a function of separation described a similar Mexican-hat pattern for each target location.

EXPERIMENT 3: EFFECT OF TARGET LOCATION



**Figure 11**

*Experiment 3 – Effect of Target Location on latencies. The figure shows distractor-present mean latencies (in ms) as a function of target-distractor compatibility (compatible or incompatible) and target location (North, North-East, East, South-East, South, South-West, West or North-West). (▲) = compatible distractor; (■) = incompatible distractor.*

**Errors**

*Effects of Compatibility (I. vs. C.) and Separation*

The results of the first repeated-measures ANOVA showed that: (1) the effect of Compatibility (I. vs. C.) was significant ( $F(1,15) = 12.53, p = 0.003, \eta_p^2 = 0.455$ ),

showing that the distractors generated significant *combined response-related interference*; (2) the effect of Separation was significant ( $F(4,60) = 13,76, p < 0.001, \eta_p^2 = 0.478$ ) showing that errors (pooled across compatible- and incompatible-distractor conditions) varied with separation; and (3) the interaction between Compatibility (I. vs. C.) and Separation was significant ( $F(4,60) = 4.80, p = 0.002, \eta_p^2 = 0.242$ ), showing that *combined response-related interference* varied with separation.

Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was best explained by a combination of linear and quadratic trends (respectively  $F(1,15) = 6.58, p = 0.022, \eta_p^2 = 0.305$  and  $F(1,15) = 6.38, p = 0.023, \eta_p^2 = 0.298$ ; the cubic and quartic trends had  $p$  values  $> 0.100$ ). Thus, *combined response-related interference* first decreased but then increased with increasing target-distractor separation (see Figure 10), consistent with a Mexican-hat profile for the profile of perceptual resources (Müller et al., 2005).

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3.4,50.7) = 11.41, p < 0.001, \eta_p^2 = 0.432$ ). Bonferroni-corrected pairwise comparisons showed that participants made significantly fewer errors (at the 0.05 level) to respond to a North-East or a South-West target than to a North, East, South, West or North-West target.

On the other hand, Target Location interacted neither with Separation ( $F(28,420) = 1.13, p = 0.30, \eta_p^2 = 0.073$ ) nor with Compatibility (I. vs. C.;  $F(7,105) = 1.51, p = 0.173, \eta_p^2 = 0.091$ ), and the interaction between Target Location, Compatibility (I. vs. C.) and Separation was not significant either ( $F(28,420) = 1.23, p = 0.198, \eta_p^2 = 0.076$ ).

The non significance of the three-way interaction suggests that *combined response-related interference* as a function of separation described a similar pattern at each target location.

#### ***2.4.2.2 Comparison of incompatible-distractor with compatible-distractor RTs as a function of separation and hemifield of distractor presentation***

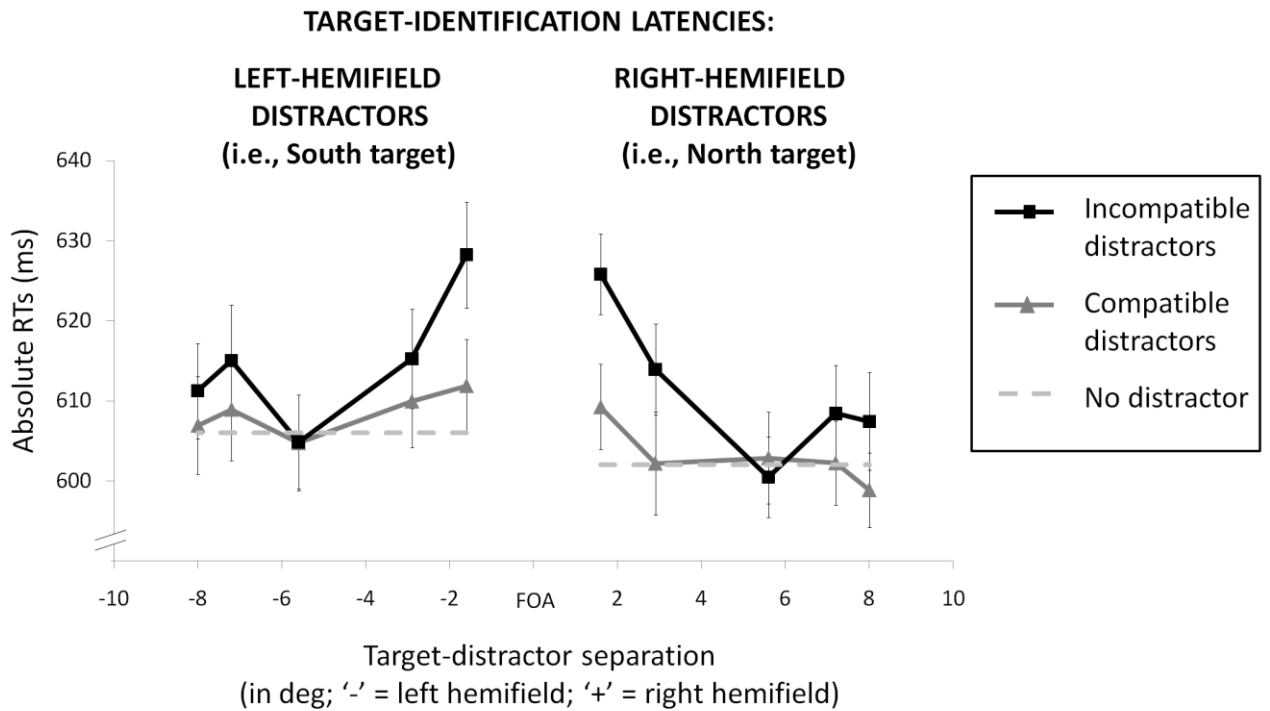
##### **Reaction times**

In this analysis, only the data obtained with North and South targets were analysed to test for the effect of Hemifield of Distractor Presentation, in addition to the effects of Compatibility (I. vs. C.) and Separation.

Neither the main effect of Hemifield of Distractor Presentation nor any of the interactions involving this factor was significant (Hemifield of Distractor Presentation:  $F(1,15) = 0.67$ ,  $p = 0.427$ ,  $\eta_p^2 = 0.043$ ; Hemifield of Distractor Presentation x Compatibility (I. vs. C.):  $F(1,15) = 0.11$ ,  $p = 0.743$ ,  $\eta_p^2 = 0.007$ ; Hemifield of Distractor Presentation x Separation:  $F(4,60) = 0.19$ ,  $p = 0.944$ ,  $\eta_p^2 = 0.012$ ; Hemifield of Distractor Presentation x Compatibility (I. vs. C.) x Separation:  $F(4,60) = 0.17$ ,  $p = 0.955$ ,  $\eta_p^2 = 0.011$ ). Thus, unlike in Experiment 2, the profile of perceptual resources was similar in the left and right hemifields (see Figure 12).



EXPERIMENT 3 : COMPARISON LEFT AND RIGHT HEMIFIELDS



**Figure 12**

*Experiment 3 – Effect of Hemifield of Distractor Presentation on latencies. The figure shows: (1) distractor-present mean latencies (in ms) as a function of target-distractor separation (in deg), target-distractor compatibility (compatible or incompatible) and hemifield of distractor presentation (left or right) – see solid lines; and (2) no-distractor mean latencies (in ms) as a function of hemifield of distractor presentation (left or right) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (FOA) = attended location.*

**Errors**

In this analysis, only the data obtained with North and South targets were analysed to test for the effect of Hemifield of Distractor Presentation, in addition to the effects of Compatibility (I. vs. C.) and Separation.

Neither the main effect of Hemifield of Distractor Presentation nor any of the interactions involving this factor was significant (Hemifield of Distractor Presentation:  $F(1,15) = 0.02$ ,  $p = 0.907$ ,  $\eta_p^2 = 0.001$ ; Hemifield of Distractor Presentation x Compatibility (I. vs. C.):  $F(1,15) = 0.71$ ,  $p = 0.412$ ,  $\eta_p^2 = 0.045$ ; Hemifield of Distractor Presentation x Separation:  $F(4,60) = 0.19$ ,  $p = 0.944$ ,  $\eta_p^2 = 0.012$ ; Hemifield of Distractor Presentation x Compatibility (I. vs. C.) x Separation:  $F(4,60) = 0.62$ ,  $p = 0.653$ ,  $\eta_p^2 = 0.039$ ). Thus, in the error data as well as in the RT data, Hemifield of Distractor Presentation did not affect the profile of perceptual resources.

### 2.4.3 Discussion

The results of Experiment 3 were consistent with those from Experiment 2 in that (1) the distractors generated significant *combined response-related interference* and (2) *combined response-related interference as a function of separation* described a Mexican-hat pattern. Müller et al.'s Mexican-hat finding can therefore be generalised to the more commonly used methodology of exogenously cueing the target location (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Yantis & Johnston, 1990).

In Experiment 3, as in Experiment 2, participants were slower with some target locations than others, but this did not have an effect on *combined response-related interference as a function of separation*. Moreover, unlike in Experiment 2, there was no effect of hemifield of distractor presentation. The profile of perceptual resources revealed in Experiment 3 was the same whether measured within the right or the left hemifield; the bottom of the Mexican-hat profile occurred around the same separation (5.6 deg) in both hemifield conditions. The profile was therefore similar to the one

measured in the *right* hemifield in Experiment 2 but it was more *defocused* than the profile measured in the *left* hemifield in Experiment 2 (compare Figures 7 and 10).

The origin of the absence of an effect of hemifield on the profile measured in Experiment 3 is not clear. It may be due to the use of an exogenous cue and/or the fact that we only sampled distractor locations removed from the target location in a clockwise direction. The experiments that follow retained the latter two features in the hope of minimising the effects of hemifield of distractor presentation on the profile. The use of an exogenous cue in subsequent experiments also made it unnecessary to track eye movements.

## **2.5 Discussion of Chapter 2**

The findings of this chapter supported Müller et al.'s finding (2005): the profile of perceptual resources was found to describe a Mexican-hat pattern in Experiments 2 and 3. This is compatible with previous findings obtained with the cue/probe paradigm supporting a Mexican-hat rather than a gradient profile of perceptual resources (Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotos, 2003; Hodgson et al., 1999; Hopf et al. 2006; Kristjansson & Nakayama, 2002; Mounts, 2000b; Müller et al., 2005; Pan & Eriksen, 1993; Schwartz, et al. 2005; Slotnick, Hopfinger, Klein, & Sutter, 2002). In the present experiments, the Mexican-hat finding was obtained when using a relatively low number of trials, when using different target locations, when using a target location that was both endogenously and exogenously defined, and when sampling both within and across visual hemifields. This suggests that, to observe a Mexican-hat profile with the flanker paradigm, it is not necessary to

follow Müller et al. (2005) and use a high number of trials and/or always use the same target location and/or only sample within the right hemifield and/or use an endogenously defined target location.

The results of Experiment 1 also showed that the Mexican-hat profile of perceptual resources could be revealed only when a sufficiently large range of separations was sampled. When the range of separation sampling was too limited, and separations only as large as 5.6 deg were indexed (in Experiment 1), we failed to reveal a Mexican-hat pattern. This may explain why previous flanker studies that sampled only a limited range of separations (e.g., Eriksen & St. James, 1986; Pan & Eriksen, 1993; these studies only sampled up to 1.5 deg) revealed a gradient rather than a Mexican-hat profile.

The findings obtained with another factor, namely, hemifield of distractor presentation, may also explain why previous studies revealed a gradient rather than a Mexican-hat profile. Indeed, it was found that, in Experiment 2, the profile of perceptual resources presented as being more focused in the left hemifield (with a bottom occurring around 2.9 deg) than in the right hemifield (with a bottom occurring around 5.6 deg). As a result, when the Mexican hats measured in the two hemifields were averaged, the resulting function resembled a gradient function (see Figure 6). This averaging process might explain why some flanker studies that did not control for the effect of hemifield of distractor presentation revealed a gradient pattern (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Yantis & Johnston, 1990).

The fact that, in Experiment 2, the profile of perceptual resources presented as being differently focused in the left and right hemifields may have been due to a rightward shift of perceptual resources due to decreased alertness (Manly, Dobler, Dodds, & George, 2005). This shift may have occurred in Experiment 2 and not in Experiment 3, because, in Experiment 2, the location of the target was always the same and endogenously defined whereas, in Experiment 3, it varied from trial to trial and was exogenously defined.

The last important finding of the present experiments is that, while the hemifield of distractor presentation changed the extent of focus of the profile of perceptual resources, the location of the target did not have such an effect (see Experiments 2 and 3). This null finding argues against the possibility that the Mexican-hat findings obtained in Experiments 2 and 3 (and also in Müller et al., 2005) resulted from irregularities in the visual field (see Introduction of this chapter). The results of Experiment 7 (see Chapter 3) further reinforces this conclusion.

## **2.6 Conclusions**

The results of the experiments of this chapter can be summarized as follows. Müller et al.'s (2005) finding that the profile of perceptual resources describes a Mexican-hat pattern was replicated. In order to be in a position to reveal such a profile, we had to sample sufficiently far from the attended location and, when we used a target location that was endogenously defined, we had to control for the hemifield of distractor presentation. Moreover, the results suggested that it is better to use a limited rather than an excessive number of trials per condition in order to avoid decreasing the power of the distractors to generate interference. Finally, using exogenous cueing did not prevent

us from showing a Mexican-hat profile. We took these elements into account in designing the experiments reported in the following chapters (i.e., Chapters 3, 4 and 5).

In the present experiments, we deliberately focused only on previous work using *combined response-related interference* to index the profile of perceptual resources. However, this profile has often been revealed using other indices and Chapter 3 tested whether these other indices measure the same separation function as *combined response-related interference* with a view to deciding on the best index (or indices).

# CHAPTER 3 – INDEXING PERCEPTUAL RESOURCES

## **3.1 Introduction: Three types of measures**

In Chapter 2, *combined response-related interference* as a function of separation was measured using Eriksen's flanker task (Eriksen & Hoffman, 1972, 1973) and was employed to index the profile of perceptual resources (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Müller et al., 2005; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990). It was found that the profile of perceptual resources described a Mexican-hat pattern: perceptual resources first decreased and then increased, before tailing off, with increasing separation from the attended location. This finding replicated that of Müller et al. (2005).

*Combined response-related interference* is not the only type of measure that has been used to index the profile of perceptual resources. In this chapter, we test three other types of measures that have been used for this purpose, namely, (1) *incompatible-distractor response-related interference* (isolated by comparing neutral-distractor performance with incompatible-distractor performance in the flanker task; see Chapter 1) as a function of separation, (2) *salience-related interference* (isolated by comparing no-distractor performance with neutral-distractor performance in the flanker task; see Chapter 1) as a function of separation, and (3) *performance at responding to a probe* (isolated in the cue/probe task; see Chapter 1) as a function of separation. There are

reasons to believe that these other types of measures may *not* index the profile of perceptual resources and, therefore, should *not* reveal the same Mexican-hat profile of perceptual resources as that obtained with *combined response-related interference*. We describe these reasons below before then addressing the possibility that the different indices agree.

### **3.1.1 Incompatible-distractor response-related interference**

The measure obtained by comparing neutral-distractor performance with incompatible-distractor performance is thought to isolate *incompatible-distractor response-related interference* (see Chapter 1). A concern is that this measure may contain residual *saliency-related interference* as, in certain circumstances, incompatible (and compatible) distractors can be predicted to be more salient than neutral distractors due to differences in their task-relatedness (Björk & Murray, 1977).<sup>11</sup> This index may therefore *not* reveal the same function as that revealed using *combined response-related interference*. This is because, unlike response-related interference, saliency-related interference might *not* measure the allocation of perceptual resources at the location of the distractor.

### **3.1.2 Saliency-related interference**

*Saliency-related interference*, obtained by comparing no-distractor performance with neutral-distractor performance (see Chapter 1), may index processes of divided, rather than selective, attention. When distractors are salient they may cause all or part of the perceptual resources present at the attended location to be reallocated to the distractor location. *Saliency-related interference* would index this process rather than (or in

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<sup>11</sup> See Footnote 3 (p34)



addition to) the perceptual resources originally present at the distractor location. The processes subserving *saliency-related interference* may be sensitive to the separation between the distractor and the target but in a different way from those subserving response-related interference (Mounts, 2000a, 2005; but see McCarley & Mounts, 2008): thus, the separation function extracted with *saliency-related interference* would be *different* from the Mexican-hat profile extracted using *combined response-related interference* (see Experiments 2 and 3, Chapter 2; Müller et al., 2005). This view is compatible with the findings of previous studies that have measured *saliency-related interference* as a function of separation (McCarley & Mounts, 2008; Mounts, 2000a, 2005, Mounts & Gavett, 2004; Mounts & Tomaselli, 2005); in these studies, *saliency-related interference* as a function of separation described a simple gradient pattern.

### **3.1.3 Performance at responding to a probe**

Just as salient distractors may cause attention to divide in the flanker task, probes may have the same effect in the cue/probe task (see Chapter 1). This is because, in this task, the profile of perceptual resources is indexed using *invalid* trials, namely, those trials in which the probe (i.e., the stimulus that is central to the task) does *not* occur at the attended location. It is possible that, in those invalid trials, the probe competes for perceptual resources that have been originally committed to the attended location, thus causing perceptual resources to divide between the attended and the probe location (Müller et al., 2005). This competition may rely on the saliency of the probe. The cue/probe paradigm would then index the division of perceptual resources rather than (or in addition to) the profile of perceptual resources around the cued location. If this hypothesis is true, the separation function extracted with the cue/probe task should be *different* from the Mexican-hat profile extracted using *combined response-related*

*interference* in the flanker task (see Experiments 2 and 3, Chapter 2; Müller et al., 2005).

In fact, to our knowledge, no cue/probe study has provided unequivocal evidence for a Mexican-hat profile. In other words, no cue/probe study has shown that performance at responding to a probe first decreases and then increases, before tailing off, with increasing separation from the attended location. Instead, numerous cue/probe studies have shown that performance at responding to a probe described an *inverted-gradient* profile that never decreased but only increased (before reaching a plateau or tailing off) with increasing separation from the attended location (Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Downing, 1988; Hodgson et al., 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Mounts 2000b ). Others have shown that performance at responding to a probe described a *gradient* profile that only *decreased* with increasing separation from the attended location (e.g., Dori & Henik, 2006; Downing, 1988; Handy et al., 1996; Henderson, 1991; Henderson & Macquistan, 1993; Shulman et al., 1985; Tsal, 1983; Williams, 1988). It is possible that these inconsistent findings reflect the fact that, in different cue/probe studies, the probe was more or less efficient at dividing attention (thus generating different functions of separation), for instance because it was more or less salient (Mounts, 2000a) or because the cue indicated the correct probe location with more or less validity (Eriksen & Yeh, 1985).

### **3.1.4 The possibility that the different indices agree**

On the other hand, it is possible that *incompatible-distractor response-related interference*, *salience-related interference* and *performance at responding to a probe* do

after all index the profile of perceptual resources. If a Mexican-hat profile of perceptual resources has not been obtained with these indices in previous studies, this may be due to the fact that, in these studies, some factors have caused changes in the focus of perceptual resources, causing the bottom of the Mexican hat to occur so close to, or so far from, the attended location as to make it impossible (or very difficult) to index all the parts of the Mexican-hat profile of perceptual resources (i.e., the initial decreasing arm, the subsequent increasing arm and the final decreasing arm; see Chapter 2). As argued in Chapter 2, factors that could have affected the extent of focus of perceptual resources in previous studies are, for instance, perceptual load, the availability (and deployment) of cognitive resources, and trait anxiety (see Chapters 1, 4 and 5).

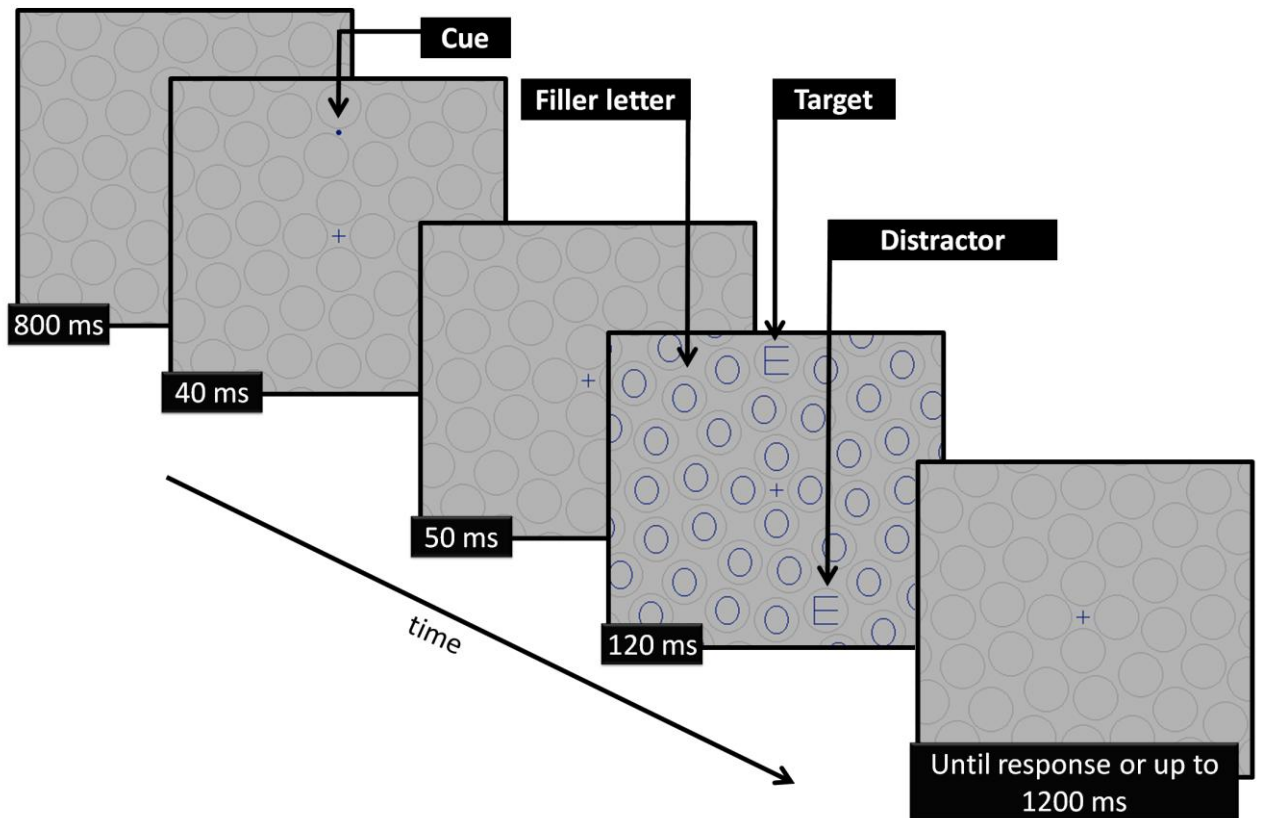
In sum, one should be able to measure a complete Mexican-hat profile when using *incompatible-distractor response-related interference*, *salience-related interference* or *performance at responding to a probe*, as long as the profile is neither too focused nor too defocused (e.g., when perceptual load is neither too high nor too low). The function of separation extracted with these three measures would then be *similar* to the Mexican-hat profile extracted with *combined response-related interference* (see Chapter 2; Müller et al., 2005). This was examined in the present experiments (see Experiments 4, 5 and 6). In addition, Experiment 7 tested whether the functions of separation obtained in Experiments 1 to 6 could not be explained by a confounding factor, namely, irregularities in the visual field.

### **3.2 EXPERIMENT 4: Comparison of different indices in the flanker task**

In Experiment 4, the participants performed a flanker task similar to the one used in Experiment 3 except that a neutral distractor (the letter ‘X’) was used in addition to compatible and incompatible distractors. In Experiment 4, distractor interference could thus be measured in three ways: (1) using *combined response-related interference* (obtained by comparing compatible-distractor with incompatible-distractor performance); (2) using *incompatible-distractor response-related interference* (obtained by comparing neutral-distractor with incompatible-distractor performance); and (3) using *saliency-related interference* (obtained by comparing no-distractor with neutral-distractor performance). It was tested whether the shapes of the profiles indexed using the three types of measures agreed and whether the bottoms of the three profiles occurred at similar separations.

Another difference between Experiments 3 and 4 was that placeholders and filler letters covered the whole screen rather than only an imaginary circle. This difference was introduced to test an alternative account for the Mexican hat pattern obtained in Experiments 2 and 3. This account invokes the fact that the separation condition that produced the least distractor interference was the only one in which a filler letter was presented on the shortest straight-line path between the target and distractor. If this fact explained the Mexican-hat pattern, then, when the screen was covered with placeholders and filler letters, distractor interference as a function of separation should no longer describe a Mexican hat.

#### EXPERIMENT 4: METHOD



**Figure 13**

*Experiment 4 - Method. A schematic representation of an experimental trial. In each trial, a target letter ('E' or 'F') occurred in the placeholder (always North, East, South or West) indicated by a 100%-valid exogenous cue. A distractor occurred in 90% of the trials at one of four possible target-distractor separations (1.8, 5.1, 7.7 and 9.0 deg, corresponding respectively to the first, third, fifth and seventh placeholder removed from the target placeholder in a clockwise direction around an imaginary circle of placeholders). The distractor could be compatible with the identity of the target (e.g., 'E' if the target was 'E'), incompatible with the identity of the target (e.g., 'F' if the target was 'E'), or neutral (i.e., 'X'). Participants signalled target identity ('E' or 'F', with a 2-AFC) while ignoring distractor ('E', 'F' or 'X') and filler letters ('O's). The figure illustrates a North 'E' target with a compatible 'E' distractor occurring at a separation of 9.0 deg.*

### **3.2.1 Method**

#### ***3.2.1.1 Design***

The design was a repeated-measures one in which target-distractor separation was manipulated (at controlled stimulus eccentricity) and the response-compatibility of distractors (compatible, incompatible or neutral) was also manipulated.

#### ***3.2.1.2 Participants***

14 participants from Goldsmiths College (5 females; 2 left-handed; mean age 22.3 yr; age range 18 to 39 yr; see Appendix 5) with reported normal or corrected-to-normal vision took part in the experiment in exchange for course credits. They were all naïve as to the aim of the study.

#### ***3.2.1.3 Stimuli and procedure***

Participants were instructed to make a two-alternative forced-choice (2-AFC) identification of a target letter, 'E' or 'F', by pressing one of two keys on an English keyboard (using two fingers of their dominant hand; the 'L' key was used to answer 'E' and the ';' key to answer 'F') as quickly but as accurately as possible while ignoring a distractor letter and filler letters. The distractor was always the letter 'E', 'F' or 'X', and the filler letters were always the letter 'O'. The stimulus letters (target, distractor and filler letters) were all of the same dark blue (CIE  $x = 0.15$ ,  $y = 0.08$  and  $L = 0.44$  cd/m<sup>2</sup>; the same dark blue as in Experiments 1 to 3) and subtended 0.9 by 1.1 deg (as compared to 0.70 by 0.80 deg in Experiments 1 to 3).

A cross (subtending 0.50 deg square; the fixation cross) and 186 outline circles (of radius 0.85 deg; the stimulus-letter placeholders) were present on the screen throughout the experiment (see Figure 13). They were dark grey (CIE  $x = 0.29$ ,  $y = 0.32$  and  $L = 4.67$  cd/m<sup>2</sup>; rather than dark blue in Experiments 1 to 3) against a light grey background (CIE  $x = 0.28$ ,  $y = 0.30$  and  $L = 13.70$  cd/m<sup>2</sup>; the background was lighter than in Experiments 1 to 3, where its luminance was of 3.71 cd/m<sup>2</sup>). The fixation cross indicated where participants had to remain fixated. Among the 186 placeholders, 16 placeholders were arranged around an *imaginary circle* of radius 4.60 deg and defined the possible locations of the target and distractor letters. Around the imaginary circle, each placeholder circle was separated from its neighbour by 1.80 deg (centre to centre) so that adjacent circles were almost touching.

On each trial, a dot cue (of radius 0.08 deg and the same dark blue as the stimulus letters) was presented 1.40 deg central of the centre of either the ‘North’, ‘East’, ‘South’ or ‘West’ placeholder on the imaginary circle. The target letter always appeared inside the placeholder that was cued (only 4 target locations, rather than 8 in Experiment 3, were used to limit the number of conditions) and 184 filler letters and one distractor letter, or 185 filler letters and no distractor letter, appeared inside the remaining placeholders. When a distractor letter was presented, it always appeared on the imaginary circle, inside a placeholder separated from the target placeholder (centre to centre) by 1.8, 5.1, 7.7 or 9.0 deg (the four target-distractor separations) in a clockwise direction. These separations corresponded to presenting distractor letters in the placeholders that were respectively one, three, five and seven placeholders removed (around the circle of placeholders) from the target placeholder (see Figure 13). The distractor was response-incompatible with the target (so that, for example, it was ‘E’ if

the target was 'F') on 28% of trials, it was response-compatible with the target (so that it was 'F' if the target was 'F') on 28% of trials and it was response-neutral (it was the letter 'X') on another 28% of trials. In the remaining 16% of trials, no distractor was presented and only the target appeared among filler letters ('O's). The latter trials constituted the no-distractor baseline condition.

Each trial started with a screen containing the fixation cross and 186 empty placeholders (for 800 ms). This was followed by the presentation of the cue for 40 ms. After the offset of the cue and a delay of 50 ms, the stimulus letters were presented in their respective placeholders for 120 ms (instead of 100 ms in Experiment 3). A wrong keypress for target identification was signalled by a soft beep. The next trial began 200 ms after a participant had responded or after 1200 ms had elapsed.

Experiment 4 lasted around 1 hour. It consisted of 1456 trials, preceded by 60 practice trials. Every 73 trials (about every 2 minutes) there were short (participant-terminated) breaks. The different conditions were presented intermixed and in randomized order.

#### ***3.2.1.4 Fixation control***

Like in Experiment 3, participants' gaze was not monitored with an eye tracker since only 210 ms separated the onset of the cue from the offset of the target and it is generally accepted that the planning and execution of eye movements requires approximately 250 ms (Darrien, Herd, Starling, Rosenberg & Morrison, 2001; Henderson, Pollatsek & Rayner, 1987).



### 33.2.2 Results

We analyzed both the speed and accuracy of forced-choice target-identification ('E' vs. 'F') responses. Response latencies (RTs) were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented an average of 91.8% of the latencies overall.

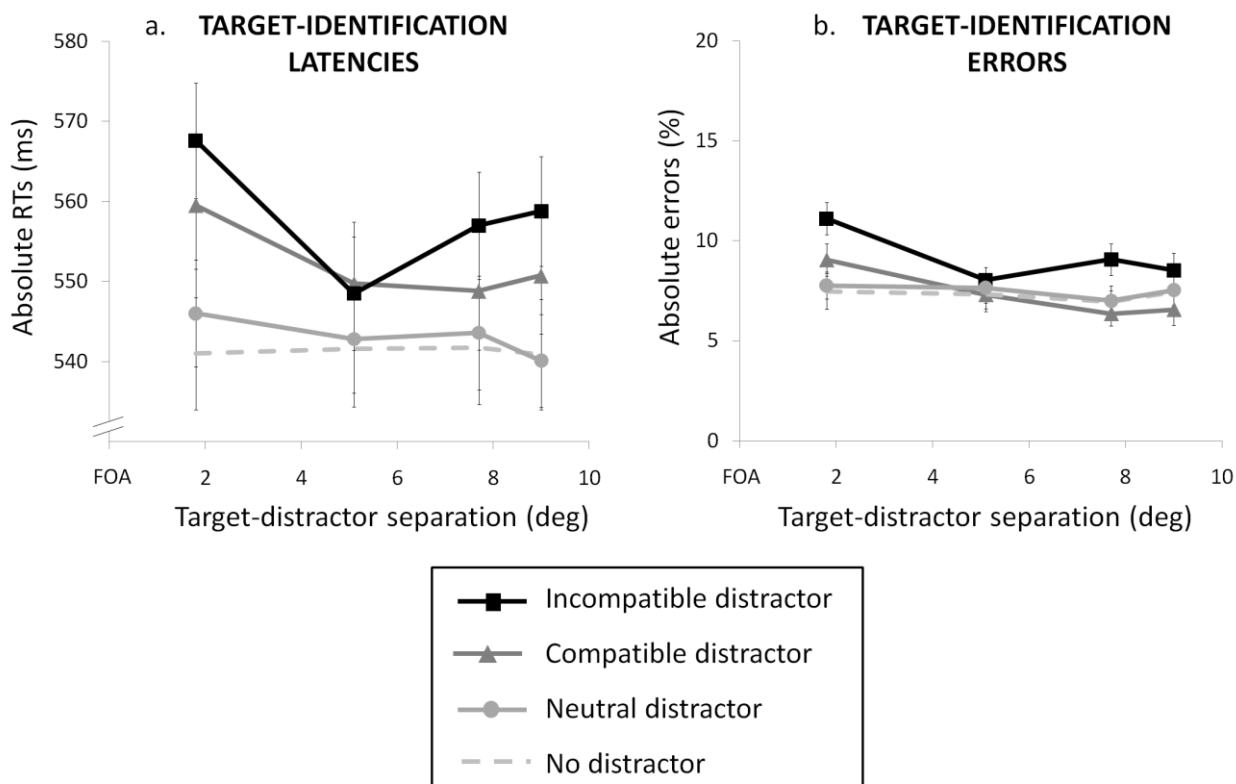
For each participant, mean RTs (and error percentages) were calculated for incompatible-distractor, compatible-distractor and neutral-distractor (distractor-present) trials at the four target locations (North, East, South and West) and at the four target-distractor separations (1.8, 5.1, 7.7 and 9.0 deg; see Figure 14). Moreover, for each participant, no-distractor (i.e. filler-letters-only) RTs (and errors) were randomly separated into four bins for each of the four target locations, and mean RTs (and error percentages) were calculated for each bin. The four bins were used as baselines to match the four target-distractor separations.

Four analyses were performed on mean RTs (and error percentages). Each of the first three analyses compared performance obtained with one type of distractor with that obtained with another type (which equated to subtracting performance obtained with one type of distractor from that obtained with another type) as a function of separation (and target location). Specifically, the first analysis compared *incompatible*-distractor with *compatible*-distractor performance as a function of separation (and target location); the second analysis compared *incompatible*-distractor with *neutral*-distractor performance as a function of separation (and target location); and the third analysis compared *neutral*-distractor with *no*-distractor performance as a function of separation

(and target location). Each of these three comparisons equated to isolating one type of distractor interference, respectively *combined response-related interference*, *incompatible-distractor response-related interference*, and *saliency-related interference* (see Chapter 1: General Introduction), and to testing whether the interference isolated was significant *across* separations (and target locations), *and* whether this interference was significantly *modulated* with target-distractor separation (and with target location). Where interference was modulated with separation, polynomial trends were applied to determine the shape of the interference function of separation.

The fourth analysis compared the shapes of the interference functions of separation obtained in the first three analyses. Where there was a significant difference between these shapes (i.e., where there was an interaction between the *type* of interference and the effect of *separation*), it was investigated whether this difference was explained because one function was more *spatially focused* than the others or, alternatively, whether the functions were equally focused but one function was *steeper* than the others (i.e., one type of interference was larger than the other types at some separations but not others).

## EXPERIMENT 4: RESULTS



**Figure 14**

*Experiment 4. Latencies and errors. The figure shows: (1) distractor-present mean latencies (in ms) and error percentages (in %) as a function of target-distractor separation (in deg) and target-distractor compatibility (compatible, incompatible or neutral) – see solid lines; and (2) no-distractor mean latencies (in ms) and error percentages (in %) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location.*

### ***3.2.2.1 Comparison of incompatible- with compatible-distractor RTs as a function of separation and target location***

#### **Reaction times**

This analysis compared *incompatible*-distractor and *compatible*-distractor RTs as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Compatibility (I. vs. C.), Separation (between target and distractor; 1.8, 5.1, 7.7 or 9.0 deg of separation) and Target Location (North, East, South or West) on target-identification RTs. In this analysis, we were particularly interested to see whether (1) the main effect of Compatibility (I. vs. C.) was significant, which would indicate that distractors generated significant *combined response-related interference* (and therefore that distractor locations were allocated significant perceptual resources; see Chapter 1: General Introduction), and whether (2) the interaction between the effects of Compatibility (I. vs. C.) and Separation was significant, which would indicate that *combined response-related interference* varied with separation. If the interaction between the effects of Compatibility (I. vs. C.) and Separation was found to be significant (in other words, if the interference function of separation was found *not to be flat*), the shape of the interference function of separation would be examined using polynomial trends, thus indexing the spatial profile of perceptual resources (see Chapter 2).

#### ***Effects of Compatibility (I. vs. C.) and Separation***

The repeated-measures ANOVA showed that the main effects of both Compatibility (I. vs. C.) and Separation were significant (respectively,  $F(1,13) = 5.06$ ,  $p = 0.042$ ,  $\eta_p^2 = 0.280$  and  $F(3,39) = 9.62$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.425$ ), and the interaction between

Compatibility (I. vs. C.) and Separation was marginally significant ( $F(3,39) = 2.54$ ,  $p = 0.070$ ,  $\eta_p^2 = 0.164$ ). These findings showed there was significant *combined response-related interference* and that this interference varied with separation. Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was explained by a cubic trend ( $F(1,13) = 6.49$ ,  $p = 0.024$ ,  $\eta_p^2 = 0.333$ ; the linear and quadratic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile (see Figure 14) and not with a gradient profile.

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,39) = 7.47$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.365$ ). Bonferroni-corrected pairwise comparisons showed that participants were significantly slower (at the 0.05 level) to respond to North targets than to East, South and West targets. On the other hand, Target Location did not interact with Compatibility (I. vs. C.) or Separation (respectively,  $F(3,39) = 1.56$ ,  $p = 0.215$ ,  $\eta_p^2 = 0.107$  and  $F(9,117) = 0.90$ ,  $p = 0.525$ ,  $\eta_p^2 = 0.065$ ) and the three-way interaction between Target Location, Compatibility (I. vs. C.) and Separation was not significant either ( $F(9,117) = 0.33$ ,  $p = 0.962$ ,  $\eta_p^2 = 0.025$ ), showing that *combined response-related interference* as a function of separation described a similar Mexican-hat pattern at each target location.

#### **Errors**

This analysis compared *incompatible*-distractor and *compatible*-distractor errors as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Compatibility (I. vs. C.), Separation and Target Location on target-identification errors.

### *Effects of Compatibility (I. vs. C.) and Separation*

The repeated-measures ANOVA showed that: (1) the effect of Compatibility (I. vs. C.) was marginally significant ( $F(1,13) = 3.86, p = 0.071, \eta_p^2 = 0.229$ ), showing that there was some *combined response-related interference* in errors; and (2) the effect of Separation was significant ( $F(3,39) = 5.70, p = 0.002, \eta_p^2 = 0.305$ ), showing that errors (pooled across compatible- and incompatible-distractor conditions) varied with separation; but (3) the interaction between Compatibility (I. vs. C.) and Separation was not significant ( $F(3,39) = 0.78, p = 0.514, \eta_p^2 = 0.056$ ), showing that *combined response-related interference* in errors did not significantly vary with separation.

### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,39) = 10.57, p < 0.001, \eta_p^2 = 0.448$ ). Bonferroni-corrected pairwise comparisons showed that participants made significantly more errors ( $p < 0.050$ ) to respond to North than South or West targets. On the other hand, Target Location did not interact with either Compatibility (I. vs. C.) or Separation (Target Location x Compatibility:  $F(3,39) = 0.07, p = 0.976, \eta_p^2 = 0.005$ ; Target Location x Separation:  $F(9,117) = 1.78, p = 0.079, \eta_p^2 = 0.121$ ; Target Location x Compatibility x Separation:  $F(9,117) = 1.84, p = 0.068, \eta_p^2 = 0.124$ ).

### ***3.2.2.2 Comparison of incompatible- with neutral-distractor RTs as a function of separation and target location***

## **Reaction times**

This analysis compared *incompatible*-distractor and *neutral*-distractor RTs as a function of separation using a repeated-measures ANOVA. This analysis tested for the effects of three factors, namely, Compatibility (Incompatible vs. Neutral distractor, or I. vs. N.), Separation, and Target Location on target-identification RTs. In this analysis, we were interested in related questions to those in the first analysis. Namely, we wanted to see whether (1) the effect of Compatibility (I. vs. N.) was significant, which would indicate that distractors generated significant *incompatible-distractor response-related interference* (see Chapter 1: General Introduction), and whether (2) the interaction between the effects of Compatibility (I. vs. N.) and Separation was significant, which would indicate that *incompatible-distractor response-related interference* varied with separation. If the latter was found to be the case, the shape of the interference function of separation would be examined using polynomial trends to index the profile of perceptual resources.

### *Effects of Compatibility (I. vs. N.) and Separation*

The repeated-measures ANOVA showed that the main effects of both Compatibility (I. vs. N.) and Separation were significant (respectively,  $F(1,13) = 47.71$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.786$  and  $F(3,39) = 6.30$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.326$ ), and the interaction between Compatibility (I. vs. N.) and Separation was also significant ( $F(3,39) = 3.27$ ,  $p = 0.031$ ,  $\eta_p^2 = 0.201$ ). These findings showed there was significant *incompatible-distractor response-related interference* and that this interference varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor response-related interference* as a function of separation was explained by a quadratic trend ( $F(1,13) = 14.24$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.523$ ; the linear and cubic trends had  $p$  values  $>$

0.100). This finding was once again consistent with a Mexican-hat profile and not with a gradient profile.

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,39) = 9.66, p < 0.001, \eta_p^2 = 0.426$ ). Bonferroni-corrected pairwise comparisons showed that participants were significantly slower (at the 0.05 level) to respond to North targets than to East, South and West targets. On the other hand, Target Location did not interact with Compatibility (I. vs. N.) or Separation (respectively,  $F(3,39) = 1.39, p = 0.261, \eta_p^2 = 0.096$  and  $F(9,117) = 0.66, p = 0.742, \eta_p^2 = 0.048$ ) and the three-way interaction between Target Location, Compatibility (I. vs. C.) and Separation was not significant either ( $F(9,117) = 0.92, p = 0.507, \eta_p^2 = 0.066$ ), showing that *Incompatible-distractor response-related interference* as a function of separation described a similar Mexican-hat pattern at each target location.

#### **Errors**

This analysis compared *incompatible-distractor* and *neutral-distractor* errors as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Compatibility (I. vs. N.), Separation and Target Location on target-identification errors.

#### *Effects of Compatibility (I. vs. N.) and Separation*

The repeated-measures ANOVA showed that: (1) the effect of Compatibility (I. vs. N.) was significant ( $F(1,13) = 9.05, p = 0.010, \eta_p^2 = 0.410$ ), showing that there was



significant *incompatible-distractor response-related interference* in errors; but (2) the effect of Separation was not significant ( $F(3,39) = 1.82, p = 0.160, \eta_p^2 = 0.123$ ), showing that errors (pooled across compatible- and incompatible-distractor conditions) did not vary with separation; and (3) the interaction between Compatibility (I. vs. N.) and Separation was not significant ( $F(3,39) = 2.12, p = 0.113, \eta_p^2 = 0.140$ ), showing that *incompatible-distractor response-related interference* in errors did not significantly vary with separation.

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,39) = 10.37, p < 0.001, \eta_p^2 = 0.444$ ). Bonferroni-corrected pairwise comparisons showed that participants made significantly more errors ( $p < 0.050$ ) to respond to North than South or West targets. On the other hand, Target Location did not interact with either Compatibility (I. vs. N.) or Separation (Target Location x Compatibility:  $F(3,39) = 0.95, p = 0.427, \eta_p^2 = 0.068$ ; Target Location x Separation:  $F(4.2,55.3) = 2.38, p = 0.059, \eta_p^2 = 0.155$ ; Target Location x Compatibility x Separation:  $F(5.5,71.9) = 1.74, p = 0.130, \eta_p^2 = 0.118$ ).

### ***3.2.2.3 Comparison of neutral- with no-distractor RTs as a function of separation and target location***

#### **Reaction times**

This analysis compared *neutral*-distractor and *no*-distractor RTs as a function of separation and target location using a repeated-measures ANOVA. This analysis tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation, and Target Location on target-identification RTs. In this analysis, we were interested in related questions to those in the first two analyses. Namely, we wanted to see whether (1) the effect of Presence of Neutral Distractor was significant, which would indicate that distractors generated significant *saliency-related interference* (see Chapter 1: General Introduction), and whether (2) the interaction between the effects of Presence of Neutral Distractor, and Separation was significant, which would indicate that *saliency-related interference* varied with separation. If the latter was found to be the case, the shape of the interference function of separation would be examined using polynomial trends to index the profile of perceptual resources.

#### *Effects of Presence of Neutral Distractor, and Separation*

The repeated-measures ANOVA showed that: (1) the effect of Presence of Neutral Distractor was not significant ( $F(1,13) = 0.58, p = 0.461, \eta_p^2 = 0.042$ ); (2) the effect of Separation was not significant ( $F(3,39) = 0.71, p = 0.555, \eta_p^2 = 0.05$ ); and (3) the interaction between Presence of Neutral Distractor, and Separation was not significant ( $F(3,39) = 0.73, p = 0.541, \eta_p^2 = 0.053$ ) either. In other words, there was no evidence that neutral distractors generated *saliency-related interference*, nor that *saliency-related interference* could be used to measure the profile of perceptual resources.

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,39) = 7.31, p = 0.001, \eta_p^2 = 0.360$ ). Bonferroni-corrected pairwise comparisons showed that participants were

significantly slower (at the 0.05 level) to respond to North targets than to East, South and West targets. On the other hand, Target Location did not interact with Presence of Neutral Distractor, or Separation (Target Location x Presence of Neutral Distractor:  $F(3,39) = 0.04$ ,  $p = 0.988$ ,  $\eta_p^2 = 0.003$ ; Target Location x Presence of Neutral Distractor:  $F(9,117) = 0.73$ ,  $p = 0.679$ ,  $\eta_p^2 = 0.053$ ; Target Location x Presence of Neutral Distractor x Separation:  $F(9,117) = 0.31$ ,  $p = 0.972$ ,  $\eta_p^2 = 0.023$ ).

### **Errors**

This analysis compared *neutral*-distractor and *no*-distractor errors as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation and Target Location on target-identification errors.

#### *Effects of Presence of Neutral Distractor and Separation*

The results of the repeated-measures ANOVA showed that: (1) the effect of Presence of Neutral Distractor was not significant ( $F(1,13) = 0.05$ ,  $p = 0.824$ ,  $\eta_p^2 = 0.004$ ); (2) the effect of Separation was not significant ( $F(3,39) = 0.48$ ,  $p = 0.699$ ,  $\eta_p^2 = 0.036$ ); and (3) the interaction between Presence of Neutral Distractor and Separation was not significant either ( $F(3,39) = 0.02$ ,  $p = 0.995$ ,  $\eta_p^2 = 0.002$ ). In other words, there was no evidence for the presence of *salience-related interference* in errors.

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,39) = 3.08$ ,  $p = 0.038$ ,  $\eta_p^2 = 0.192$ ). Bonferroni-corrected pairwise comparisons showed that participants made significantly more errors ( $p < 0.050$ ) to respond to North than West targets. On the

other hand, Target Location did not interact with Presence of Neutral Distractor or Separation (Target Location x Presence of Neutral Distractor:  $F(3,39) = 0.20, p = 0.894, \eta_p^2 = 0.015$ ; Target Location x Separation:  $F(9,117) = 1.28, p = 0.256, \eta_p^2 = 0.090$ ; Target Location x Presence of Neutral Distractor x Separation:  $F(9,117) = 1.23, p = 0.283, \eta_p^2 = 0.087$ ).

### ***3.2.2.4 Comparison of the interference functions of separation***

#### **Reaction times**

The final analysis tested further the *interference* data measured in the previous analyses. As there was no significant interference and no modulation of interference by separation in the last analysis, the data from this analysis were not included; only the data from the first two analyses were tested. Moreover, as there was no significant effect of Target Location on distractor interference, the effect of this factor was not tested. We were interested to see whether (1) one type of interference was larger across separations than the other, and whether (2) the functions of separation measured with the two types of interference described the same shape.

In order to perform this comparison, the interference functions from the first two analyses were extracted by subtracting the relevant distractor RTs from each other at each separation: *combined response-related interference* as a function of separation was obtained by subtracting compatible-distractor from incompatible-distractor RTs at each separation, and *incompatible-distractor response-related interference* as a function of separation was obtained by subtracting neutral-distractor from incompatible-distractor RTs at each separation. The two functions were compared using a repeated-measures

ANOVA which tested for the effects of two factors, namely, Type of Interference (i.e., *combined or incompatible-distractor response-related interference*) and Separation.

The results of the ANOVA showed that the effect of Type of Interference was significant ( $F(1,13) = 8.37, p = 0.013, \eta_p^2 = 0.392$ ). Thus, *incompatible-distractor response-related interference* was larger across separations than *combined response-related interference*. The effect of Separation was also significant ( $F(3,39) = 3.90, p = 0.016, \eta_p^2 = 0.231$ ) but the interaction between Type of Interference and Separation was not significant ( $F(3,39) = 0.96, p = 0.422, \eta_p^2 = 0.069$ ). The absence of significant interaction means that the functions of separation measured with *incompatible-distractor response-related interference* and *combined response-related interference* described similar patterns and the bottoms of these functions occurred at similar separations.

### **Errors**

As none of the types of interference in errors significantly varied with separation, the fourth analysis was not performed on errors.

### **3.2.3 Discussion**

In Experiment 4, participants were tested on an adaptation of Eriksen's flanker task (Eriksen & Hoffman, 1972, 1973), in order to measure at four different separations from the attended location: (1) the combined response-related interference of compatible and incompatible distractors, (2) the response-related interference of incompatible distractors, and (3) the salience-related interference of neutral distractors.

The first important finding from this experiment was that *combined* and *incompatible-distractor response-related interference* were significant and they first decreased but then increased with increasing separation, describing a Mexican-hat pattern (see Figure 14). Experiment 4 therefore confirmed Müller et al.'s result (2005) and the results of Experiments 2 and 3 that the profile of perceptual resources is shaped like a Mexican hat. It also disconfirmed the proposition outlined in the Introduction to this experiment that the Mexican-hat pattern observed in previous experiments could be explained by the fact that the separation condition that produced the least distractor interference was the only one in which a filler letter was presented on the shortest straight-line path between the target and distractor.

Another important finding of Experiment 4 was that neutral distractors did not generate significant *saliency-related interference* and it was therefore not possible to test whether this type of interference can be used to index the profile of perceptual resources in the same way as response-related interference. The absence of *saliency-related interference* from neutral distractors was probably the result of a reduction in the *stimulus-driven* saliency of these distractors due to the filler letters that surrounded and masked them.

Compatible distractors, unlike neutral distractors, *would* appear to have generated substantial *saliency-related interference* (they increased RTs overall; see Figure 14) which was probably the result of the presence of additional *task-driven* saliency for compatible distractors compared to neutral distractors (as in Experiment 1, see Chapter 2). Given that compatible distractors generated substantial saliency-related interference, there is no reason why incompatible distractors should not also have done so. This

being the case, the comparison between incompatible-distractor and neutral-distractor performance (referred to above) should not have provided the pure measure of response-related interference often assumed. Yet, the same function of separation was obtained with this measure (that arguably combined salience-related and response-related interference) as with *combined response-related interference* (which isolates pure response-related interference). This finding suggests that (1) salience-related interference, just like response-related interference, indexes the allocation of perceptual resources and (2) *incompatible-distractor response-related interference* can be used to index perceptual resources (e.g., Kramer et al., 1994; Lavie, 1995; Lavie & de Fockert, 2003).

In conclusion, the findings of Experiment 4 confirmed that the profile of perceptual resources can be indexed using either *combined* or *incompatible-distractor response-related interference* and that this profile is shaped like a Mexican hat (Müller et al., 2005). On the other hand, the findings of Experiment 4 did not provide *direct* evidence that the profile of perceptual resources can be indexed using *salience-related interference* from neutral distractors. It is likely that neutral distractors were not sufficiently salient in Experiment 4. Experiment 5 was an attempt to measure *salience-related interference* with neutral distractors by increasing *stimulus-driven* distractor salience. This was done by using similar displays to those in Experiment 4, except omitting placeholders and filler letters.

### **3.3 EXPERIMENT 5: Comparison of different indices in the flanker task with increased salience of distractors**

As well as omitting placeholders and filler letters, Experiment 5 used only two target locations (North and South) to limit the number of trials and one additional separation to increase the density of separation sampling.

In Experiment 5, like in Experiment 4, distractor interference was measured in three ways: (1) using *combined response-related interference* (obtained by comparing compatible-distractor with incompatible-distractor performance); (2) using *incompatible-distractor response-related interference* (obtained by comparing neutral-distractor with incompatible-distractor performance); and (3) using *saliency-related interference* (obtained by comparing no-distractor with neutral-distractor performance).

### **3.3.1 Method**

#### ***3.3.1.1 Design***

The design was a repeated-measures one in which target-distractor separation was manipulated (at controlled stimulus eccentricity) and the response-compatibility of distractors (compatible, incompatible or neutral) was also manipulated.

#### ***3.3.1.2 Participants***

15 participants from Goldsmiths College (11 females; 1 left-handed; mean age 22.5 yr; age range 19 to 30 yr; see Appendix 6) with reported normal or corrected-to-normal vision took part in the experiment in exchange for course credits. They were all naïve as to the aim of the study.

#### ***3.3.1.3 Stimuli and procedure***



The same stimuli and procedure were used as in Experiment 4, except for the following three differences: (1) placeholders and filler letters were no longer present (the removal of filler letters and placeholders meant that a target and a distractor were the only stimuli presented in each display, except for the presence of the fixation cross), (2) the target only ever occurred at the North and South locations, and (3) one more target-distractor separation was tested, yielding five target-distractor separations (i.e., 1.8, 3.5, 5.1, 7.7 and 9.0 deg).

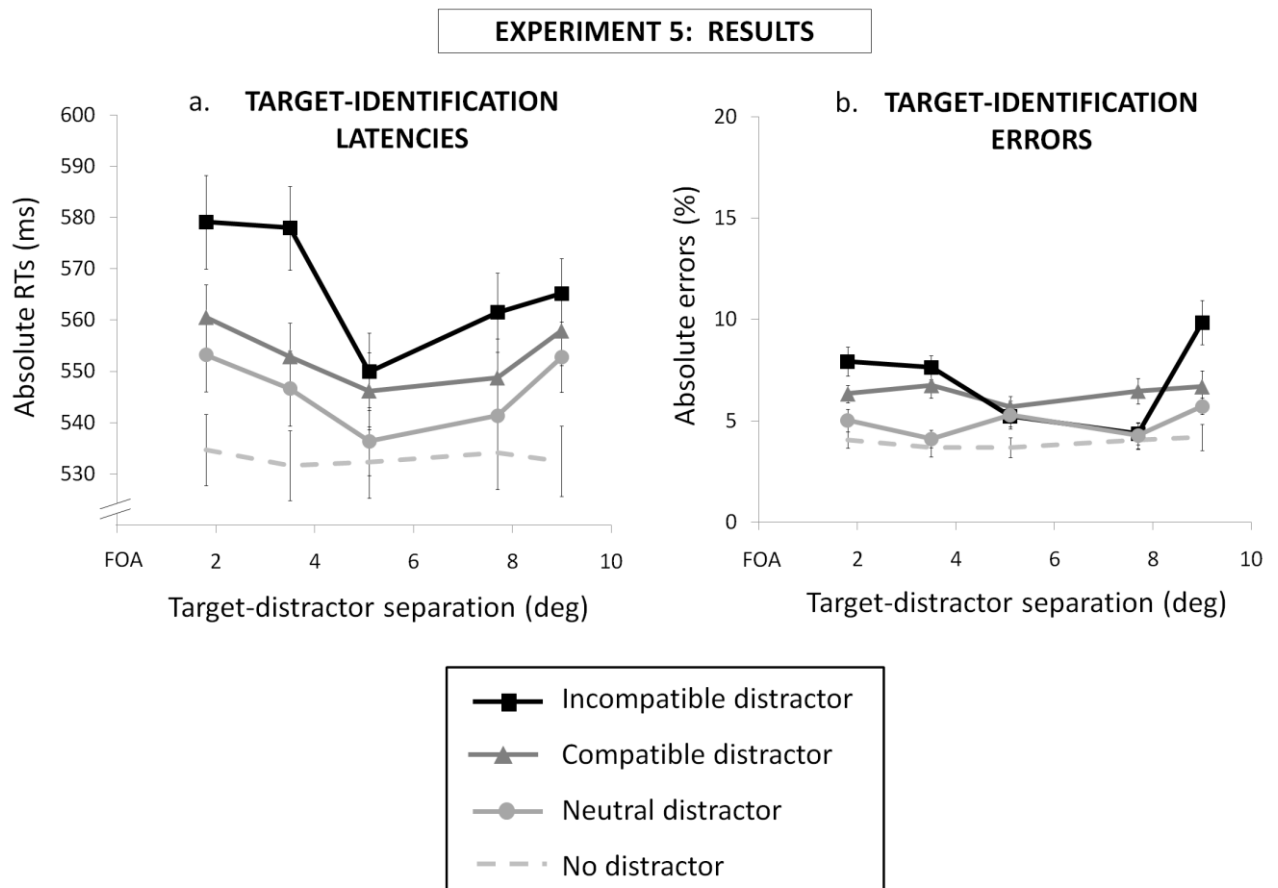
Experiment 5 lasted around 45 minutes. It consisted of 1024 trials, preceded by 60 practice trials. Every 65 trials (about every 2 minutes) there were short (participant-terminated) breaks. Trials from the different conditions were presented intermixed and in randomized order.

### **3.3.2 Results**

We analyzed both the speed and accuracy of forced-choice target-identification ('E' vs. 'F') responses (see Figure 15). Latencies were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented an average of 93.2% of the latencies overall.

For each participant, mean RTs (and error percentages) were calculated for incompatible-distractor, compatible-distractor and neutral-distractor (distractor-present) trials at the four target locations (North, South, East and West) and at the five target-distractor separations (1.8, 3.5, 5.1, 7.7 and 9.0 deg; see Figure 15). Moreover, for each participant, no-distractor (i.e. filler-letters-only) RTs (and errors) were randomly

separated into five bins at each of the four target locations, and mean RTs (and error percentages) were calculated for each bin. The bins were used as baselines to match the five target-distractor separations. The same four analyses were performed as in Experiment 4.



**Figure 15**

*Experiment 5. Latencies and errors. The figure shows: (1) distractor-present mean latencies (in ms) and error percentages (in %) as a function of target-distractor separation (in deg) and target-distractor compatibility (compatible, incompatible or neutral) – see solid lines; and (2) no-distractor mean latencies (in ms) and error percentages (in %) – see dashed lines. Error bars depict  $\pm 0.5$  SEM. ( $\blacktriangle$ ) = compatible distractor; ( $\blacksquare$ ) = incompatible distractor; ( $\bullet$ ) = neutral distractor; (FOA) = attended location.*

### ***3.3.2.1 Comparison of incompatible- with compatible-distractor RTs as a function of separation and target location***

#### **Reaction Times**

This analysis compared *incompatible*-distractor and *compatible*-distractor RTs as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Compatibility (I. vs. C.), Separation and Target Location on target-identification RTs.

#### *Effects of Compatibility (I. vs. C.) and Separation*

The main effects of both Compatibility (I. vs. C.) and Separation were significant (respectively,  $F(1,14) = 15.18$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.520$  and  $F(4,56) = 8.89$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.388$ ) and the interaction between Compatibility (I. vs. C.) and Separation was significant ( $F(4,56) = 2.61$ ,  $p = 0.045$ ,  $\eta_p^2 = 0.157$ ). These findings show that there was significant *combined response-related interference* and that this interference varied with separation. Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was explained by a quartic trend ( $F(1,14) = 4.50$ ,  $p = 0.052$ ,  $\eta_p^2 = 0.243$ ; the linear, quadratic and cubic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile (as quartic trends, just like quadratic and cubic trends, reveal the presence of an increasing arm in the function of separation).

#### *Effect of Target Location*

The main effect of Target Location was not significant ( $F(1,14) = 3.91$ ,  $p = 0.068$ ,  $\eta_p^2 = 0.218$ ). Neither were any interactions involving this factor (Target Location x

Compatibility:  $F(1,14) = 0.44$ ,  $p = 0.520$ ,  $\eta_p^2 = 0.030$ ; Target Location x Separation:  $F(4,56) = 1.10$ ,  $p = 0.368$ ,  $\eta_p^2 = 0.073$ ; Target Location x Compatibility x Separation:  $F(4,56) = 1.99$ ,  $p = 0.109$ ,  $\eta_p^2 = 0.124$ ).

## **Errors**

This analysis compared *incompatible*-distractor and *compatible*-distractor errors as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Compatibility (I. vs. C.), Separation and Target Location on target-identification errors.

### *Effects of Compatibility (I. vs. C.) and Separation*

The effect of Compatibility (I. vs. C.) was not significant ( $F(1,14) = 0.76$ ,  $p = 0.398$ ,  $\eta_p^2 = 0.052$ ) but the effect of Separation and the interaction between Compatibility (I. vs. C.) and Separation were significant (respectively,  $F(2.3,32.1) = 3.79$ ,  $p = 0.028$ ,  $\eta_p^2 = 0.213$  and  $F(4,56) = 2.95$ ,  $p = 0.028$ ,  $\eta_p^2 = 0.174$ ). The significance of the interaction suggests that there was some *combined response-related interference* in errors and that this interference varied with separation. Polynomial trends for the interaction showed that *combined response-related interference* as a function of separation was explained by a combination of quadratic and cubic trends (respectively  $F(1,14) = 6.48$ ,  $p = 0.023$ ,  $\eta_p^2 = 0.316$  and  $F(1,14) = 5.96$ ,  $p = 0.028$ ,  $\eta_p^2 = 0.299$ ; the linear and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

### *Effect of Target Location*

The main effect of Target Location was not significant ( $F(1,14) = 2.91$ ,  $p = 0.110$ ,  $\eta_p^2 = 0.172$ ). Neither was any interaction involving this factor (Target Location x

Compatibility:  $F(1,14) = 0.78, p = 0.391, \eta_p^2 = 0.053$ ; Target Location x Separation:  $F(4,56) = 0.70, p = 0.595, \eta_p^2 = 0.048$ ; Target Location x Compatibility x Separation:  $F(4,56) = 0.10, p = 0.983, \eta_p^2 = 0.007$ ).

### ***3.3.2.2 Comparison of incompatible- with neutral-distractor RTs as a function of separation and target location***

#### **Reaction times**

This analysis compared *incompatible*-distractor and *neutral*-distractor RTs as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Compatibility (I. vs. N.), Separation and Target Location on target-identification RTs.

#### *Effects of Compatibility (I. vs. N.) and Separation*

The main effects of both Compatibility (I. vs. N.) and Separation were significant (respectively,  $F(1,14) = 63.06, p < 0.001, \eta_p^2 = 0.818$  and  $F(4,56) = 9.20, p < 0.001, \eta_p^2 = 0.396$ ) and the interaction between Compatibility (I. vs. N.) and Separation was also significant ( $F(4,56) = 2.51, p = 0.052, \eta_p^2 = 0.152$ ). These findings show that there was significant *incompatible-distractor response-related interference* and that this interference varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor response-related interference* as a function of separation was explained by a quartic trend ( $F(1,14) = 7.59, p = 0.015, \eta_p^2 = 0.352$ ; the linear, quadratic and cubic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

#### *Effect of Target Location*

The main effect of Target Location was not significant ( $F(1,14) = 0.83, p = 0.380, \eta_p^2 = 0.056$ ). Neither was any interaction involving this factor (Target Location x Compatibility:  $F(1,14) = 3.01, p = 0.101, \eta_p^2 = 0.185$ ; Target Location x Separation:  $F(4,56) = 0.25, p = 0.909, \eta_p^2 = 0.017$ ; Target Location x Compatibility x Separation:  $F(4,56) = 1.92, p = 0.121, \eta_p^2 = 0.120$ ).

## **Errors**

This analysis compared *incompatible*-distractor and *neutral*-distractor errors as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Compatibility (I. vs. N.), Separation and Target Location on target-identification errors.

### *Effects of Compatibility (I. vs. N.) and Separation*

The main effects of both Compatibility (I. vs. N.) and Separation were significant ( $F(1,14) = 10.13, p = 0.007, \eta_p^2 = 0.420$  and  $F(4,56) = 5.46, p = 0.001, \eta_p^2 = 0.280$ ), and the interaction between Compatibility (I. vs. N.) and Separation was marginally significant ( $F(4,56) = 2.07, p = 0.096, \eta_p^2 = 0.129$ ). These findings suggest that there was *incompatible-distractor response-related interference* in errors, and that this interference varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor response-related interference* as a function of separation was explained by a marginally significant cubic trend ( $F(1,14) = 3.75, p = 0.073, \eta_p^2 = 0.180$ ; the linear, quadratic and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

### *Effect of Target Location*

The main effect of Target Location was not significant ( $F(1,14) = 0.142, p = 0.712, \eta_p^2 = 0.010$ ). Neither was any interaction involving this factor (Target Location x Compatibility:  $F(1,14) = 1.31, p = 0.271, \eta_p^2 = 0.086$ ; Target Location x Separation:  $F(4,56) = 0.96, p = 0.436, \eta_p^2 = 0.064$ ; Target Location x Compatibility x Separation:  $F(4,56) = 0.20, p = 0.935, \eta_p^2 = 0.014$ ).

### ***3.3.2.3 Comparison of neutral- with no-distractor RTs as a function of separation and target location***

#### **Reaction times**

This analysis compared *neutral*-distractor and *no*-distractor RTs as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation and Target Location on target-identification RTs.

#### *Effects of Presence of Neutral Distractors and Separation*

The main effects of both Presence of Neutral Distractor, and Separation were significant (respectively,  $F(1,14) = 18.06, p = 0.001, \eta_p^2 = 0.563$  and  $F(4,56) = 5.75, p = 0.001, \eta_p^2 = 0.291$ ) and the interaction between Presence of Neutral Distractor, and Separation was also significant ( $F(4,56) = 3.35, p = 0.016, \eta_p^2 = 0.193$ ). These findings show that, in Experiment 5, neutral distractors generated significant *salience-related interference* and that this interference varied with separation. Polynomial trends for the interaction showed that *salience-related interference* as a function of separation was explained by a quadratic trend ( $F(1,14) = 16.76, p = 0.001, \eta_p^2 = 0.545$ ; the linear, cubic and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

### *Effect of Target Location*

The main effect of Target Location was not significant ( $F(1,14) = 0.36, p = 0.558, \eta_p^2 = 0.025$ ). Neither was any interaction involving this factor (Target Location x Compatibility:  $F(1,14) = 0.06, p = 0.806, \eta_p^2 = 0.004$ ; Target Location x Separation:  $F(4,56) = 1.17, p = 0.335, \eta_p^2 = 0.077$ ; Target Location x Compatibility x Separation:  $F(4,56) = 1.36, p = 0.260, \eta_p^2 = 0.088$ ).

### **Errors**

This analysis compared *neutral*-distractor and *no*-distractor errors as a function of separation and target location using a repeated-measures ANOVA. It tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation and Target Location on target-identification errors.

### *Effects of Presence of Neutral Distractor and Separation*

The results of the repeated-measures ANOVA showed that, while the effect of Separation was significant ( $F(4,56) = 3.23, p = 0.019, \eta_p^2 = 0.187$ ), neither the effect of Presence of Neutral Distractor, nor the interaction between Presence of Neutral Distractor, and Separation was significant (respectively,  $F(1,14) = 1.58, p = 0.230, \eta_p^2 = 0.101$  and  $F(4,56) = 0.34, p = 0.852, \eta_p^2 = 0.024$ ). In other words, there was no evidence for the presence of *saliency-related interference* and that *saliency-related interference* varied with separation.

### *Effect of Target Location*



The main effect of Target Location was not significant ( $F(1,14) = 0.04, p = 0.854, \eta_p^2 = 0.004$ ). Neither was any interaction involving this factor (Target Location x Presence of Neutral Distractor:  $F(1,14) = 0.24, p = 0.635, \eta_p^2 = 0.017$ ; Target Location x Separation:  $F(4,56) = 0.41, p = 0.801, \eta_p^2 = 0.028$ ; Target Location x Presence of Neutral Distractor x Separation:  $F(4,56) = 0.38, p = 0.820, \eta_p^2 = 0.027$ ).

### ***3.3.2.4 Comparison of the interference functions of separation***

#### **Reaction times**

The final analysis used a repeated-measures ANOVA to compare the interference as a function of separation obtained in the previous analyses. We were interested to see whether (1) the amplitude of the three types of interference across separations was the same or different and whether (2) the functions of separation measured with the three types of interference described the same shapes and were similarly focused. The repeated-measures ANOVA tested for the effects of two factors, namely, Type of Interference (i.e., *combined response-related interference, incompatible-distractor response-related interference* or *salience-related interference*) and Separation.

The repeated-measures ANOVA showed that, while the effect of Separation was significant ( $F(4,56) = 3.90, p = 0.016, \eta_p^2 = 0.231$ ), neither the effect of Type of Interference nor the interaction between Type of Interference and Separation was significant (respectively,  $F(1.2,16.7) = 2.79, p = 0.109, \eta_p^2 = 0.166$  and  $F(4.3,60.6) = 1.45, p = 0.225, \eta_p^2 = 0.094$ ). In other words, the amplitude across separations of the three types of interference was at similar levels and the functions of separation of the

three types of interference described similar patterns, with a bottom occurring at similar separations.

### **Errors**

Like in the RT data (see above), a final analysis was used to compare the interference as a function of separation obtained in the previous analyses. Only the data from the first two analyses were included in this analysis as there was no significant effect in the last analysis. None of the main effects or interactions reached significance in the final analysis (all  $p$  values  $> 0.100$ ). In other words, the two types of interference were not significantly different and the functions of separation described similar patterns, with bottoms occurring at similar separations.

### **3.3.3 Discussion**

First, the findings of Experiment 5 replicated those of Experiment 4 showing that both *combined response-related interference* and *incompatible-distractor response-related interference* as a function of separation described a similar Mexican-hat pattern.

Another finding of Experiment 5 was that neutral distractors can generate *saliency-related interference* when they are sufficiently salient. Importantly, *neutral-distractor saliency-related interference* as a function of separation was found to describe a similar Mexican-hat pattern to those described by *combined response-related interference* and *incompatible-distractor response-related interference*. In fact, the bottom of all three functions of separation occurred around the same separation. This finding is not consistent with the suggestion that *saliency-related interference* generates a function of separation that is *different* from the function generated by response-related interference

(see Introduction of this chapter). Instead, this finding showed that *salience-related interference* and *response-related interference* could be used interchangeably to index the profile of perceptual resources. By implication, combining both types of interference into one measure (i.e., by using *incompatible-distractor total interference*, namely, by comparing no-distractor performance with incompatible-distractor performance), one obtains a more sensitive index of perceptual resources and, therefore, a more powerful tool for studying selective attention.

It is noteworthy that, in this experiment, the difference between the effect of compatible and neutral distractors appeared to be reduced compared to that in Experiment 4 (compare Figures 14 and 15). This suggests that *task-driven* effects on salience were smaller in this experiment than in Experiment 4, arguably because *stimulus-driven* effects on salience were overall higher. By implication, the comparison of neutral-distractor performance with incompatible-distractor performance provided a purer measure of response-related interference in Experiment 5 than in Experiment 4. Even if the latter comparison still contained some residual *salience-related interference* from incompatible distractors, this would not be a problem given that *salience-related interference* also indexes the profile of perceptual resources.

In sum, Experiment 5 showed that *salience-related interference*, just like *response-related interference*, can be used to index the profile of perceptual resources, provided the distractors are salient enough. Given that salience-related and response-related interference produced similar results in the flanker paradigm and given that the cue/probe paradigm arguably relies on the salience of the probe, it becomes more likely that the cue/probe paradigm can reveal the same function of separation as the flanker

paradigm (i.e., *probe-detection performance* as a function of separation may describe the same Mexican-hat profile as in the flanker task). This was examined in Experiment 6 using a new paradigm that is a composite of the cue/probe and the flanker paradigms.

### **3.4 EXPERIMENT 6: Qualitative comparison of flanker and cue/probe tasks**

In this experiment, the participants performed, in turn, (1) an adaptation of the flanker task (Eriksen & Hoffman, 1972, 1973) and (2) an adaptation of the cue/probe task (Posner, 1980), on exactly the same stimuli. Each participant performed flanker and cue/probe tasks in separate experimental sessions and in counterbalanced order. Target and distractor letters were always present but relevant *only* to the flanker task. In addition, the background of the distractor location (or of the target location when no distractor was present) was *brightened* in *half* the trials; this brightening created a bright disk that was irrelevant to the flanker task but that functioned as the detection probe in the cue/probe task. Given that the probe location always occurred at the distractor location (on distractor-present trials), manipulating cue-probe separation equated to manipulating target-distractor separation.

Experiment 6 was run *prior* to Experiments 4 and 5 (but is reported *after* them in this chapter in order to appeal to the findings of Experiments 4 and 5 in interpreting the data). As a result, some elements of its design are more similar to those of Experiment 3, namely, both placeholders and filler letters were again present and no neutral distractor was used; it was therefore not possible to isolate *saliency-related interference* using neutral distractors in the flanker task. In the flanker task, distractor

interference could be measured only in two ways, by comparing incompatible-distractor performance with compatible-distractor performance (as in Experiments 1 to 5) and by comparing incompatible-distractor performance with no-distractor performance (as suggested in the discussion of Experiment 5 to be the most sensitive measure of the profile of perceptual resources). The first comparison isolated *combined response-related interference* and the second one *incompatible-distractor total interference*, namely, the *total* of salience-related and response-related interference. The shapes of the two functions of separation extracted in the flanker task were qualitatively compared to probe-detection performance as a function of separation extracted in the cue/probe task.

### **3.4.1 Method**

#### ***3.4.1.1 Design***

##### *Flanker task*

The response-compatibility of the distractor (compatible or incompatible), the target-distractor separation and the location of the target were manipulated at fixed stimulus eccentricity in a repeated-measures design.

##### *Cue/probe task*

The cue-probe separation and the location of the cue were manipulated at fixed stimulus eccentricity in a repeated-measures design.

### ***3.4.1.2 Participants***

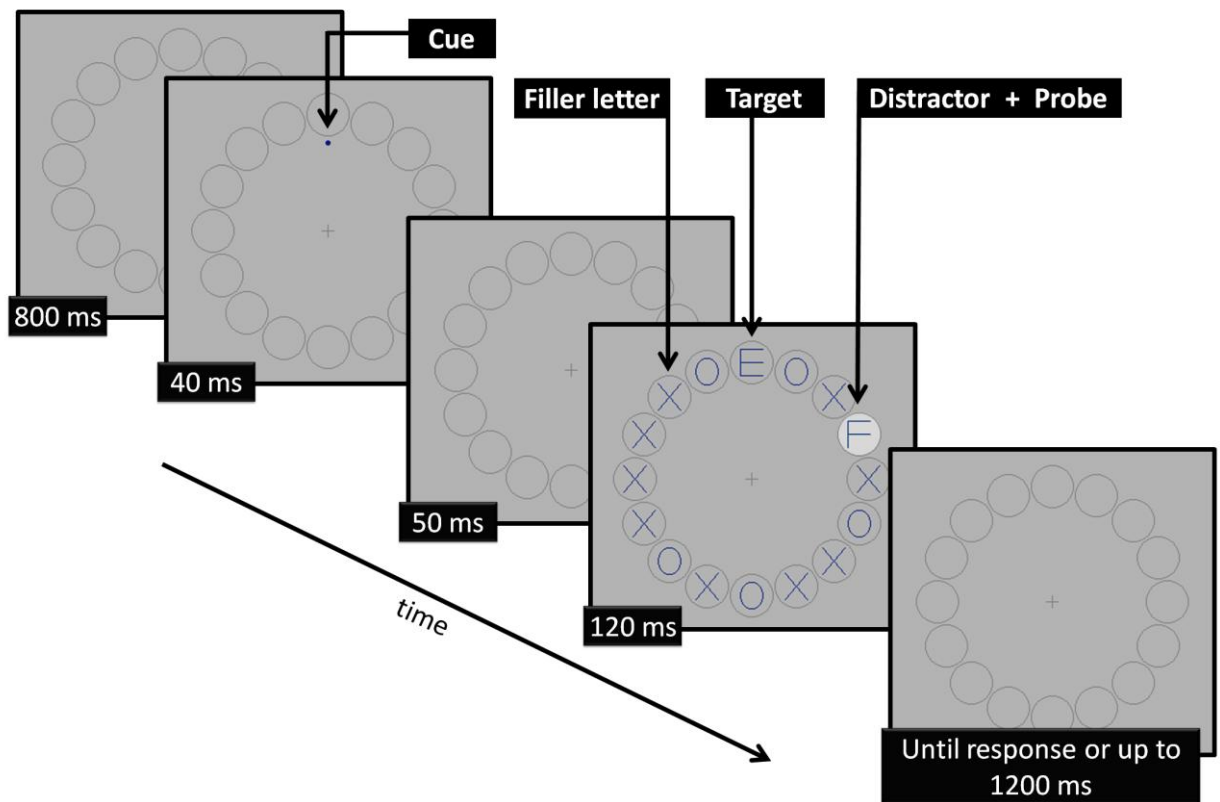
16 participants from Goldsmiths College (12 females; 1 left-handed; mean age 20 yr; age range 18 to 26 yr; see Appendix 7) with reported normal or corrected-to-normal vision took part in the experiment in exchange for course credits. All of them were first-year undergraduates and received course credits for their participation. They were all naïve as to the aim of the study.

### ***3.4.1.3 Stimuli and procedure***

In the flanker task, participants were instructed to ignore the distractor, filler letters and probe, and to make a two-alternative forced-choice (2-AFC) identification of the target ('E' vs. 'F') by pressing one of two keys on an English keyboard ('L' for 'E' or ';' for 'F') as quickly but as accurately as possible, using their dominant hand. The letters were of the same size and colour as in Experiments 4 and 5. In the cue/probe task, participants were instructed to ignore the stimulus letters and to make a 2-AFC detection ('present' vs. 'absent') of the probe by pressing one of two keys on an English keyboard ('L' for 'present' or ';' for 'absent'), using their dominant hand. In both tasks, feedback was given for incorrect answers.

A cross (the fixation cross) and 16 placeholders were present on the screen throughout the experiment (see Figure 16). They were grey (the same dark grey as in Experiment 4) against a light grey background (the same light grey as in Experiment 4). The 16 placeholders were arranged around an imaginary circle of radius 4.6 deg and circumscribed the locations of the 16 stimulus letters (selected from the subset 'E', 'F', 'X' and 'O' and used as target, distractor and filler letters) and of the probe (the bright disk). Each placeholder was separated from its neighbour by 1.8 deg (centre to centre).

## EXPERIMENT 6: METHOD



**Figure 16**

*Experiment 6 - Method. A schematic representation of an experimental trial. In each trial, a target letter ('E' or 'F') occurred in the placeholder (always North, East, South or West) indicated by a 100%-valid exogenous cue. A distractor occurred in 80% of the trials at one of four possible target-distractor separations (1.8, 5.1, 7.7 and 9.0 deg, corresponding respectively to the first, third, fifth and seventh placeholder removed from the target placeholder in a clockwise direction). The distractor could be compatible with the identity of the target (e.g., 'E' if the target was 'E') or incompatible with the identity of the target (e.g., 'F' if the target was 'E'). A probe (a bright disk) occurred in 50% of the trials. When it occurred, it did so at the distractor location (when a distractor was present) or at the target location (when no distractor was present). In the flanker-task session, participants signalled target identity ('E' or 'F', with a 2-AFC) while ignoring probe, distractor ('E' or 'F') and filler letters ('X's and 'O's). In the cue/probe-task session, participants signalled the presence of the probe ('present' or 'absent', with a 2-AFC) while ignoring target, distractor and filler letters.*

*The sessions were performed in a counterbalanced order. The figure illustrates a 'North' target ('E') with a probe and an incompatible distractor ('F') occurring at a separation of 5.1 deg.*

On each trial, the cue was presented 1.4 deg central of the centre of the 'North', 'East', 'South' or 'West' placeholders. The letter that appeared inside the cued placeholder was defined as the target ('E' or 'F'). 14 filler letters (randomly selected from the letters 'X' or 'O') and one distractor ('E' or 'F'), or 15 filler letters and no distractor, appeared inside the remaining placeholders. In half the trials, the background of the placeholder containing the distractor - when a distractor was present - or the background of the placeholder containing the target - when no distractor was present - was brighter than the remaining background (CIE  $x = 0.28$ ,  $y = 0.31$  and  $L = 16.70$  cd/m<sup>2</sup>). This created a bright disk that was defined as the probe (see Figure 16).

The distractor was response-compatible with the target (so that it was 'F' if the target was 'F') on 40% of trials or it was response-incompatible with the target (so that, for example, it was 'E' if the target was 'F') on another 40% of trials (when a probe occurred at the distractor location, it did so equally often with compatible and with incompatible distractors). In the remaining 20% of trials, no distractor was presented and the target appeared amongst 15 filler letters. These trials constituted the no-distractor baseline condition in the flanker task. When a distractor was present, it always appeared inside a placeholder separated from the (cued) target placeholder (centre to centre) by 1.8, 5.1, 7.7 or 9.0 deg (the four levels of target-distractor separation) in a clockwise direction. These separations corresponded to presenting the distractor in the placeholders that were respectively one, three, five and seven placeholders removed (around the circle of placeholders) from the cued target-



placeholder (see Figure 16). The probe occurred in 50% of trials, either in the target placeholder (when the distractor was absent) or in the distractor placeholder (when the distractor was present). There were therefore five levels of cue-probe separation (0.0, 1.8, 5.1, 7.7 or 9.0 deg).

Each trial started with a screen containing the fixation cross and 16 empty placeholders (for 800 ms). This was followed by the presentation of the cue for 40 ms. After the offset of the cue and a delay of 50 ms, the stimulus letters and the probe (when it occurred) were presented in their respective placeholders for 120 ms. The next trial began 200 ms after a participant had responded or after 1200 ms had elapsed.

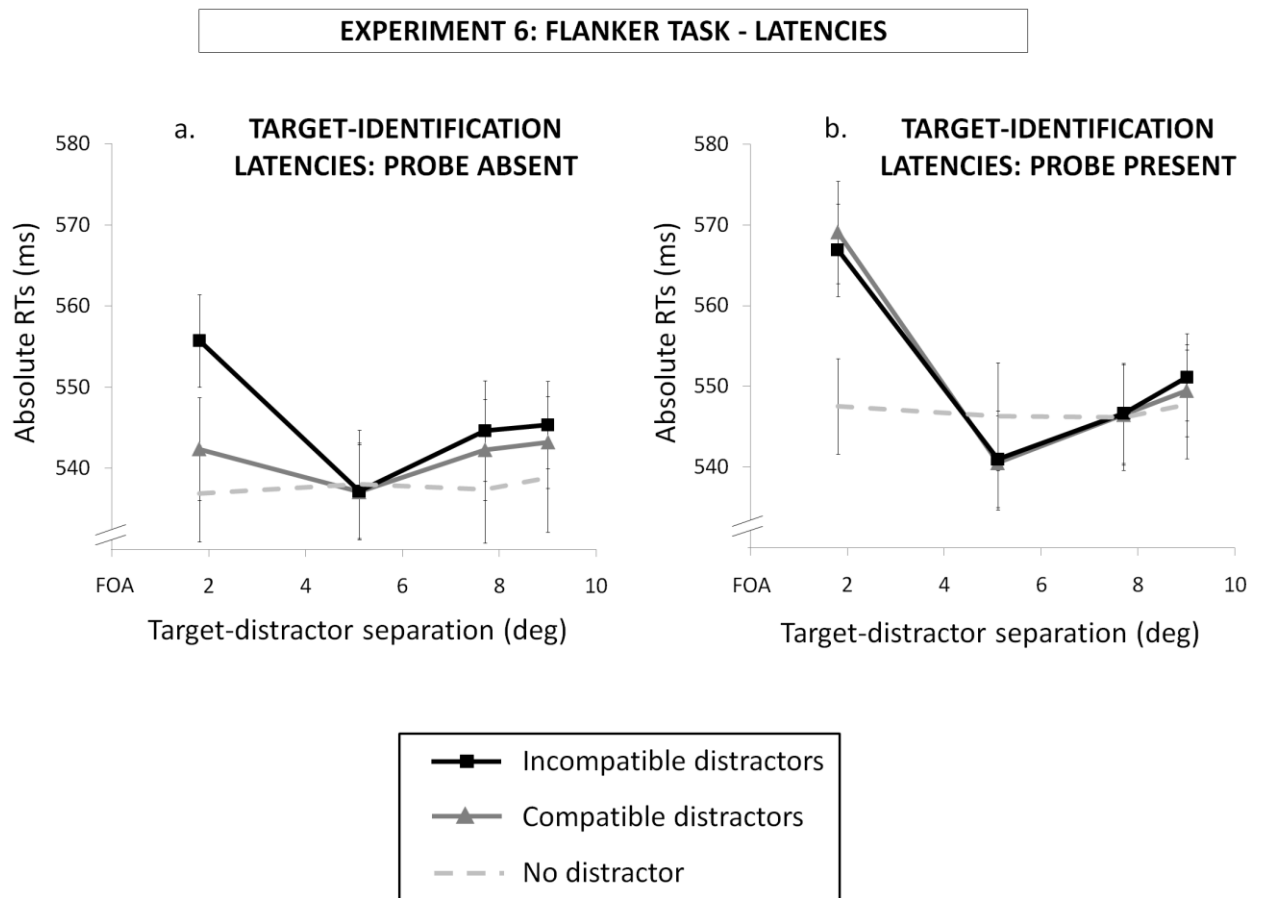
Experiment 6 lasted about 1.5 hr and consisted of 1120 trials, preceded by 60 practice trials, for each task. Every 80 trials (about every 2 minutes), there were participant-terminated breaks. The experimental conditions within each task (combinations of distractor compatibility, target-distractor/cue-probe separation, location of the target/cue and presence of probe) were presented in a randomised order.

### **3.4.2 Results**

We analysed both the speed and accuracy of forced-choice target-identification ('E' vs. 'F') and probe-detection ('present' vs. 'absent') responses. Latencies were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented an average of 90.2% of the latencies overall.

#### **3.4.2.1 Flanker task**

For each participant, mean RTs (and error percentages) were calculated for incompatible-distractor and compatible-distractor (distractor-present) trials at each of the four levels of target location ('North', 'East', 'South' and 'West'), at each of the four levels of target-distractor separation (1.8, 5.1, 7.7 and 9.0 deg), and at each of the two levels of presence of probe ('present' or 'absent'; see Figure 17 for RTs and Figure 18 for errors). Moreover, for each participant, no-distractor (i.e. filler-letters-only) RTs (and errors) were randomly separated into four bins at each of the four levels of target location and at each of the two levels of presence of probe, and mean RTs (and error percentages) were calculated for each bin. The bins were used as baselines to match the four levels of target-distractor separation in each condition of target location and presence of probe.

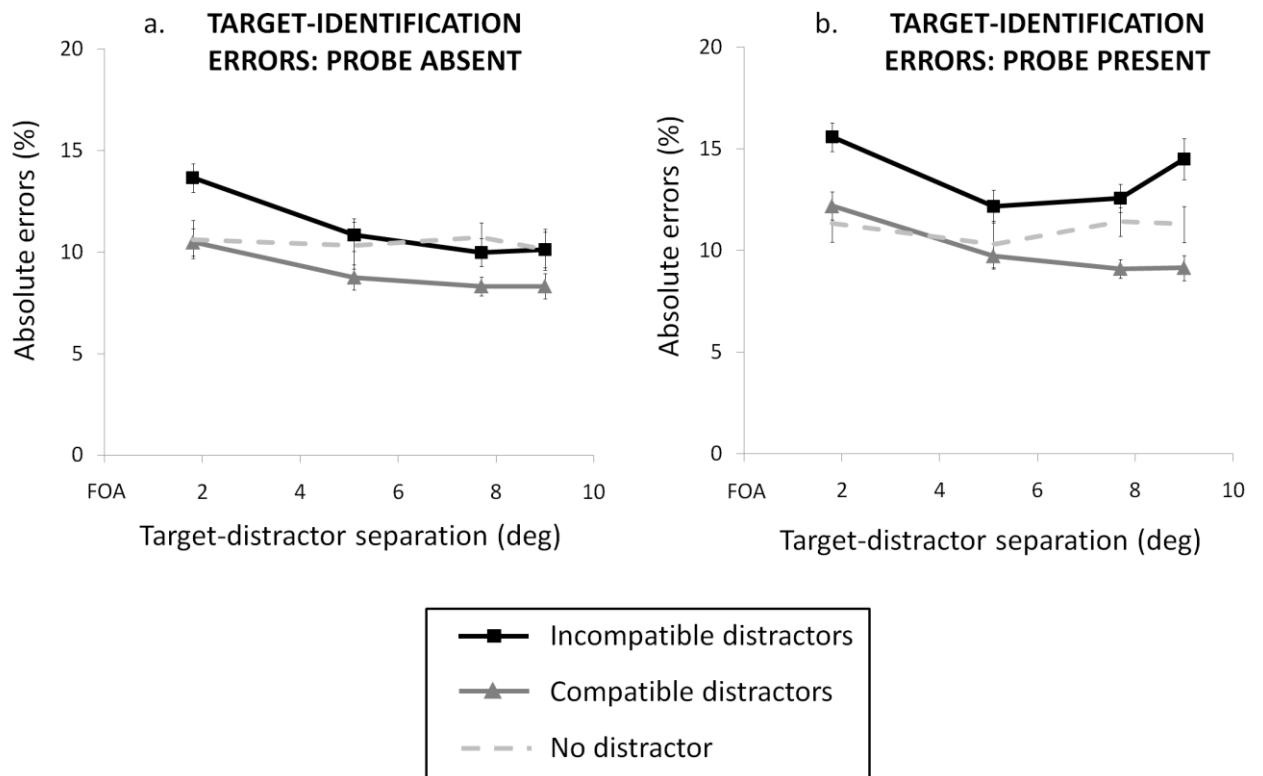


### **Figure 17**

*Experiment 6 – Latencies in the flanker task. The figure shows: (1) distractor-present mean latencies (in ms) as a function of target-distractor separation (in deg), target-distractor compatibility (compatible or incompatible), and presence of probe (present or absent) – see solid lines; and (2) no-distractor mean latencies (in ms) as a function of presence of probe (present or absent) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (FOA) = attended location.*

Two analyses on mean RTs (and error percentages) were performed. The first analysis compared *incompatible*-distractor with *compatible*-distractor performance as a function of separation and presence of probe (and also target location). This comparison allowed us to isolate *combined response-related interference* and to test whether this interference was *modulated* by target-distractor separation and/or presence of probe. The second analysis compared *incompatible*-distractor with *no*-distractor performance as a function of separation and presence of probe (and also target location). This comparison allowed us to isolate *incompatible-distractor total interference* and to test whether this interference was *modulated* by target-distractor separation and/or presence of probe.

**EXPERIMENT 6: FLANKER TASK - ERRORS**



**Figure 18**

*Experiment 6 – Errors in the flanker task. The figure shows: (1) distractor-present error percentages (in %) as a function of target-distractor separation (in deg), target-distractor compatibility (compatible or incompatible), and presence of probe (present or absent) – see solid lines; and (2) no-distractor error percentages (in %) as a function of presence of probe (present or absent) – see dashed lines. Error bars depict +/- 0.5 SEM. (▲) = compatible distractor; (■) = incompatible distractor; (FOA) = attended location.*

**3.4.2.1.1 Comparison of incompatible-distractor with compatible-distractor RTs as a function of separation, presence of probe and target location**

**Reaction Times**

This analysis compared *incompatible*-distractor and *compatible*-distractor RTs as a function of separation, target location and presence of probe using a repeated-measures ANOVA. It tested for the effects of four factors, namely, Compatibility (I. vs. C.), Separation, Target Location and Presence of Probe on target-identification RTs.

#### *Effects of Compatibility (I. vs. C.) and Separation*

The results of the repeated-measures ANOVA showed that, while the effect of Separation was significant ( $F(3,45) = 27.37, p < 0.001, \eta_p^2 = 0.646$ ), the effect of Compatibility (I. vs. C.) and the interaction between Compatibility (I. vs. C.) and Separation were not significant (respectively,  $F(1,15) = 0.17, p = 0.684, \eta_p^2 = 0.011$  and  $F(3,45) = 0.541, p = 0.656, \eta_p^2 = 0.035$ ). These findings showed that there was no significant *combined response-related interference* overall and that *combined response-related interference* did not vary with separation.

#### *Effect of Target Location*

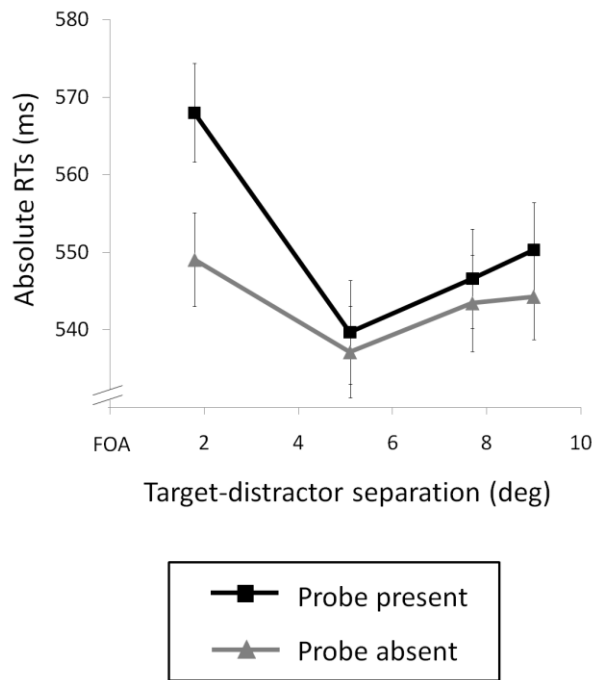
The main effect of Target Location was significant ( $F(3,45) = 20.18, p < 0.001, \eta_p^2 = 0.574$ ). Bonferroni-corrected pairwise comparisons showed that participants were significantly faster (at the 0.05 level) to respond to East and West targets than to North and South targets. Target location did not interact with Compatibility (I. vs. C.) or Separation (Target Location x Compatibility:  $F(3,45) = 0.985, p = 0.409, \eta_p^2 = 0.062$ ; Target Location x Separation:  $F(9,135) = 1.39, p = 0.199, \eta_p^2 = 0.085$ ; Target Location x Compatibility x Separation:  $F(9,135) = 0.52, p = 0.858, \eta_p^2 = 0.033$ ).

#### *Effect of Presence of Probe*

The main effect of Presence of Probe was not significant ( $F(1,15) = 1.79, p = 0.201, \eta_p^2 = 0.106$ ), showing that the probe did not affect RTs *overall*. On the other hand, the interaction between Presence of Probe and Separation was significant ( $F(3,45) = 3.39, p = 0.026, \eta_p^2 = 0.184$ ). This was because the probe increased RTs (pooled across compatible and incompatible conditions) more at small (and arguably at large), than at intermediate, separations (see Figure 19). In other words, the RT function of separation was *steeper* in probe-present trials.

Presence of Probe did not interact with any other factor (Presence of Probe x Compatibility:  $F(1,15) = 0.22, p = 0.643, \eta_p^2 = 0.015$ ; Presence of Probe x Target Location:  $F(3,45) = 0.24, p = 0.865, \eta_p^2 = 0.016$ ; Presence of Probe x Compatibility x Separation:  $F(3,45) = 1.03, p = 0.389, \eta_p^2 = 0.064$ ; Presence of Probe x Compatibility x Target Location:  $F(3,45) = 0.959, p = 0.420, \eta_p^2 = 0.060$ ; Presence of Probe x Separation x Target Location:  $F(9,135) = 0.575, p = 0.816, \eta_p^2 = 0.037$ ; Presence of Probe x Compatibility x Separation x Target Location:  $F(9,135) = 1.41, p = 0.189, \eta_p^2 = 0.086$ ).

**EXPERIMENT 6: FLANKER TASK**  
**LATENCIES (POOLED ACROSS COMPATIBLE AND INCOMPATIBLE CONDITIONS)**  
**AS A FUNCTION OF PRESENCE OF PROBE**



**Figure 19**

*Experiment 6 – Latencies in the flanker task. The figure shows distractor-present (pooled across compatible and incompatible conditions) mean latencies (in ms) as a function of target-distractor separation (in deg) and presence of probe (present or absent). Error bars depict +/- 0.5 SEM. (▲) = probe absent; (■) = probe present; (FOA) = attended location.*

**Errors**

This analysis compared *incompatible*-distractor and *compatible*-distractor errors as a function of separation, target location and presence of probe using a repeated-measures ANOVA. It tested for the effects of four factors, namely, Compatibility (I. vs. C.), Separation, Target Location and Presence of Probe on target-identification errors.

### *Effects of Compatibility (I. vs. C.) and Separation*

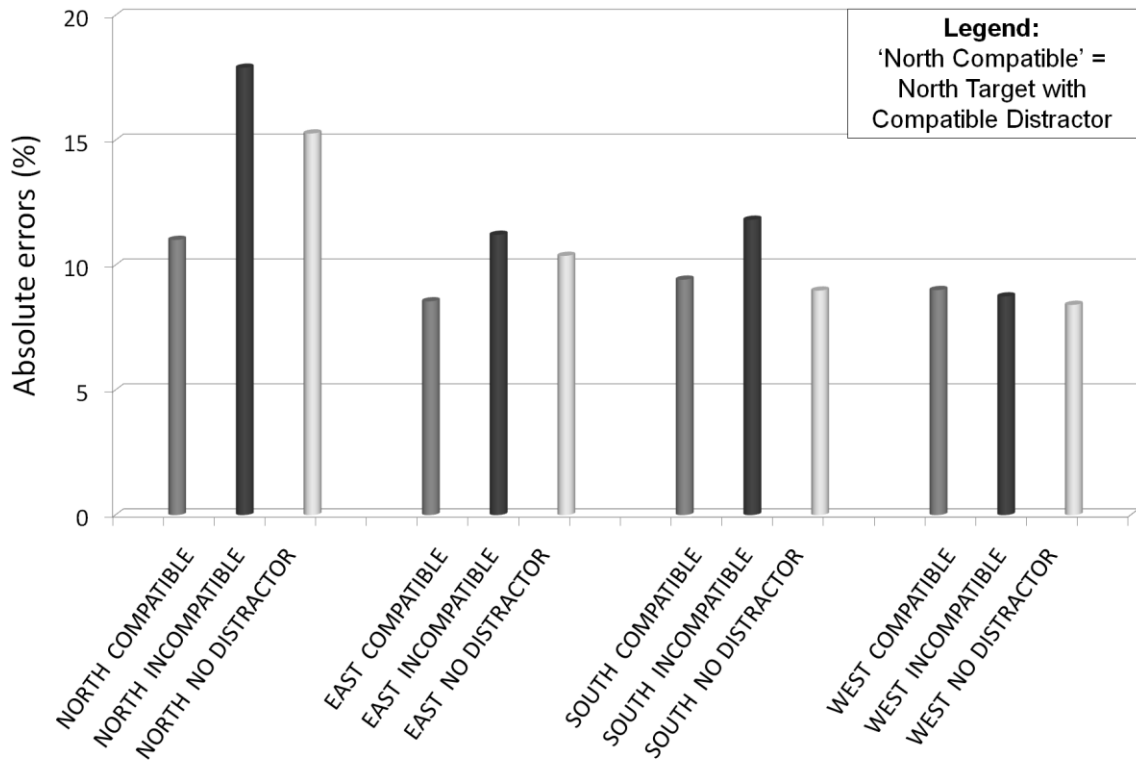
The results of the first repeated-measures ANOVA showed that: (1) the effect of Compatibility (I. vs. C.) was significant ( $F(1,15) = 15.24, p = 0.001, \eta_p^2 = 0.504$ ), showing that there was significant *combined response-related interference* in errors; and (2) the effect of Separation was significant ( $F(3,45) = 9.17, p < 0.001, \eta_p^2 = 0.379$ ), showing that errors (pooled across compatible- and incompatible-distractor conditions) varied with separation; but (3) the interaction between Compatibility (I. vs. C.) and Separation was not significant ( $F(3,45) = 0.36, p = 0.779, \eta_p^2 = 0.024$ ), showing that *combined response-related interference* did not significantly vary with separation (see Figure 18).

### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,45) = 11.37, p < 0.001, \eta_p^2 = 0.431$ ). Bonferroni-corrected pairwise comparisons showed that participants made significantly more errors ( $p < 0.050$ ) to respond to North than East, South or West targets. Moreover, Target Location interacted with Compatibility ( $F(3,45) = 6.28, p = 0.001, \eta_p^2 = 0.295$ ). This interaction was explained by the fact that incompatible distractors significantly increased errors (compared to compatible distractors) when the target was at the North location ( $F(1,15) = 14.58, p = 0.002, \eta_p^2 = 0.493$ ) or at the East location ( $F(1,15) = 7.95, p = 0.013, \eta_p^2 = 0.346$ ) but not when it was at the South location ( $F(1,15) = 3.76, p = 0.072, \eta_p^2 = 0.200$ ) or at the West location ( $F(1,15) = 0.090, p = 0.768, \eta_p^2 = 0.006$ ; see Figure 20).



**EXPERIMENT 6: FLANKER TASK**  
**ERRORS AS A FUNCTION OF DISTRACTOR COMPATIBILITY AND TARGET LOCATION**



**Figure 20**

*Experiment 6 – Errors in the flanker task. The figure shows error percentages (in %) for the compatible-, incompatible- and no-distractor conditions as a function of target location (North, East, South or West). (dark grey) = incompatible distractor; (medium grey) = compatible distractor; (light grey) = no distractor.*

Target location did not significantly interact with Separation ( $F(4.5,67.2) = 2.31, p = 0.060, \eta_p^2 = 0.134$ ). Finally, the interaction between Target Location, Compatibility and Separation was not significant either ( $F(9,135) = 1.66, p = 0.106, \eta_p^2 = 0.099$ ).

### *Effect of Presence of Probe*

The main effect of Presence of Probe was significant ( $F(1,15) = 8.53, p = 0.011, \eta_p^2 = 0.363$ ): the presence of the probe caused errors to increase overall. On the other hand, Presence of Probe did not interact significantly with any other factor (Presence of Probe x Compatibility:  $F(1,15) = 1.53, p = 0.235, \eta_p^2 = 0.093$ ; Presence of Probe x Separation:  $F(3,45) = 0.34, p = 0.798, \eta_p^2 = 0.022$ ; Presence of Probe x Target Location:  $F(3,45) = 0.32, p = 0.813, \eta_p^2 = 0.021$ ; Presence of Probe x Compatibility x Separation:  $F(3,45) = 1.07, p = 0.372, \eta_p^2 = 0.066$ ; Presence of Probe x Compatibility x Target Location:  $F(3,45) = 0.193, p = 0.901, \eta_p^2 = 0.013$ ; Presence of Probe x Separation x Target Location:  $F(9,135) = 0.875, p = 0.549, \eta_p^2 = 0.055$ ; Presence of Probe x Compatibility x Separation x Target Location:  $F(9,135) = 0.894, p = 0.533, \eta_p^2 = 0.056$ ).

### ***3.4.2.1.2 Comparison of incompatible-distractor with no-distractor RTs as a function of separation, presence of probe and target location***

#### **Reaction times**

This analysis compared *incompatible*-distractor and *no*-distractor RTs as a function of separation, target location and presence of probe using a repeated-measures ANOVA. It tested for the effects of four factors, namely, Presence of Incompatible Distractor, Separation, Target Location and Presence of Probe on target-identification RTs.

### *Effects of Presence of Incompatible Distractor, and Separation*

The results of the repeated-measures ANOVA showed that both the main effects of Presence of Incompatible Distractor and Separation were significant (respectively,  $F(1,15) = 9.49, p = 0.008, \eta_p^2 = 0.388$  and  $F(3,45) = 8.19, p < 0.001, \eta_p^2 = 0.353$ ) and

the interaction between Presence of Incompatible Distractor, and Separation was also significant ( $F(3,45) = 11.45, p < 0.001, \eta_p^2 = 0.433$ ). These findings showed that there was significant *incompatible-distractor total interference* (i.e., total of response-related and salience-related interference) and this interference varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was best explained by a combination of linear, quadratic and cubic trends (respectively:  $F(1,15) = 9.03, p = 0.009, \eta_p^2 = 0.376$ ;  $F(1,15) = 17.22, p = 0.001, \eta_p^2 = 0.535$ ; and  $F(1,15) = 8.14, p = 0.012, \eta_p^2 = 0.352$ ), consistent with a Mexican-hat profile.

#### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,45) = 18.44, p < 0.001, \eta_p^2 = 0.551$ ). Bonferroni-corrected pairwise comparisons showed that participants were significantly faster (at the 0.05 level) to respond to East and West targets than to North and South targets. Target location did not interact with Presence of Incompatible Distractor, or Separation (Target Location x Presence of Incompatible Distractor:  $F(3,45) = 1.07, p = 0.372, \eta_p^2 = 0.067$ ; Target Location x Separation:  $F(9,135) = 1.22, p = 0.290, \eta_p^2 = 0.075$ ; Target Location x Presence of Incompatible Distractor x Separation:  $F(9,135) = 0.55, p = 0.834, \eta_p^2 = 0.036$ ).

#### *Effect of Presence of Probe*

The main effect of Presence of Probe was significant ( $F(1,15) = 1.79, p = 0.201, \eta_p^2 = 0.106$ ): the presence of a probe increased RTs *overall*. On the other hand, Presence of Probe did not interact with any other factor (Presence of Probe x Presence of Incompatible Distractor:  $F(1,15) = 0.41, p = 0.534, \eta_p^2 = 0.026$ ; Presence of Probe x

Separation:  $F(3,45) = 0.36$ ,  $p = 0.782$ ,  $\eta_p^2 = 0.023$ ; Presence of Probe x Target Location:  $F(3,45) = 0.50$ ,  $p = 0.687$ ,  $\eta_p^2 = 0.032$ ; Presence of Probe x Presence of Incompatible Distractor x Separation:  $F(3,45) = 0.29$ ,  $p = 0.831$ ,  $\eta_p^2 = 0.019$ ; Presence of Probe x Presence of Incompatible Distractor x Target Location:  $F(3,45) = 0.41$ ,  $p = 0.744$ ,  $\eta_p^2 = 0.027$ ; Presence of Probe x Separation x Target Location:  $F(9,135) = 1.29$ ,  $p = 0.247$ ,  $\eta_p^2 = 0.079$ ; Presence of Probe x Presence of Incompatible Distractor x Separation x Target Location:  $F(9,135) = 1.13$ ,  $p = 0.345$ ,  $\eta_p^2 = 0.070$ ).

## **Errors**

This analysis compared *incompatible*-distractor and *no*-distractor errors as a function of separation, target location and presence of probe using a repeated-measures ANOVA. It tested for the effects of four factors, namely, Presence of Incompatible Distractor, Separation, Target Location and Presence of Probe on target-identification errors.

### *Effects of Presence of Incompatible Distractor and Separation*

The results of the repeated-measures ANOVA showed that: (1) the effect of Presence of Incompatible Distractor was marginally significant ( $F(1,15) = 3.44$ ,  $p = 0.083$ ,  $\eta_p^2 = 0.187$ ), showing that *incompatible-distractor total interference* was marginally significant in errors; and (2) the effect of Separation was marginally significant ( $F(3,45) = 2.63$ ,  $p = 0.061$ ,  $\eta_p^2 = 0.149$ ), showing that errors (pooled across *incompatible*- and *no*-distractor conditions) marginally varied with separation; but (3) the interaction between Presence of Incompatible Distractor, and Separation was not significant ( $F(3,45) = 1.42$ ,  $p = 0.249$ ,  $\eta_p^2 = 0.087$ ), showing that *incompatible-distractor total interference* did not significantly vary with separation (see Figure 18).

### *Effect of Target Location*

The main effect of Target Location was significant ( $F(3,45) = 18.52, p < 0.001, \eta_p^2 = 0.552$ ). Bonferroni-corrected pairwise comparisons showed that participants made significantly more errors ( $p < 0.050$ ) to respond to North than East, South or West targets. On the other hand, Target Location interacted with neither Presence of Incompatible Distractor nor with Separation (respectively,  $F(3,45) = 1.04, p = 0.385, \eta_p^2 = 0.065$  and  $F(9,135) = 1.63, p = 0.112, \eta_p^2 = 0.098$ ), and the three-way interaction between Target Location, Presence of Incompatible Distractor and Separation was not significant either ( $F(9,135) = 0.87, p = 0.554, \eta_p^2 = 0.055$ ).

### *Effect of Presence of Probe*

The main effect of Presence of Probe was significant ( $F(1,15) = 6.04, p = 0.027, \eta_p^2 = 0.287$ ): the presence of the probe caused errors to increase overall. On the other hand, Presence of Probe did not interact significantly with any other factor (Presence of Probe x Presence of Incompatible Distractor:  $F(1,15) = 1.06, p = 0.320, \eta_p^2 = 0.066$ ; Presence of Probe x Separation:  $F(3,45) = 0.64, p = 0.596, \eta_p^2 = 0.041$ ; Presence of Probe x Target Location:  $F(3,45) = 0.21, p = 0.892, \eta_p^2 = 0.014$ ; Presence of Probe x Presence of Incompatible Distractor x Separation:  $F(3,45) = 0.11, p = 0.953, \eta_p^2 = 0.007$ ; Presence of Probe x Presence of Incompatible Distractor x Target Location:  $F(3,45) = 0.183, p = 0.907, \eta_p^2 = 0.012$ ; Presence of Probe x Separation x Target Location:  $F(9,135) = 0.874, p = 0.550, \eta_p^2 = 0.055$ ; Presence of Probe x Presence of Incompatible Distractor x Separation x Target Location:  $F(9,135) = 1.23, p = 0.281, \eta_p^2 = 0.076$ ).

### **3.4.2.2 Cue/probe task**

For each participant, mean probe-detection ('present' vs. 'absent') RTs (and error percentages) were calculated for probe-present trials at each of the four levels of Cued Location ('North', 'East', 'South' and 'West') and at each of the five levels of Cue-probe Separation (0.0, 1.8, 5.1, 7.7 or 9.0 deg; see Figure 21<sup>12</sup>). Moreover, RTs (and error percentages) were calculated for probe-absent trials at each of the four levels of Cued Location. It was found that the probe was falsely reported in only 5.4% of probe-absent trials (to the same extent for all four cued locations, namely, between 5.1 and 5.8%). Additionally, the probe was missed in 7.4% of probe-present trials, showing a small bias towards responding that the probe was absent ( $t(21) = 3.08$ ,  $p = 0.006$ ,  $d = 0.51$ ). Two analyses were performed on *probe-present* RTs (and errors).

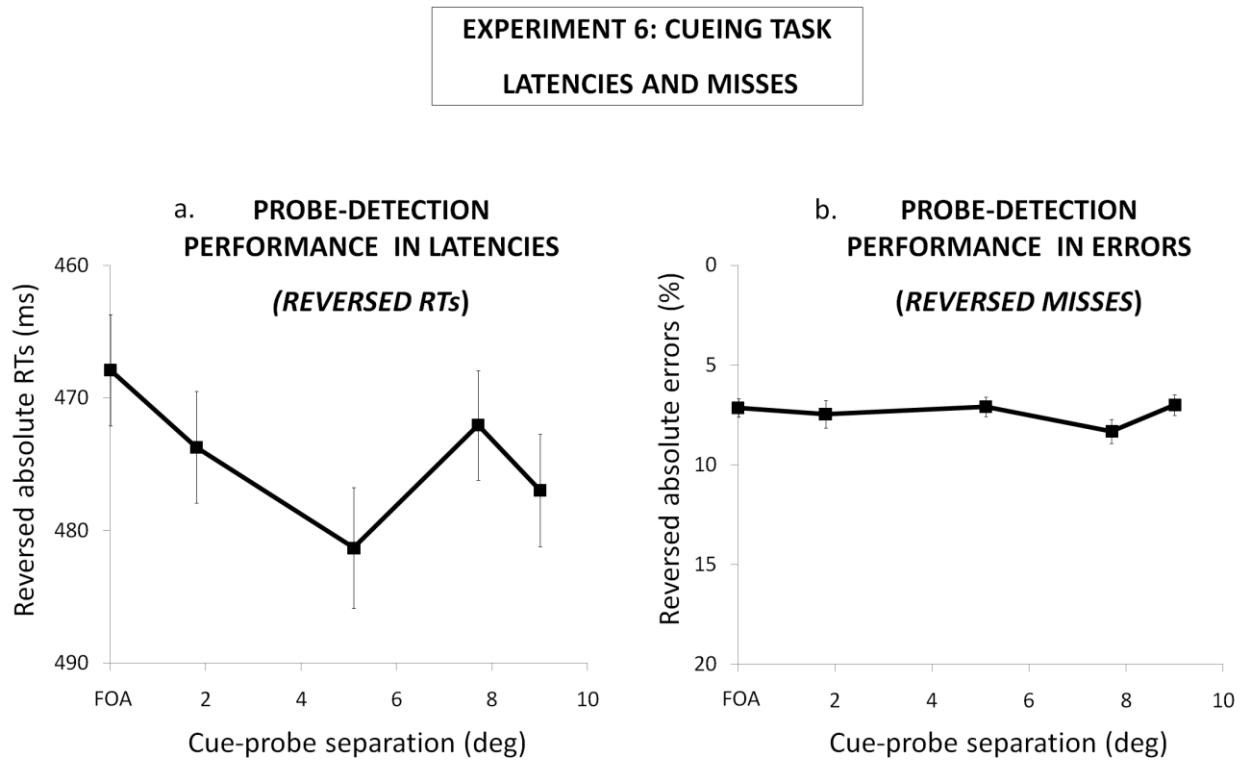
The first analysis compared RTs (and errors) for probe detection when the probe occurred at the cued location (separation 0.0 deg) with RTs (and errors) for probe detection when the probe occurred at an uncued location (separations 1.8 to 9.0 deg pooled together) by means of a *t*-test. This analysis tested whether performance at detecting the probe was better when the probe occurred at the cued location than at other (uncued) locations. If this was found to be the case, it would show that the cue was effective at focusing perceptual resources around the cued location.

The second analysis tested for the effect of cue-probe separation and cued location on probe-detection performance, when the probe occurred at an *uncued* location, using a

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<sup>12</sup> note that, on Figures 21, 22 and 23, performance at detecting the probe is plotted by *reversing* RTs and errors. This mode of presentation of the data allows a direct comparison between the results of the cue/probe and flanker tasks.

repeated-measures ANOVA. This analysis allowed us to test whether probe-detection performance was modulated by the separation between probe and cued location. If this was found to be the case, polynomial trends were applied to determine the shape of the function of separation.



**Figure 21**

*Experiment 6 – Performance on latencies and errors in the cue/probe task. The figure shows probe-detection performance on latencies (i.e., latencies presented on a reversed axis, in ms) and on error percentages (i.e., error percentages presented on a reversed axis, in%) as a function of cue-probe separation (in deg). Error bars depict +/- 0.5 SEM. (FOA) = attended location (i.e., cued location).*

### ***3.4.2.2.1 Comparison of probe-detection performance at cued and uncued locations***

#### **Reaction times**

Consistent with numerous previous studies (e.g., Posner, 1980; Henderson, 1991; Henderson & Macquistan, 1993), the *t*-test analysis showed that probe-detection RTs were faster when the probe occurred at the cued location than at the uncued locations (pooled across cue-probe separations;  $t(15) = 2.97$ ,  $p = 0.010$ ,  $d = 0.21$ ): the cue was effective at attracting perceptual resources to the cued location.

#### **Errors (misses)**

The first analysis showed that misses for probe detection were not different when the probe occurred at the cued location compared to when it occurred at uncued locations (pooled across all cue-probe separations;  $t(15) = 0.542$ ,  $p = 0.596$ ,  $d = 0.077$ ): there was no evidence in the error data that the cue attracted perceptual resources to the cued location.

### ***3.4.2.2.2 Effect of Cue-probe Separation and Cued Location on probe-detection performance when the probe occurred at uncued locations***

#### **Reaction times**

The second analysis showed that the main effect of Separation was significant ( $F(3,45) = 4.73$ ,  $p = 0.006$ ,  $\eta_p^2 = 0.240$ ): probe-detection performance varied with the separation between probe and cued location. Polynomial trends for the effect of Separation showed that probe-detection performance as a function of separation was best explained by a



cubic trend ( $F(1,15) = 11.76, p = 0.004, \eta_p^2 = 0.439$ ; the  $p$  values for linear and quadratic trends were above 0.100): performance at detecting the probe first decreased and then increased, before tailing off, with increasing separation, consistent with a Mexican-hat profile for the profile of perceptual resources (Müller et al., 2005).

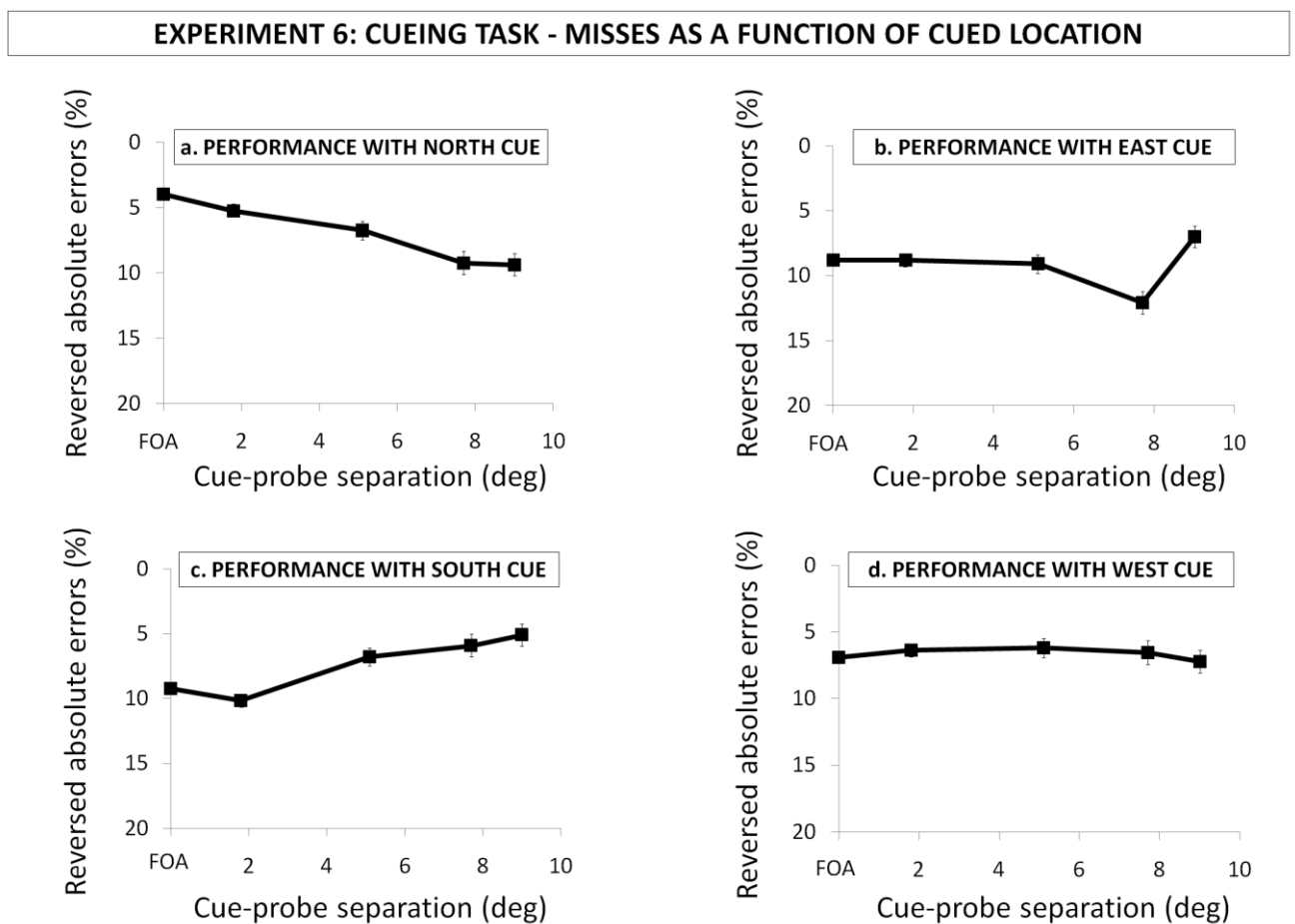
Probe-detection performance was not significantly affected by Cued Location ( $F(3,45) = 0.51, p = 0.680, \eta_p^2 = 0.033$ ) and the interaction between Separation and Cued Location was not significant either ( $F(4.1,61.3) = 1.99, p = 0.105, \eta_p^2 = 0.117$ ).

### **Errors (misses)**

The second analysis showed that the main effect of Separation was not significant ( $F(3,45) = 1.06, p = 0.375, \eta_p^2 = 0.066$ ): probe-detection misses overall did not vary with the separation between probe and cued location. The main effect of Cued Location was not significant either ( $F(3,45) = 2.01, p = 0.126, \eta_p^2 = 0.118$ ).

On the other hand, the interaction between Separation and Cued Location was significant ( $F(4.0,60.0) = 3.77, p < 0.001, \eta_p^2 = 0.201$ ). In order to investigate the origins of this interaction, the effect of Separation on probe-detection performance was tested at each level of Cued Location. It was found that probe-detection performance significantly varied with separation for the North cued location ( $F(3,45) = 4.44, p = 0.008, \eta_p^2 = 0.229$ ). Polynomial trends for the effect of Separation showed that the function of separation was best explained by a linear trend ( $F(1,15) = 13.05, p = 0.003, \eta_p^2 = 0.465$ ; the  $p$  values for the quadratic and cubic trends were higher than 0.100). Probe-detection performance also significantly varied with separation for the East cued location ( $F(3,45) = 3.94, p = 0.014, \eta_p^2 = 0.208$ ). Polynomial trends for the effect of

Separation showed that the function of separation was best explained by a combination of quadratic and cubic trends (respectively  $F(1,15) = 8.28, p = 0.012, \eta_p^2 = 0.356$  and  $F(1,15) = 3.32, p = 0.088, \eta_p^2 = 0.181$ ; the  $p$  value for the linear trend was  $> 0.100$ ). On the other hand, probe-detection performance did not significantly vary with separation for the South cued location ( $F(1.63,24.4) = 3.35, p = 0.061, \eta_p^2 = 0.182$ ) or for the West cued location ( $F(3,45) = 0.413, p = 0.745, \eta_p^2 = 0.027$ ; see Figure 22).



**Figure 22**

*Experiment 6 – Performance on errors in the cue/probe task. The figure shows probe-detection performance on error percentages (i.e., error percentages presented on a reversed axis, in %) as a function of cue-probe separation (in deg) and cued location (North, East, South or West). Error bars depict  $\pm 0.5$  SEM. (FOA) = attended location (i.e., cued location).*

### 3.4.3 Discussion

In Experiment 6, participants were tested on two different tasks, namely, the flanker task (Eriksen & Hoffman, 1973) and the cue/probe task (Posner, 1980), in order to index, at four different separations from the attended location, (1) *incompatible-distractor total interference* (in the flanker task), (2) *combined response-related interference* (in the flanker task), and (3) *probe-detection performance* (in the cue/probe task).

First, we discuss the findings for the flanker task. It was found that *incompatible-distractor total interference* was significant and that it was modulated by separation, describing a Mexican-hat pattern similar to those observed in Experiments 2 to 5. Unlike in Experiments 2 to 5, however, *combined response-related interference* was not significant (in RTs; it was significant in errors but did not significantly vary with separation and could therefore not be used to index the profile of perceptual resources in errors). The fact that *incompatible-distractor total interference* was significant when *combined response-related interference* was not suggests that, in the RTs of Experiment 6, the effect of incompatible distractors was mostly exerted through *salience-related interference*.

It is unclear why incompatible distractors did not produce response-related interference in Experiment 6 (unlike in Experiments 2 to 5). This may have been linked to the presence of a probe at the distractor location in half the trials. Indeed, the absence of response-related interference was especially apparent when a probe was present at the

distractor location (see Figure 17). It is possible that the presence of a probe at the distractor location reduced its capacity to exert response-related interference by masking its identity. The latter possibility is consistent with the observation that, in no-distractor trials, when the probe occurred at the target location, participants appeared to be slower at target identification (see Figure 17).

One implication of the above findings is that using *combined response-related interference*, as indexed by comparing compatible-distractor performance with incompatible-distractor performance (e.g., Anderson & Kramer, 1993; Debener, Ullsperger, Siegel, Fiehler, von Cramon, & Engle, 2005; Forster & Lavie, 2007; Hommel, 2003; Iani, Ricci, Gherri, Rubichi, 2006; Kramer & Jacobson, 1991; LaBerge et al., 1991; Lavie et al., 2004; Maruff, Danckert, Camplin, & Currie, 1999; Matchock & Mordkoff, 2007; Mattler, 2006; McCarley & Mounts, 2008; Müller et al., 2005; Murphy & Eriksen, 1987; Paquet, 2001; Pan & Eriksen, 1993), is not always the most sensitive way to probe the profile of perceptual resources. By using *incompatible-distractor total interference*, as indexed by comparing no-distractor performance with incompatible-distractor performance, the sensitivity of the task is increased. In the following experiments where an incompatible distractor was used we therefore continued the practice of extracting *incompatible-distractor total interference* in addition to the other measures of distractor interference.

We now move to discussing the findings obtained with the cue/probe task. Firstly, it was found that performance at detecting the probe was better at the cued location than at any uncued location (see Figure 21), suggesting that the cue successfully attracted perceptual resources to the cued location despite being completely irrelevant to the task

(Henderson & Macquistan, 1993; Luck & Thomas, 1999). Secondly, it was found that, when the probe occurred at an uncued location, *probe-detection performance* varied with cue-probe separation, describing a Mexican-hat pattern similar to the one obtained in the flanker task (compare Figures 17 and 21): probe-detection performance first decreased but then increased, before tailing off, with increasing separation.

The consistency between the shapes of the functions of separation measured in the flanker and the cue/probe tasks dispelled the doubts as to whether the cue/probe paradigm actually measures the same processes as the flanker paradigm. This finding opens up the possibility to use a variant of the cue/probe task to show that what is measured in both the flanker and cue/probe paradigms is an attentional phenomenon, namely, the profile of perceptual resources. This can be done by repeating the cue/probe task of Experiment 6 in the absence of a cue. If performance as a function of separation really reflects the profile of perceptual resources then, when the cue is absent, the separation function should become flat. This possibility was tested in Experiment 7.

### **3.5 EXPERIMENT 7: The attentional nature of the separation function**

In this experiment, the participants had to detect a probe that occurred in half the trials at any one of 12 possible locations (the same positions as in Experiment 6). The display was exactly the same as the one used in Experiment 6 (see Figure 16), except that there was *no cue*. In other words, target and distractor letters were present in Experiment 7, albeit irrelevant to the task. The probe occurred at the distractor location (on 80% of the trials) or, when no distractor was present, it occurred at the target location (on 20% of

the trials). The separation between the target (irrelevant in this task) and the probe was systematically manipulated (it varied from 0.0 to 9.0 deg). The manipulation of target-probe separation in this experiment was *equivalent* to the manipulation of cue-probe separation in Experiment 6 (since, in Experiment 6, target-probe and cue-probe separations were *equivalent*; see Experiment 6).

### **3.5.1 Method**

#### ***3.5.1.1 Design***

Target-probe separation and target location were manipulated at fixed stimulus eccentricity in a repeated-measures design.

#### ***3.5.1.2 Participants***

16 participants from Goldsmiths College (11 females; 2 left-handed; mean age 21 yr; age range 18 to 27 yr; see Appendix 8) with reported normal or corrected-to-normal vision took part in the experiment in exchange for course credits. All of them were first-year undergraduates. They were all naïve as to the aim of the study.

#### ***3.5.1.3 Stimuli and procedure***

The stimuli and procedure were exactly the same as in the cue/probe task of Experiment 6 except that there was no cue.

### **3.5.2 Results**

We analyzed both the latencies and errors (i.e., misses and false alarms) of probe-detection ('present' vs. 'absent') responses. It was found that the probe was falsely

reported in only 3.5% of probe-absent trials. Additionally, the probe was missed in 7.4% of probe-present trials, showing a bias towards responding that the probe was absent ( $t(15) = 5.20, p < 0.001, d = 0.74$ ). Latencies were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented an average of 93.5% of the latencies overall.

For each participant, mean probe-detection RTs (and misses) were calculated for probe-present trials at each of the four levels of Target Location (i.e., ‘North’, ‘East’, ‘South’ and ‘West’, corresponding to the four levels of Cued Location in Experiment 6) and at each of the five levels of Target-probe Separation (i.e., 0.0, 1.8, 5.1, 7.7 or 9.0 deg, corresponding to the five levels of Cue-probe Separation in Experiment 6; see Figure 23). Moreover, RTs (and false alarms) were calculated for probe-absent trials at each of the four levels of Target Location. Three analyses were performed on *probe-present* RTs (and misses).

The first analysis compared RTs (and misses) for probe detection when the probe occurred at the target location (separation 0.0 deg, corresponding to the cued location in Experiment 6) with RTs (and misses) for probe detection when the probe occurred at a location other than the target location (i.e., separations 1.8 to 9.0 deg pooled together, corresponding to the uncued locations in Experiment 6) by means of a *t*-test. If it was found that, in the *absence* of a cue, performance at detecting the probe was similar when the probe occurred at the target location to when it occurred at other locations, this would show that the effect of the cue on overall performance in Experiment 6 was

really due to perceptual resources being focused around the cued location rather than only due to irregularities in the visual field.

The second analysis tested for the effect of target-probe separation on performance at detecting the probe, when the probe occurred at a location other than the target location, using a repeated-measures ANOVA. This analysis extracted probe-detection performance as a function of target-probe separation (and target location). If the function of separation was found to be flat in the *absence* of a cue, this would show that the function of separation observed in Experiment 6 really expressed the profile of perceptual resources rather than only irregularities in the visual field.

The third analysis compared probe-detection performance as a function of target-probe separation measured in this experiment with probe-detection performance as a function of cue-probe separation measured in Experiment 6. If an interaction was found between the factors Experiment and Separation, this would show that the effects observed in Experiment 6 were not only due to irregularities in the visual field.

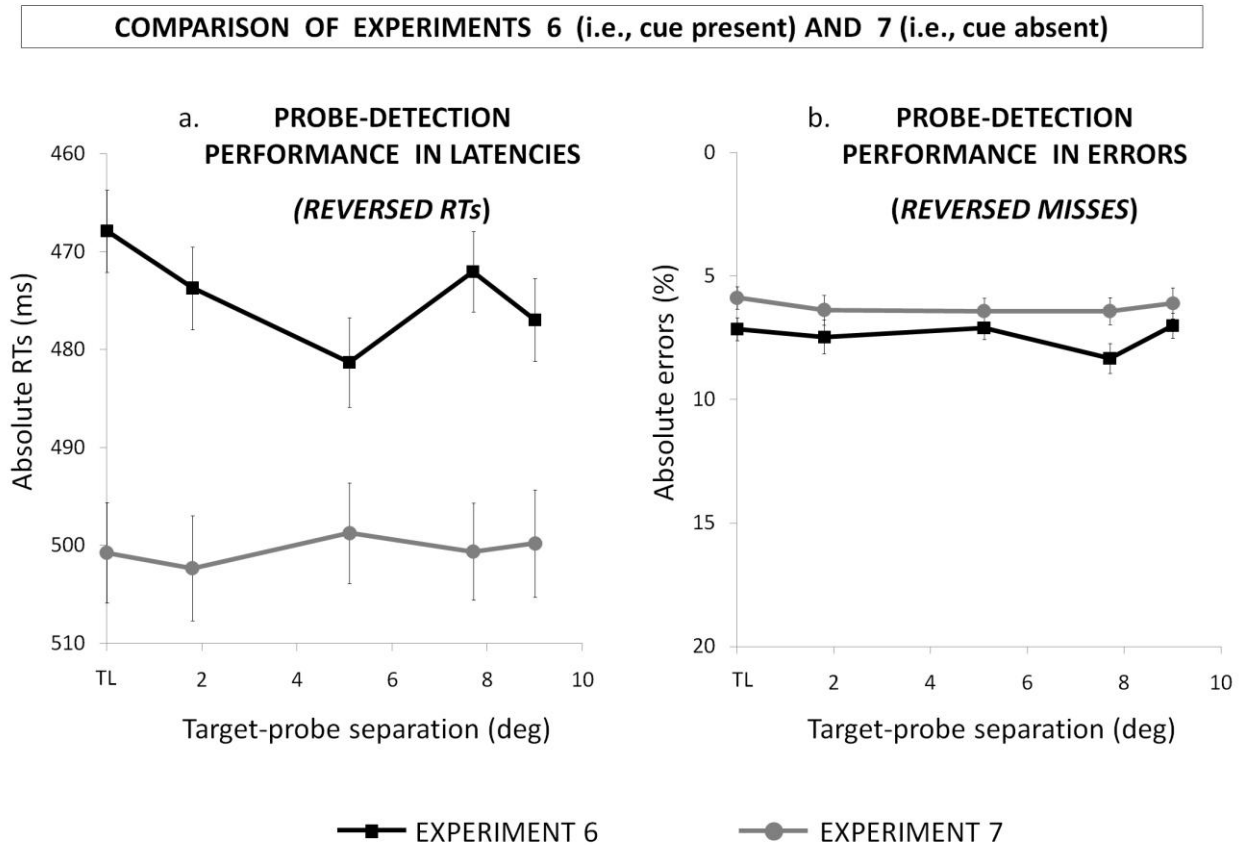
### ***3.5.2.1 Comparison of probe-detection performance at target and non-target locations***

#### **Reaction times**

This analysis showed that there was no significant difference between probe-detection RTs for a probe occurring at the target location and for a probe occurring at another (non-target) location (pooled across separations 1.8 to 9.0 deg;  $t(15) = 0.17$ ,  $p = 0.870$ ,



$d = 0.005$ ). This finding shows that the difference between performance at the cued location and performance at uncued locations in Experiment 6 was really due to the presence of the cue. In the absence of a cue, perceptual resources are not focused on the target location (see Figure 23).



**Figure 23**

*Experiments 6 and 7— Performance on latencies and errors in the cue/probe task. The figure shows probe-detection performance on latencies (i.e., latencies presented on a reversed axis, in ms) and on error percentages (i.e., error percentages presented on a reversed axis, in%) as a function of target-probe separation (in deg) and experiment (Experiment 6 or 7). Error bars depict +/- 0.5 SEM. (■) = Experiment 6; (●) = Experiment 7. (TL) = Target Location.*

## **Errors**

The analysis showed that there was no significant difference between probe-detection errors for a probe occurring at the target location and for a probe not occurring at the target location (pooled across separations 1.8 to 9.0 deg;  $t(15) = 0.76$ ,  $p = 0.459$ ,  $d = 0.095$ ).

### ***3.5.2.2 Effect of Target-probe Separation and Target Location on probe-detection performance***

## **Reaction times**

The analysis showed that the main effect of Separation was not significant ( $F(3,45) = 0.832$ ,  $p = 0.483$ ,  $\eta_p^2 = 0.053$ ): probe-detection performance did *not* vary with the separation between target and probe.

Probe-detection performance was also not affected by Target Location ( $F(3,45) = 2.11$ ,  $p = 0.112$ ,  $\eta_p^2 = 0.124$ ) and the interaction between Separation and Target Location was not significant ( $F(9,135) = 0.99$ ,  $p = 0.451$ ,  $\eta_p^2 = 0.062$ ), showing that probe-detection performance as a function of target-probe separation was flat irrespective of the target location.

## **Errors**

The analysis showed that neither the main effect of Separation, nor the main effect of Target Location, nor the interaction between Separation and Target Location were significant (respectively,  $F(3,45) = 0.23$ ,  $p = 0.877$ ,  $\eta_p^2 = 0.015$ ;  $F(3,45) = 0.84$ ,  $p = 0.479$ ,  $\eta_p^2 = 0.053$ ; and  $F(9,135) = 0.73$ ,  $p = 0.678$ ,  $\eta_p^2 = 0.047$ ).

### **3.5.2.3 Comparison of probe-detection performance as a function of separation measured in Experiments 6 and 7**

#### **Reaction times**

This analysis showed that the main effect of Experiment (i.e., Presence of Cue) was not significant ( $F(1,30) = 1.10, p = 0.303, \eta_p^2 = 0.035$ ), in other words, RTs were not *overall* significantly different whether a cue was present or absent. On the other hand, there was a significant interaction between the factors Separation and Experiment ( $F(3,90) = 3.00, p = 0.035, \eta_p^2 = 0.101$ ), confirming that, while probe-detection as a function of separation described a Mexican-hat pattern in Experiment 6, it was flat in Experiment 7 (see Figure 23). Finally, the interaction between Target Location and Experiment was not significant ( $F(3,90) = 0.67, p = 0.575, \eta_p^2 = 0.022$ ), and nor was the three-way interaction between Target Location, Separation and Experiment ( $F(9,270) = 0.63, p = 0.775, \eta_p^2 = 0.020$ ).

#### **Errors**

The analysis showed that neither the main effect of Experiment (i.e., Presence of Cue) on errors, nor the interaction between Separation and Experiment, were significant (respectively,  $F(1,30) = 0.519, p = 0.477, \eta_p^2 = 0.017$  and  $F(3,90) = 0.16, p = 0.922, \eta_p^2 = 0.005$ ). The interaction between Target Location and Experiment was not significant either ( $F(3,90) = 0.48, p = 0.701, \eta_p^2 = 0.016$ ) and nor was the three-way interaction between Target Location, Separation and Experiment ( $F(6.2,186.5) = 1.76, p = 0.107, \eta_p^2 = 0.055$ ).

### 3.5.3 Discussion

In the absence of a cue in the cue/probe task, probe-detection performance as a function of separation was *flat*. The Mexican-hat functions measured in Experiment 6 were truly attentional, namely, the expression of the profile of perceptual resources.

## **3.6 Discussion of Chapter 3**

The experiments of this chapter tested three indices that have been used to index the profile of perceptual resources, namely, (1) *incompatible-distractor response-related interference* (in the flanker task), (2) *saliency-related interference* (in the flanker task), and (3) *probe-detection performance* (in the cue/probe task). It was examined whether the functions of separation obtained with these three indices agreed with the function of separation obtained with another commonly-used index, namely, *combined response-related interference* (see Chapter 2). This was found to be the case; the functions of separation obtained with all four indices followed a similar *Mexican-hat* pattern (see Experiments 4, 5 and 6). Importantly, it was confirmed in this chapter that the Mexican-hat functions obtained in Experiments 1 to 6 (Chapters 2 and 3) were the expression of the attentional distribution (Experiment 7).

The main implications of the findings of the experiments presented in this chapter are that (1), when using the flanker task, *incompatible-distractor response-related interference* and *saliency-related interference*, as well as *combined response-related interference*, can be used to measure the profile of perceptual resources, and that (2), when using the cue/probe task, a ‘complete’ Mexican-hat can be measured, with an

initial decreasing arm followed by an increasing arm, and this profile agrees with the one obtained with the flanker task. These findings are discussed below.

### 3.6.1 Results of the flanker task

The present experiments confirmed that the Mexican-hat profile of perceptual resources can be measured using both *saliency-related interference* or *incompatible-distractor response-related interference* (which can contain residual *saliency-related interference*; see Introduction of this chapter). If previous studies measuring *saliency-related interference* or *incompatible-distractor response-related interference* as a function of separation have *not* shown such a Mexican-hat pattern, it is likely to be because these studies sampled only part of the profile of perceptual resources (because the latter was too defocused; see Introduction of this chapter and Chapter 2).

Because saliency-related and response-related interference index the same Mexican-hat profile (see Figure 15), it follows that these two types of interference can be used interchangeably to measure the profile of perceptual resources (see Experiment 5). An implication of this finding is that studies that measure the profile of perceptual resources by looking only at response-related interference arguably use a blunter measure. Indeed, in Experiment 6, the profile of perceptual resources could not be measured using response-related interference.<sup>13</sup> In this experiment, the distractors generated mainly saliency-related interference. Thus, by combining both types of interference into one measure (i.e., by using *incompatible-distractor total interference*, namely, by comparing no-distractor performance with incompatible-distractor

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<sup>13</sup> While there was evidence for response-related interference in errors, the latter did not significantly vary with separation and, therefore, it could not be used to measure the profile of perceptual resources.

performance), one obtains a more sensitive index of perceptual resources and, therefore, a more powerful tool for studying selective attention.

### **3.6.2 Results of the cue/probe task**

In the Introduction of this chapter, we proposed that the reason why some cue/probe studies have revealed *inverted gradients* when others have revealed simple *gradients* is due to the fact that different studies have sampled different parts of the Mexican-hat profile: these studies may have *missed* either the first decreasing arm or the subsequent increasing arm of the Mexican-hat profile due to methodological limitations. One such limitation is that, in some studies, the bottom of the Mexican hat may have occurred so close to, or so far from, the attended location that it was *not possible* to sample, respectively, the first decreasing arm, or the subsequent increasing arm, of the Mexican hat.

This idea could account for several findings in the literature: in Mounts (2000b), the bottom of the Mexican hat occurred at around 1.0 deg, in Hopf et al. (2006), at around 1.5 deg, in Cutzu and Tsotsos (2003) and in Bahcall and Kowler (1999), at around 2.0 deg. A first decreasing arm would have been difficult (or impossible) to observe in these studies (indeed, in our experiments we could not have sampled closer than 1.5 deg). Several factors could have caused the bottom of the Mexican hat to occur so close to the attended location in these studies (compared to our experiments where it occurred at around 5.1 deg). For instance, it is possible that load and individual differences focused perceptual resources (see Chapters 4 and 5).

Another limitation that could explain why previous studies have *missed* either the first decreasing arm or the subsequent increasing arm of the Mexican-hat profile is that previous studies may have used a methodology that was not sensitive enough (see Chapter 2). The most obvious lack of sensitivity comes from insufficient density or range of separation sampling. For instance, some studies that have revealed inverted-gradient patterns have sampled only beyond 3.0 deg of separation (Hodgson et al., 1999; Kristjansson & Nakayama, 2002). If the bottom of the Mexican hat had occurred closer than, or at, 3.0 deg in these studies, they would have missed the first decreasing arm of the Mexican hat. Moreover, several studies that revealed gradient patterns have sampled only three separations (Henderson, 1991; Henderson & Macquistan, 1993; Shulman et al., 1985; Williams, 1988). In these studies, the increasing arm of the Mexican hat could easily have been missed altogether due to the insufficient density of separation sampling.

In sum, a highly focused profile and/or a lack of sensitivity may have caused previous cue/probe studies to reveal either gradient or inverted-gradient functions of separation. In the present experiment, we have shown a complete Mexican-hat pattern, with a first decreasing arm and a subsequent increasing arm. In addition, the function of separation was very similar to the one observed in the flanker task. This finding argues against the suggestion by Müller et al. (2005) that the cue/probe task is not adequate to index the profile of perceptual resources (because it would divide attention) and suggests that both cue/probe and flanker paradigms index the same mechanisms.

### **3.7 Conclusions**

The present experiments confirmed that, in the flanker task, both salience-related and response-related interference can be used to index a Mexican-hat profile of perceptual resources. What is more, just like the flanker task, the cue/probe task can be used to index this profile. Nevertheless, in the coming experiments, we employ only the flanker task because it is arguably more sensitive than the cue/probe task since it can index the profile of perceptual resources using *both* salience-related and response-related interference of distractors. Moreover, the flanker task is arguably more immune to the criticism that it examines divided attention. Even though our data did not support this criticism, the latter may become more valid as more spatial separations are sampled and the validity of the cue decreases (in the following experiments we sample five, instead of four, separations).

In the next chapter, we use a flanker task similar to the one described in this chapter and probe attention using both salience-related and response-related interference. We test whether perceptual load and the availability of cognitive resources affect the focus of perceptual resources, which could explain why previous flanker and cue/probe studies have revealed gradient or inverted-gradient rather than Mexican-hat profiles.



# CHAPTER 4 – PERCEPTUAL AND COGNITIVE LOAD

## **4.1 Introduction: Effects of load on the focus of perceptual resources**

In Chapter 3, we confirmed the results from Chapter 2 and from the literature (Müller et al., 2005) that the profile of perceptual resources describes a Mexican-hat pattern. In the present chapter, we built upon this finding, and upon the finding that the Mexican-hat profile can be measured using both response-related and salience-related interference (see Chapter 3), to apply our new approach to investigate whether perceptual and cognitive load affect the focus of perceptual resources.

When load has been exerted on perceptual processes (by increasing the difficulty of the perceptual task), a decrease in distractor interference has been *assumed* to result from a focusing of perceptual resources, namely, an increase in the efficiency of the perceptual level of selection (e.g., Forster & Lavie, 2007; LaBerge, Brown, Carter, Bash, & Hartley, 1991; Lavie, 1995; Lavie et al., 2004; Lavie & Tsal, 1994; Madden & Langley, 2003; Maylor & Lavie, 1998). On the other hand, when load has been exerted on cognitive-control mechanisms (by increasing the difficulty of a cognitive task performed in addition to a primary selection task), an increase in distractor interference has been *assumed* to result from a decrease in the efficiency of the cognitive blocking of perceptually processed distractors, namely, of the post-perceptual level of selection

(e.g., de Fockert et al., 2001; Lavie & de Fockert, 2005, 2006; Lavie et al., 2004; Maylor & Lavie, 1998), rather than from a defocusing of perceptual resources. Below we summarise the results of these perceptual- and cognitive-load studies and describe a limitation that they all suffer from and how to tackle this limitation.

#### **4.1.1 Perceptual and cognitive load: a common limitation of previous studies**

Studies combining the flanker paradigm with perceptual-load manipulations have typically suggested that perceptual load determines the efficiency of perceptual selection by changing the focus of perceptual resources (e.g., LaBerge et al., 1991; Kahneman & Chajczyk, 1983; Lavie, 1995; 2000; 2005; Lavie et al., 2004; Lavie & Fox, 2000; Lavie & Tsal, 1994; MacDonald & Lavie, 2008). For example, LaBerge et al. (1991) had their participants identify two target elements occurring at the same location in rapid temporal succession. The *second* target was always flanked by peripheral distractors (at a constant target-distractor separation). When the *first* target was perceptually harder to process, the distractors flanking the second target produced less interference. The authors suggested that when perceptual difficulty increased, perceptual resources became more spatially focused on the attended location, thus causing them to be withdrawn from the peripheral distractor locations, or ‘sucked in’.

While it is widely accepted that perceptual resources can be focused by bottom-up perceptual mechanisms, the possibility that they can be focused by top-down cognitive-control mechanisms has been ignored. Indeed, top-down cognitive-control mechanisms have been hypothesised only to affect post-perceptual levels of selection (de Fockert et al., 2001; Lavie et al., 2004; Lavie & de Fockert, 2005, 2006; Macdonald & Lavie, 2008; Yi, Woodman, Widders, Marois, & Chun, 2004). For example, Lavie et al.

(2004) had their participants perform a working-memory task in addition to a target-identification one. The extent to which a peripheral distractor affected performance (at constant separation and perceptual load) was measured as a function of cognitive load. It was shown that when the memory task was harder (i.e., cognitive load was higher), distractors affected performance more. The authors suggested that, under high cognitive load, post-perceptual levels of selection (e.g., the mechanisms rehearsing task priorities) were not as efficient at excluding perceptually processed distractors.

Summarising the literature on the flanker paradigm, whenever perceptual load has been *increased*, a decrease in distractor interference has been interpreted as reflecting a spatial focusing of perceptual resources (e.g., LaBerge et al., 1991; Lavie, 1995). On the other hand, whenever cognitive load has been *decreased*, the identical decrease in distractor interference has been interpreted as reflecting an increase in the efficiency of post-perceptual levels of selection with no effect on the focus of perceptual resources (Lavie et al., 2004). While these interpretations are entirely reasonable, they are undersupported by the data if a change in distractor interference can equally well originate at perceptual or post-perceptual levels of selection. For example, a change in distractor interference accompanying manipulations of perceptual load could also have been effected (at least in part) by changes in post-perceptual processing if perceptual manipulations can affect post-perceptual levels. In addition, if cognitive effects can penetrate to perceptual levels (as suggested by the work of Soto, Heinke, Humphreys, & Blanco, 2005), a change in distractor interference accompanying manipulations of cognitive load could have been effected (at least in part) by changes in the focus of perceptual resources (and consequent changes in perceptual processing). This latter possibility is arguably the more likely. The uncertainty emerges from the fact that two

hypothesized processes (i.e., perceptual and post-perceptual levels of selection) both read out into one dependent variable (i.e., the amplitude of distractor interference at a fixed separation).

#### **4.1.2 Tackling the limitation of previous studies**

The aim of the experiments in this chapter was to use a combination of two dependent variables in order to be in a position to distinguish between perceptual and post-perceptual levels of attentional selection (using purely behavioural measures that obviate the need to look inside the brain). These experiments capitalised on the inherently spatial nature of the perceptual level of selection (i.e., of the focusing of perceptual resources) compared to the non-spatial nature of the post-perceptual level. It extracted two dependent variables, one spatial (the extent of focus of the distractor-interference function; see Chapter 2) and the other non-spatial (the amplitude of distractor interference across separations). The spatial dependent variable was obtained by measuring where the bottom of the Mexican-hat function of separation occurred, thus indexing the efficiency of the perceptual level of selection. The non-spatial dependent variable, namely, the *amplitude* of distractor interference across separations, was used to index the efficiency of the post-perceptual level of selection. Note that the amplitude of distractor interference across separations was informative *only* when considered together with the extent of focus of the function of separation. Changes in the amplitude of distractor interference across separations were proposed to index variations in the efficiency of post-perceptual selection only when these changes were *not* accompanied by changes in the extent of focus of the function of separation; on the other hand, when they *were* accompanied by changes in the extent of focus of the

separation function, these same amplitude changes could have resulted from variations in the efficiency of perceptual and/or post-perceptual selection.

We tested the effect of perceptual and cognitive load on distractor interference as a function of separation. We were interested to see whether (i) increasing perceptual load does indeed focus the distractor-interference function of separation (i.e., whether increasing perceptual load focuses the Mexican-hat profile of perceptual resources) and whether (ii) increasing cognitive load penetrates perceptual processing and defocuses the distractor-interference function of separation (rather than *just* affecting post-perceptual processing by increasing the amplitude of distractor interference *without* affecting the extent of focus of the function of separation).

Both the amplitude of distractor interference across separations and the extent of focus can be extracted by using the flanker paradigm with a manipulation of separation as was done in Chapters 2 and 3. While most previous flanker studies that have used load to examine selective attention (see above) have sampled only one separation or pooled across separations<sup>14</sup>, one flanker study has already manipulated separation but only to examine the effects of perceptual load (not cognitive load) and then without showing that perceptual load focuses perceptual resources (Müller, Mollenhauer, Rösler & Kleinschmidt, 2005). The authors argued that increasing perceptual load caused

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<sup>14</sup> On the other hand, this lack of separation sampling is not characteristic of studies that have tested the effect of load on the extent of focus of perceptual resources using the *cue/probe paradigm* (Posner, 1980). Indeed, the findings of some of these studies (Downing, 1988; Handy, Kingston, & Mangun, 1996; Williams, 1988) are consistent with a focusing effect of perceptual load and our study is in part an attempt to generalise these findings to the flanker paradigm.

participants to draw upon *additional* perceptual resources rather than *focusing* extant ones. Nevertheless, it is possible that Müller et al.'s load manipulation was insufficiently strong to cause variations in the spatial focus of perceptual resources.

In contrast to Müller et al.'s (2005) study manipulating perceptual load and separation, there have been no studies that have manipulated cognitive load and separation and examined the focus of perceptual resources. Yet, some data suggest that cognitive load may affect not only post-perceptual levels of selection but also the spatial focus of perceptual resources (i.e., the perceptual level of selection). Indeed, Scerif, Worden, Davidson, Seiger and Casey (2006) showed that increasing the expectation of distraction caused early perceptual components in the ERPs to distractors to decrease. These findings imply that cognitive-control mechanisms *may* make perceptual resources more tightly focused.

Experiments 8 to 11 tested the effects of perceptual and cognitive load on the perceptual and/or post-perceptual levels of selective attention by combining load manipulations with a flanker task such as that used in Chapter 3.

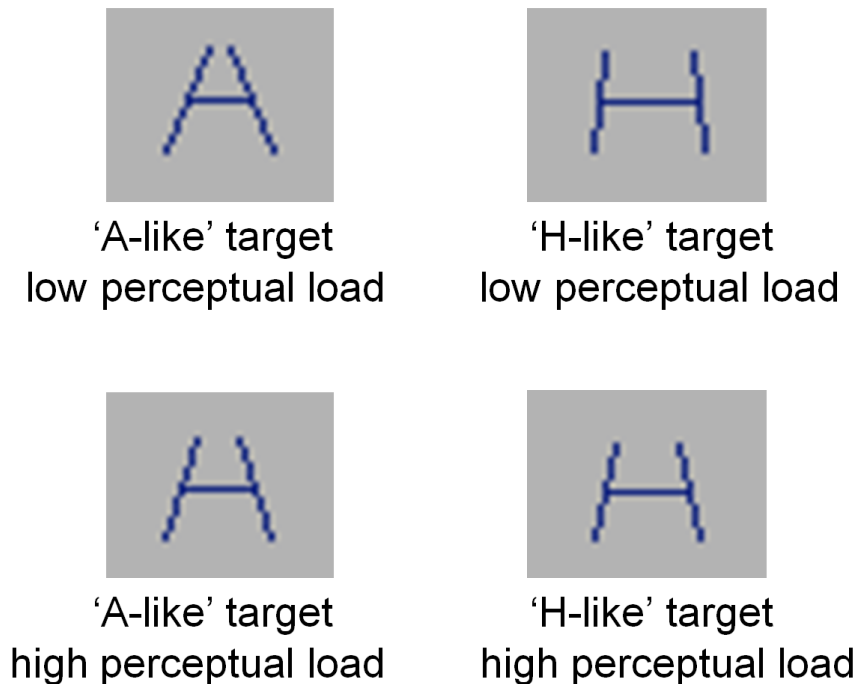
## **4.2 EXPERIMENT 8: Perceptual load and working-memory span**

This experiment tested whether an increase in perceptual load only affects the amplitude of distractor interference across separations (as suggested by the findings of Müller et al., 2005) or causes a spatial focusing of the interference function of separation (as indexed by a shifting of the bottom of the Mexican-hat function towards the attended location). Each participant was tested under high- and low-perceptual-load

conditions using a high-salience paradigm similar to that used in Experiment 5 (see Chapter 3).

Perceptual-load manipulations have typically consisted in varying the visual noise around a target letter by adding peripheral noise stimuli (e.g., Lavie, 1995; Lavie et al., 2004). This manipulation cannot be used when target-distractor separation is varied, since a distractor at small separations will be masked more by the noise stimuli than a distractor at large separations. For this reason, the manipulation of perceptual load in Experiment 8 rather consisted in rendering the target more or less difficult to identify perceptually. Following Handy and Mangun (2000), the letters 'A' and 'H' were morphed to produce ambiguous target letters which were either 'A-like', in more resembling 'A', or 'H-like', in more resembling 'H'. The participants had to signal whether the morphed letter was more similar to 'A' or 'H' with a 2-AFC. Critically, in the low-perceptual-load condition, this discrimination was relatively easy (the 'A-like' letter closely resembled 'A' and the 'H-like' letter closely resembled 'H'; see upper half of Figure 24) whereas, in the high-perceptual-load condition, it was difficult (the 'A-like' and 'H-like' letters were much harder to categorise; see lower half of Figure 24).

## EXPERIMENT 8: TARGET STIMULI



**Figure 24**

*Experiment 8 - Method. A representation of the four possible target letters. The left column presents the two possible 'A-like' targets and the right column the two possible 'H-like' targets. The top row presents the targets used in the low-perceptual-load condition and the bottom row those used in the high-perceptual-load condition.*

It should be noted that, when the target is ambiguous, a response-relevant (i.e., *incompatible* or *compatible*) distractor can produce interference going in *two opposite directions*. Namely, the distractor can generate its traditional response-related interference (i.e., competition for incompatible distractors and facilitation for compatible distractors) but also an effect going in the opposite direction (known as the 'negative flanker effect'; Rouder & King, 2003). For instance, due to the negative flanker effect an incompatible 'H' distractor can facilitate identification of an 'A-like' target – by providing a contrast with the target – while due to response-competition it can impair target identification. In order to avoid performance reflecting a combination



of effects going in opposite directions, response-relevant (i.e., both compatible and incompatible) distractors were not used in Experiment 8. Instead, neutral distractors (that cannot generate response-related interference and can generate only *saliency-related interference*) were used, as it was shown in Experiment 5 (see Chapter 3) that these distractors can index the profile of perceptual resources.

Experiment 8 also tested whether working-memory span (i.e., the availability of cognitive resources; Engle et al., 1992; Engle, 2002; Kane & Engle, 2002; Lépine et al., 2005) affects the spatial focus of perceptual resources (as suggested by the findings of Scerif et al., 2006; see Introduction of this chapter). Participants' working-memory span was assessed in a separate session before the main experiment using the automated operation-span (OSPAN) task (Unsworth, Heitz, Schrock, & Engle, 2005).

Since Experiment 8 tested the effect of individual differences on distractor interference *and* used a distractor that could only generate saliency-related interference and thus created less distraction (see Experiment 5, Chapter 3), a larger number of participants was tested than in previous experiments.

#### **4.2.1 Method**

##### ***4.2.1.1 Design***

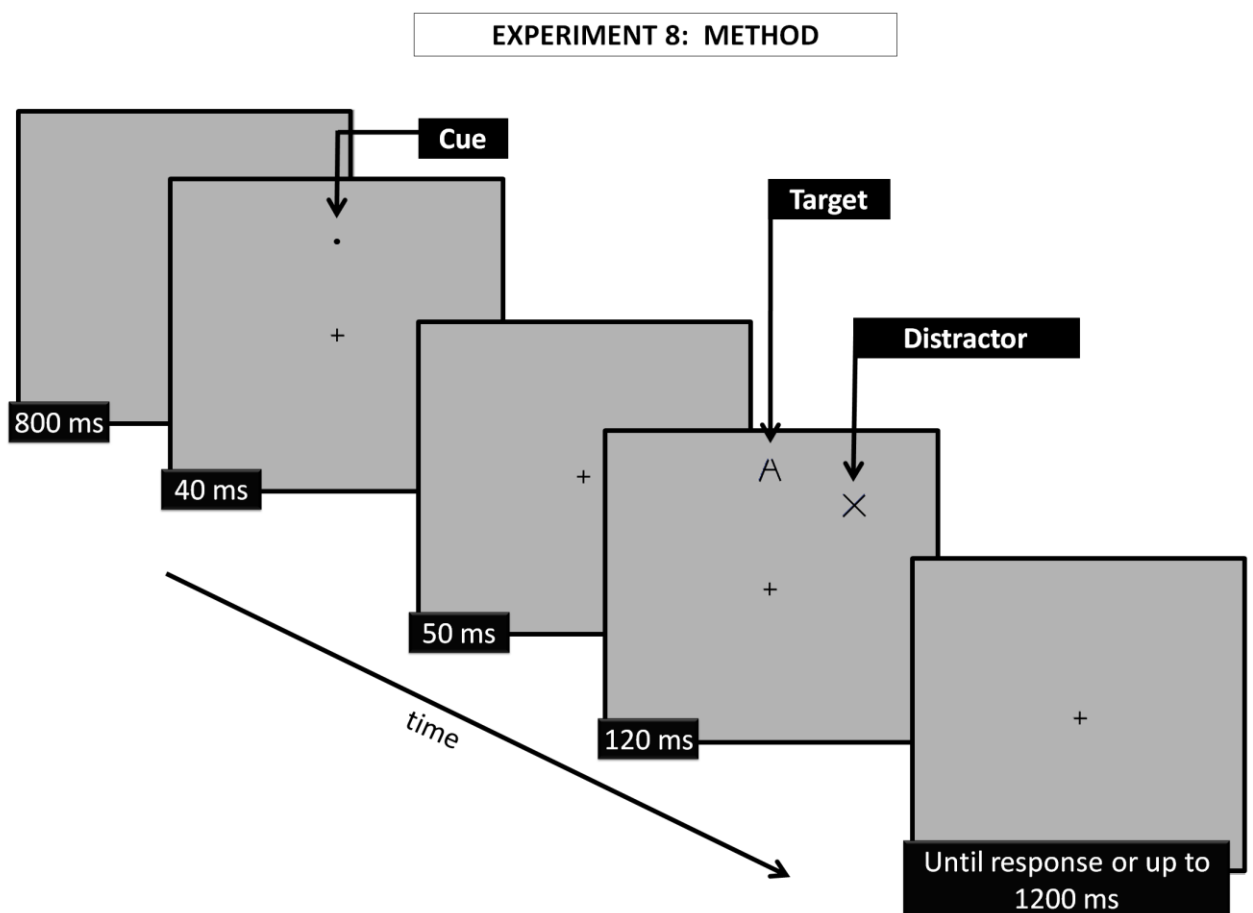
A mixed design was used in which target-distractor separation (at controlled stimulus eccentricity) and perceptual load were manipulated within participants and working-memory span was 'manipulated' across participants.

#### 4.2.1.2 Participants

54 participants from Goldsmiths College (47 females; 6 left-handed; mean age 22.8 yr; age range 18 to 29 yr; see Appendix 9) with normal or corrected-to-normal vision took part in the experiment in exchange for course credits. They were all naïve as to the aims of the study.

#### 4.2.1.3 Stimuli and procedure for the target-identification task

The method was similar to that used in Experiment 5 (see Chapter 3) except for the differences detailed below (see Figure 25).



**Figure 25**

*Experiment 8 – Method. A schematic representation of an experimental trial. The presentation of an exogenous cue indicated the location (always North, East, South or*

West) of the target ('A-like' or 'H-like') with 100% validity. Participants signalled target identity (with a 2-AFC) while ignoring a neutral ('X') distractor letter that occurred in 72% of trial at one of five possible target-distractor separations (1.8, 3.5, 5.1, 7.7 or 9.0 deg). The figure illustrates an 'A-like' target and a target-distractor separation of 3.5 deg.

The target and distractor letters subtended 0.80 by 0.80 deg. The target letter was an ambiguous letter that was either 'A-like' (in more resembling 'A' than 'H') or 'H-like' (in more resembling 'H' than 'A'; see Figure 24). Both 'A-like' and 'H-like' letters were made up of a horizontal line, and two oblique lines that slanted in toward each other at the top of the letter. Perceptual load was manipulated by altering the separation between the oblique lines at the *top* of the letters (the separation at the bottom of letters was always 0.80 deg). The 'A-like' letter was more similar to a *real* 'A' in the low-perceptual-load condition (where the separation at the top of the letter was 0.16 deg) than in the high-perceptual-load condition (where the separation at the top of the letter was 0.32 deg). Similarly, the 'H-like' letter resembled a real 'H' more in the low-perceptual-load condition (where the separation at the top of the letter was 0.72 deg) than in the high-perceptual-load condition (where the separation at the top of the letter was 0.48 deg).

When the distractor letter was present (in 72% of trials), it was always neutral (the letter 'X'). In 28% of trials, there was no distractor and the target appeared on its own. The latter constituted the no-distractor, baseline condition.

Experiment 8 lasted 45 minutes. It consisted of two separate load sessions (low and high perceptual load) performed by participants in counterbalanced order. Each load session comprised 448 trials (in 7 blocks), preceded by 60 practice trials.

#### ***4.2.1.4 Stimuli and procedure for the working-memory task***

The mouse-driven automated version of the operation-span (OSPAN) task was used to assess participants' working-memory span (for a full description and analysis of the task, see Unsworth et al., 2005). It was performed during lab classes on a different day from the target-identification task.

In order to derive the operation span of participants, the latter performed a memory task interleaved with a maths task. Each trial went as follows: first, a letter was presented (for 800 ms) that had to be memorized. It was replaced by the presentation of a maths problem that the participants had to solve within a limited time that was determined for each participant on the basis of their performance in the practice session. After participants had solved the maths problem, or after the limited time had elapsed, a new letter appeared on the screen that was also to be memorized. After the presentation of three to seven letters and as many maths problems, participants were asked to recall all the letters they had memorized in their order of presentation.

The participants memorized a total of 75 letters presented across 15 trials (three trials each of three-, four-, five-, six- and seven-letter trials) and therefore also solved 75 problems. After every trial, feedback was given for both the memory and the maths task. Participants were asked to maintain an accuracy of at least 85% in the maths task while doing as well as possible on the memory task. OSPAN scores were calculated as follows: if a participant correctly recalled three letters on a three-letter trial (correct recall), four letters on a four-letter trial (correct recall) and three letters on a five-letter trial (incorrect recall), his or her OSPAN score after these three trials would be:  $3 + 4 +$

0 = 7. The maximum possible OSPAN score after the full complement of 15 trials was 75 (if all letters on all trials were correctly recalled) and the minimum score was zero.

#### **4.2.2 Results**

In the working-memory task, the average score was 33.5 and the median score 32.5. The participants were median split into two groups of 27 participants each (with scores ranging from 6 to 32 in the ‘low-working-memory’ group and from 33 to 68 in the ‘high-working-memory’ group).

We analyzed both the speed and accuracy of forced-choice target-identification (A-like vs. H-like) responses. Response latencies (RTs) were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented 89.1% of the latencies overall.

For each participant, mean RTs (and error percentages) were calculated for neutral-distractor trials at the five target-distractor separations (1.8, 3.5, 5.1, 7.7 and 9.0 deg) and in each condition of perceptual load (low and high; see Figure 26). Moreover, for each participant, no-distractor RTs (and errors) were randomly separated into five bins in each condition of perceptual load, and mean RTs (and error percentages) were calculated for each bin. The bins were used as baselines to match the five target-distractor separations in each condition of perceptual load.

*Neutral*-distractor performance was compared with *no*-distractor performance as a function of (1) separation, (2) perceptual load and (3) working-memory span using a

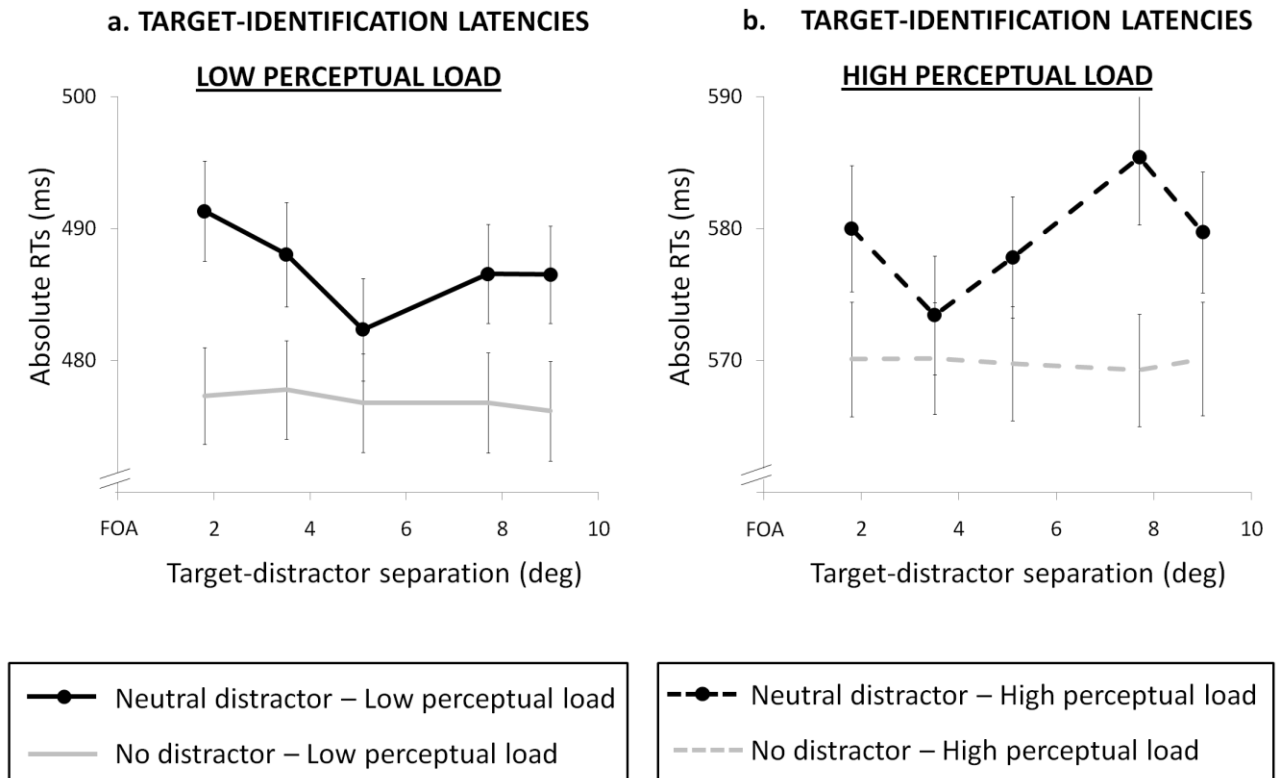
mixed-design ANOVA on both the latency and error data.<sup>15</sup> This allowed us to isolate *salience-related interference* and to test whether the interference function of separation was affected by perceptual load and working-memory span.

A difference in the shapes of the interference functions between the two perceptual-load conditions, or between the two working-memory-span conditions, would emerge if (1) the function in one condition was more focused than the function in the other condition or (2) the function in one condition was steeper than the function in the other condition while being *similarly focused*. These two possibilities can be discriminated by testing whether the bottom of one function occurs closer to the attended location than the bottom of the other function, indicating that one function is *more focused* than the other one, or whether the bottoms of the two functions occur at similar separations from the attended location, indicating that the functions are *similarly focused* but one function is *steeper* than the other one. These two possibilities can be tested using interpolation analyses on the interference functions of separation. These interpolations allow us to derive the separation at which the bottom of each function occurs. It is then possible to test whether these separations are different or not.

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<sup>15</sup> Note that, in this experiment and following ones, the effect of Target Location was also tested but is not reported as Target Location did not interact with other factors.

**EXPERIMENT 8: EFFECT OF PERCEPTUAL LOAD**



**Figure 26**

*Experiment 8 – Latencies. The figure shows: (1) neutral-distractor mean latencies (in ms) as a function of target-distractor separation (in deg) and perceptual load (high or low) – see black lines; and (2) no-distractor mean latencies (in ms) as a function of perceptual load (high or low) – see grey lines. Error bars depict +/- 0.5 SEM. (FOA) = attended location.*

**4.2.2.1 Comparison of neutral- with no-distractor RTs as a function of separation, perceptual load and working-memory span**

**Reaction times**

This analysis tested for the effects of four factors, namely, Presence of Neutral Distractor, Separation, Perceptual Load and Working-memory Span on target-identification RTs using a mixed-design ANOVA. Where there was a significant

interaction, additional analyses, namely, ANOVAs and interpolation analyses, were performed to understand the origin of the interaction.

#### *Effects of Presence of Neutral Distractor, and Separation*

The main effects of both Presence of Neutral Distractor, and Separation were significant (respectively,  $F(1,52) = 56.63$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.521$  and  $F(3.4,177.6) = 3.16$ ,  $p = 0.021$ ,  $\eta_p^2 = 0.057$ ) and the interaction between Presence of Neutral Distractor, and Separation was also significant ( $F(4,208) = 3.94$ ,  $p = 0.004$ ,  $\eta_p^2 = 0.170$ ). In other words, neutral distractors generated significant *salience-related interference* and the latter varied with separation. Polynomial trends for the interaction showed that *salience-related interference* as a function of separation was explained by a combination of quadratic and cubic trends (respectively  $F(1,52) = 4.26$ ,  $p = 0.044$ ,  $\eta_p^2 = 0.076$  and  $F(1,52) = 8.71$ ,  $p = 0.005$ ,  $\eta_p^2 = 0.143$ ; the linear and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile (thus replicating the findings of Experiment 5).

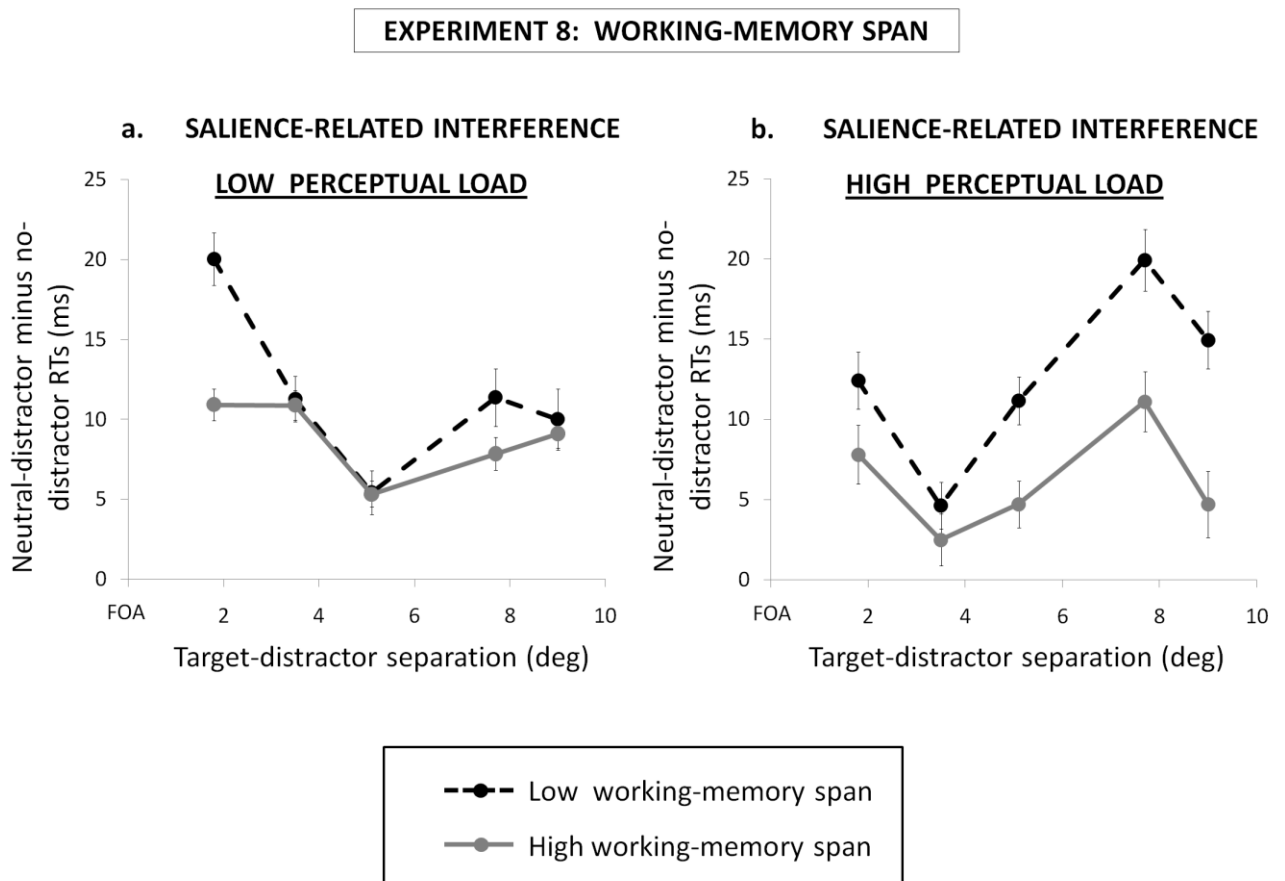
#### *Effect of Working-memory Span*

The main effect of Working-memory Span was not significant ( $F(1,52) = 0.16$ ,  $p = 0.690$ ,  $\eta_p^2 = 0.003$ ), suggesting that task performance was overall the same in low- as in high-span participants. On the other hand, Working-memory Span marginally interacted with Presence of Neutral Distractor ( $F(1,52) = 3.56$ ,  $p = 0.065$ ,  $\eta_p^2 = 0.064$ ),



suggesting that neutral distractors generated more *saliency-related interference* pooled across separations in low- than high-span participants (see Figure 27).<sup>16</sup>

Working-memory Span did not interact significantly with Separation ( $F(4,208) = 1.03$ ,  $p = 0.394$ ,  $\eta_p^2 = 0.019$ ). Moreover, the three-way interaction between Working-memory Span, Presence of Neutral Distractor, and Separation was not significant ( $F(4,208) = 0.662$ ,  $p = 0.619$ ,  $\eta_p^2 = 0.013$ ), showing that working-memory span did not affect the *extent of focus of saliency-related-interference* as a function of separation: the bottom of the function occurred at the same separation in low- as in high-span participants.



<sup>16</sup> Additional analyses also showed that there was an inverted correlation between working-memory span and the amplitude of saliency-related interference across separations ( $r = -0.27$ ,  $p = 0.052$ ).

### **Figure 27**

*Experiment 8 – Latencies. Saliency-related interference of neutral distractors, derived by subtracting no-distractor latencies from neutral-distractor latencies, as a function of target-distractor separation (in deg), perceptual load (high or low), and working-memory span (high or low). (●) = low working-memory span; (●) = high working-memory span; (FOA) = attended location.*

#### *Effect of Perceptual load*

The main effect of Perceptual Load was significant (participants were overall slower by 95 ms in the high-perceptual-load condition;  $F(1,52) = 167.84, p < 0.001, \eta_p^2 = 0.763$ ), showing that the perceptual-load manipulation successfully affected the difficulty of target identification (see Figure 26). The two-way interaction between Perceptual Load and Separation was also significant ( $F(4,208) = 2.70, p = 0.032, \eta_p^2 = 0.149$ ). Moreover, the three-way interaction between Perceptual Load, Presence of Neutral Distractor, and Separation was significant ( $F(4,208) = 2.66, p = 0.034, \eta_p^2 = 0.149$ ), showing that *saliency-related interference* as a function of separation was different in low- and high-perceptual-load conditions (see further analyses below).

No other interactions were significant. First, Perceptual Load did not interact significantly with Presence of Neutral Distractor ( $F(1,52) = 0.06, p = 0.814, \eta_p^2 = 0.001$ ). This showed that *saliency-related interference* pooled across separations was similar in both load conditions. Second, none of the interactions involving Perceptual Load and Working-memory Span were significant (all  $p$  values  $> 0.100$ ). This shows that the effects of Perceptual Load were not affected by the working-memory span of the participants.

Given that the interaction between Perceptual Load, Presence of Neutral Distractor, and Separation was significant, the effects of Presence of Neutral Distractor, and Separation were investigated separately for each condition of Perceptual Load.

In both perceptual-load conditions, the interaction between Presence of Neutral Distractor, and Separation was significant (respectively, for low and high load:  $F(4,212) = 3.89, p = 0.005, \eta_p^2 = 0.068$  and  $F(3.4,178.3) = 3.00, p = 0.027, \eta_p^2 = 0.054$ ). Polynomial trends for the interactions showed that the *salience-related interference* as a function of separation was explained by a quadratic trend in the low-load condition ( $F(1,53) = 12.82, p = 0.001, \eta_p^2 = 0.195$ ; the linear, cubic and quartic trends had  $p$  values  $> 0.100$ ) and by a cubic trend in the high-load condition ( $F(1,53) = 6.27, p = 0.015, \eta_p^2 = 0.106$ ; the linear, quadratic and quartic trends had  $p$  values  $> 0.100$ ). In the low-load condition, *salience-related interference* as a function of separation described a similar Mexican-hat shape to the function measured in Experiment 5 (compare Figures 15 and 26). In the high-perceptual-load condition, on the other hand, while *salience-related-interference* as a function of separation also described a Mexican-hat pattern, it appeared to be *more focused*, with a bottom occurring closer to the attended location (see Figures 26). This finding was tested using interpolation analyses that isolated the location of the bottom of each participant's interference function in each perceptual-load condition.

#### *Comparison of the locations of the bottoms of the functions of separation*

A cubic model was used for these interpolation analyses (see Results of Experiment 2, Chapter 2, for details on the methodology used). For each perceptual-load condition and for each participant, the separation at which the 'local minimum' or bottom of the

interference function occurred (i.e., the point where the function stopped decreasing and started increasing) was estimated by calculating the derivative of the fitted function. The local minima so derived were compared across the two perceptual-load conditions for all participants. The group-mean local minimum occurred at 5.43 deg (SEM = 0.26) in the low-perceptual-load condition and 4.56 deg (SEM = 0.29) in the high-perceptual-load condition. This difference was significant ( $t(52) = 2.21, p = 0.032, d = 0.441$ ). In other words, the bottom of the function occurred closer to the attended location in the high- than the low-perceptual-load condition.

### **Errors**

This analysis tested for the effects of four factors, namely, Presence of Neutral Distractor, Separation, Perceptual Load and Working-memory Span on target-identification errors using a mixed-design ANOVA.

The main effect of Perceptual Load was significant (participants made 8% more errors in the high-perceptual-load condition;  $F(1,52) = 181.56, p < 0.001, \eta_p^2 = 0.777$ ), confirming that the perceptual-load manipulation successfully affected the difficulty of target-identification. On the other hand, none of the other main effects or interactions on errors was significant (all  $p$  values  $> 0.100$ ).

### **4.2.3 Discussion**

First of all, the low-perceptual-load condition of Experiment 8 produced a Mexican-hat interference function of separation similar to those observed in Experiments 2 to 6 (see Chapters 2 and 3). Thus, neutral ('X') distractors were again found to be effective in mapping the spatial profile of perceptual resources. Nevertheless, as neutral distractors

can generate only *saliency-related interference*, they are less sensitive probes of the profile of perceptual resources than incompatible distractors (which can generate *both* saliency-related and response-related interference). For this reason, incompatible distractors were again used in the following experiment.

Experiment 8 showed that an increase in perceptual load causes the spatial profile of perceptual resources to focus (as indexed by the moving in of the bottom of the Mexican-hat function). This finding is consistent with several findings of cue/probe studies (Downing, 1988; Handy et al., 1996; Williams, 1988).

Experiment 8 also showed that although the efficiency of cognitive-control mechanisms (as indexed by participants' working-memory span; Engle et al., 1992; Engle, 2002; Kane & Engle, 2002; Lépine et al., 2005) affected the amplitude of *saliency-related interference* across separations (i.e., the lower the memory span, the more distractors generated *saliency-related interference*; as in Lavie & de Fockert, 2005, 2006) it had no effect on the spatial focus of perceptual resources (i.e., changes in memory span did not cause any shift in the bottom of the interference function of separation; see Figure 27). This finding is consistent with the suggestion that cognitive-control mechanisms are involved in rejecting perceptually-processed distractors at a post-perceptual level but not involved in the control of the spatial focusing of perceptual resources (de Fockert et al., 2001; Lavie et al., 2004; Lavie & de Fockert, 2005; 2006; MacDonald & Lavie, 2008; Yi et al., 2004). It is possible, however, that the null effect of working-memory span on the focus of perceptual resources in Experiment 8 stemmed from a lack of power of the cognitive manipulation. In fact, even participants with poor cognitive control (i.e., low working-memory span) may have had enough cognitive resources to

focus perceptual resources in Experiment 8, which arguably involved only a low cognitive load. Experiment 9 was designed to put cognitive-control mechanisms under more stress. This was achieved by adding a secondary memory task to the target-identification task (de Fockert et al., 2001; Lavie et al., 2004; Lavie & de Fockert, 2005; 2006; MacDonald & Lavie, 2008).

### **4.3 EXPERIMENT 9 : Cognitive load**

Experiment 9 used a method similar to that used in Experiment 5 (see Chapter 3), except that a secondary cognitive-load task was intercalated between trials. In the cognitive-load task, the participants had to memorize either one (low-cognitive-load condition) or six (high-cognitive-load condition) digits before the beginning of each set of twenty trials. In addition, only incompatible distractors were used in this experiment. This is because, as incompatible distractors generate *both* salience-related and response-related interference, they are more sensitive probes of the profile of perceptual resources than neutral distractors (see Figure 15). The reason why we did not include other types of distractors is that we wanted to limit the number of trials in this experiment. Indeed, the effect of cognitive load wears off with practice (data from several of our pilot experiments have shown this). Since only incompatible distractors were used in Experiment 9, their effect was measured by comparing no-distractor performance with incompatible-distractor performance. This index isolates the *total* of salience-related and response-related interference and is referred to as *incompatible-distractor total interference* (see Experiment 6, Chapter 3).

### **4.3.1 Method**

#### ***4.3.1.1 Design***

A repeated-measures design was used in which target-distractor separation (at controlled stimulus eccentricity) and cognitive load were manipulated.

#### ***4.3.1.2 Participants***

31 participants from Goldsmiths College (22 females; 4 left-handed; mean age 21 yr; age range 18 to 27 yr; see Appendix 10) with normal or corrected-to-normal vision took part in the experiment in exchange for course credits or £8. They were all naïve as to the aims of the study.

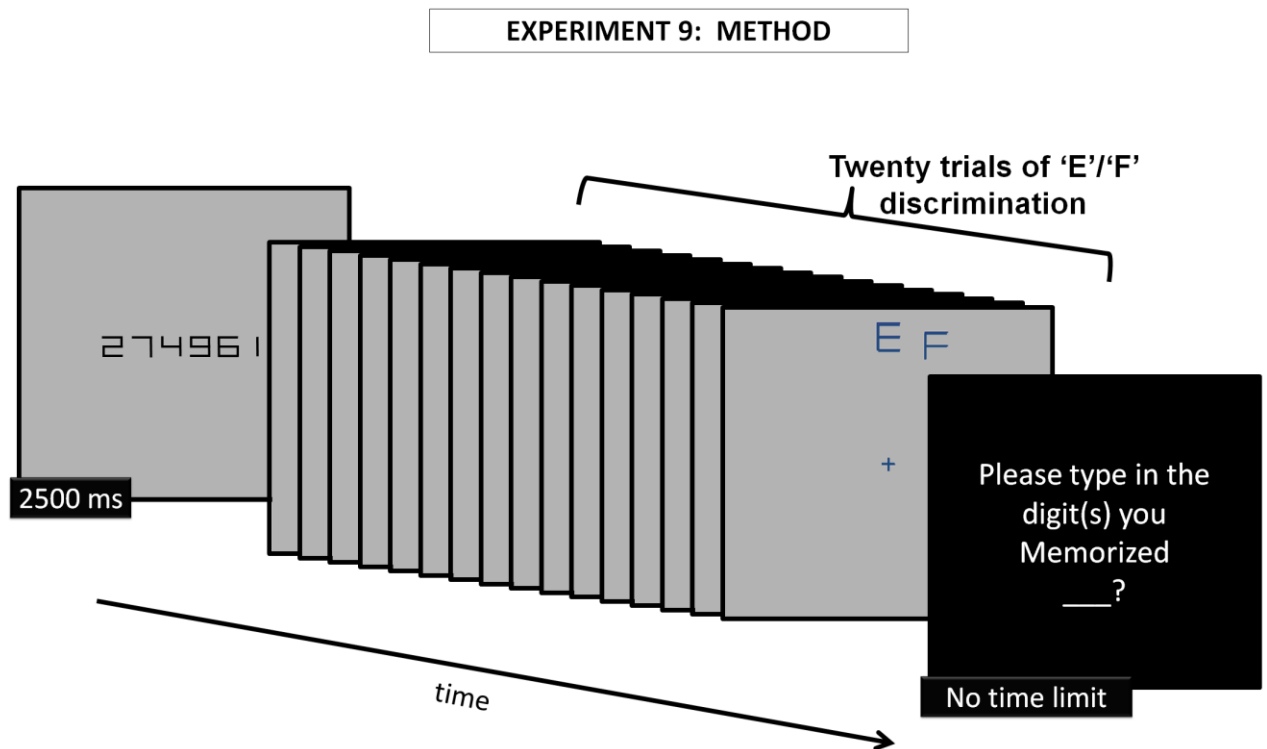
#### ***4.3.1.3 Stimuli and procedure for the target-identification task***

The method for the target-identification task was as in Experiment 5 (see Chapter 3). The target and distractor were always the letters ‘E’ or ‘F’. The distractor, when present (in 75% of the trials), was always response-incompatible (e.g., if the target was ‘E’, the distractor was ‘F’). On 25% of trials, no distractor was presented and the target appeared on its own. The latter constituted the no-distractor, baseline condition.

#### ***4.3.1.4 Stimuli and procedure for the cognitive task***

A working-memory task was interleaved between target-identification trials in order to manipulate cognitive load (see Figure 28). Each block of 20 target-identification trials was preceded by the presentation of six digits (displayed in a horizontal array at the centre of the screen) for 2500 ms. Participants had to memorise either the lowest number of the sequence (in the low-cognitive-load condition) or the whole sequence of

six numbers in the correct order (in the high-cognitive-load condition); after completing the 20 target-identification trials, they then had to type in the one or six digits they had memorized (there was no time limit, but sequence knowledge was required in the high-cognitive-load condition). No feedback was given.



**Figure 28**

*Experiment 9 – Method. A schematic representation of one block of twenty target-identification trials. Each block of trials started with the presentation of six digits. Participants had to memorise either the lowest digit (low-cognitive-load condition) or the whole sequence of six digits (high-cognitive-load condition). Then they performed twenty trials of 'E'/'F' target identification (see Method of Experiment 5). Finally, they were asked to type in the digit(s) they had memorised before the next block of trials started.*

Experiment 9 lasted about 50 minutes. It consisted of two separate load sessions (low- and high-cognitive-load) performed by participants in counterbalanced order. Each load



condition comprised 500 target-identification trials (in 25 blocks each of 20 trials), preceded by 60 practice trials (in 3 blocks each of 20 trials).

### **4.3.2 Results**

In each cognitive-load condition, the working-memory task involved 25 memorisations. Correct memorisation was defined as the recall of the single digit that had to be memorized, in the low-cognitive-load condition, or as the recall in the correct order of at least five out of the six digits that had to be memorized, in the high-cognitive-load condition. The working-memory task was well performed by all participants (96% accuracy in both cognitive-load conditions). Thus, on average, participants performed 24 out of the 25 memorisations correctly and no participant ever performed less than 20 memorisations correctly.

We analyzed both the speed and accuracy of forced-choice target-identification responses. Target-identification trials were only analysed when they occurred in a block of trials that was followed by a correct memory-task memorisation. In addition, and as usual, response latencies (RTs) were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented 87.6% of the latencies overall.

For each participant, mean RTs (and error percentages) were calculated for incompatible-distractor trials at each of the five target-distractor separations (1.8, 3.5, 5.1, 7.7 and 9.0 deg) and in each condition of cognitive load (low and high; see Figure 29). Moreover, for each participant, no-distractor RTs (and errors) were randomly separated into five bins in each condition of cognitive load, and mean RTs (and error

percentages) were calculated for each bin. The bins were used as baselines to match the five target-distractor separations in each condition of cognitive load.

*Incompatible*-distractor performance was compared with *no*-distractor performance as a function of (1) separation and (2) cognitive-load using a repeated-measures ANOVA on both the latency and error data. This allowed us to isolate *incompatible-distractor total interference* (i.e., the sum of incompatible-distractor salience-related and response-related interference) and to test whether the interference function of separation was affected by cognitive load. A difference in the shape of the interference function between the two cognitive-load conditions would emerge if (1) the function in one load condition was *more focused* than the function in the other load condition or (2) the function in one load condition was *steeper* than the function in the other load condition while being *similarly focused*. These two possibilities can be discriminated using interpolation analyses on the interference functions of separation (see Results of Experiment 8).

#### ***4.3.2.1 Comparison of incompatible- with no-distractor RTs as a function of separation and cognitive load***

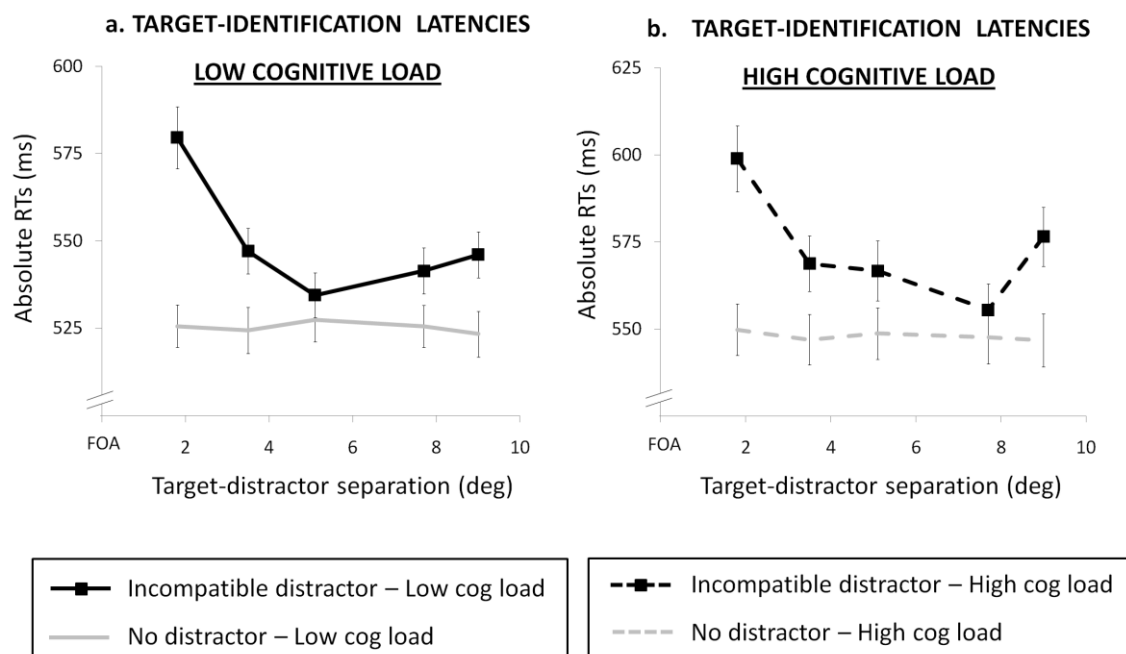
##### **Reaction times**

This analysis tested for the effects of three factors, namely, Presence of Incompatible Distractor, Separation and Cognitive Load on target-identification RTs using a repeated-measures ANOVA. Where there was a significant interaction, additional analyses, namely, ANOVAs and interpolation analyses, were performed to understand the origin of the interaction.

### Effects of Presence of Incompatible Distractor, and Separation

The main effects of both Presence of Incompatible Distractor, and Separation were significant (respectively,  $F(1,30) = 60.80$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.670$  and  $F(2.4,70.4) = 19.06$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.389$ ) and the interaction between Presence of Incompatible Distractor, and Separation was also significant ( $F(2.5,71.9) = 18.81$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.385$ ). In other words, there was evidence for the presence of significant *incompatible-distractor total interference*, and this interference varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear and quadratic trends (respectively  $F(1,30) = 22.41$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.429$  and  $F(1,30) = 30.21$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.502$ ; the cubic and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

#### EXPERIMENT 9: EFFECT OF COGNITIVE LOAD



### **Figure 29**

*Experiment 9 – Latencies. The figure shows: (1) incompatible-distractor mean latencies (in ms) as a function of target-distractor separation (in deg) and cognitive load (high or low) – see black lines; and (2) no-distractor mean latencies (in ms) as a function of cognitive load (high or low) – see grey lines. Error bars depict +/- 0.5 SEM. (FOA) = attended location.*

#### *Effect of Cognitive load*

First, the main effect of Cognitive Load was significant (participants were overall slower by 25 ms in the high-cognitive-load condition;  $F(1,30) = 7.31, p = 0.011, \eta_p^2 = 0.196$ ), showing that the cognitive-load manipulation affected performance at identifying the target (see Figure 29). Second, Cognitive Load did not interact significantly with Presence of Incompatible Distractor ( $F(1,30) = 0.05, p = 0.827, \eta_p^2 = 0.002$ ). This showed that *incompatible-distractor total interference* pooled across separations was similar in both cognitive-load conditions. Third, whereas the two-way interaction between Cognitive Load and Separation was not significant ( $F(3.0,91.3) = 1.72, p = 0.168, \eta_p^2 = 0.054$ ), the three-way interaction between Cognitive Load, Presence of Incompatible Distractor, and Separation was significant ( $F(4,120) = 2.62, p = 0.039, \eta_p^2 = 0.149$ ). The significance of the latter interaction showed that *incompatible-distractor total interference* as a function of separation was different in low- and high-cognitive-load conditions.

Given the significance of the three-way interaction, the effects of Presence of Incompatible Distractor, and Separation were investigated separately for each condition of Cognitive Load. In both load conditions, the interaction between Presence of Incompatible Distractor, and Separation was significant (respectively, for low and high load:  $F(4,120) = 13.42, p < 0.001, \eta_p^2 = 0.309$  and  $F(4,120) = 11.99, p < 0.001, \eta_p^2 =$

0.286). Polynomial trends for the interactions showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear and quadratic trends in *both* low- and high-load conditions (*Low load*, for linear and quadratic trends respectively:  $F(1,30) = 15.73$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.344$  and  $F(1,30) = 28.60$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.488$ , the cubic and quartic trends had  $p$  values  $> 0.100$ ; *High load*, for linear and quadratic trends respectively:  $F(1,30) = 11.43$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.276$  and  $F(1,30) = 21.52$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.418$ , the cubic and quartic trends had  $p$  values  $> 0.100$ ). Thus, the significant interaction between Cognitive Load, Presence of Incompatible Distractor, and Separation was not explained by qualitative differences in the shapes of the functions of separation. Instead, it seemed that this interaction was explained by a difference in the location of the bottom the two functions. Thus, in the low-cognitive-load condition, the bottom of the interference function of separation appeared to have occurred around the same separation as in Experiments 4, 5 and 6 (compare Figures 14, 15, 17 and 29) whereas, in the high-cognitive-load condition, the bottom of the function appeared to have occurred further away from the attended location (see Figure 29). This hypothesis was tested using interpolation analyses that isolated the location of the bottom of each participant's interference function in each cognitive-load condition.

#### *Comparison of the locations of the bottoms of the functions of separation*

Interpolation analyses were performed on the *incompatible-distractor total interference* as a function of separation in each cognitive-load condition (see Results of Experiment 2, Chapter 2, for details on the methodology used). The local minima derived from the interpolation analyses were compared across load conditions.

The group-mean local minimum occurred at 5.56 deg (SEM = 0.23) in the low-cognitive-load condition and at 6.35 deg (SEM = 0.30) in the high-cognitive-load condition. This difference was significant ( $t(52) = 2.21, p = 0.032, d = 0.441$ ). In other words, the bottom of the function occurred closer to the attended location in the low- than the high-cognitive-load condition.

## **Errors**

This analysis tested for the effects of three factors, namely, Presence of Incompatible Distractor, Separation and Cognitive Load on target-identification errors using a repeated-measures ANOVA. Where there was a significant interaction, additional analyses, namely, ANOVAs and interpolation analyses, were performed to understand the origin of the interaction.

### *Effects of Presence of Incompatible Distractor, and Separation*

The main effect of Presence of Incompatible Distractor was significant ( $F(1,30) = 18.59, p < 0.001, \eta_p^2 = 0.383$ ): errors were higher (by 2.5%) in the incompatible- than in the no-distractor condition, showing that there was significant *incompatible-distractor total interference* in the error data. Moreover, both the main effect of Separation and the interaction between Presence of Incompatible Distractor, and Separation were significant (respectively,  $F(4,120) = 6.01, p < 0.001, \eta_p^2 = 0.167$  and  $F(3.1,93.1) = 6.73, p < 0.001, \eta_p^2 = 0.183$ ). The significance of the latter interaction showed that *incompatible-distractor total interference* varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear and quadratic trends (respectively

$F(1,30) = 7.61, p = 0.010, \eta_p^2 = 0.202$  and  $F(1,30) = 12.66, p = 0.001, \eta_p^2 = 0.297$ ; the cubic and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

#### *Effect of Cognitive load*

The main effect of Cognitive Load was marginally significant (participants made 2% more errors in the high-cognitive-load condition;  $F(1,30) = 3.99, p = 0.055, \eta_p^2 = 0.117$ ), confirming that the cognitive-load manipulation affected performance at the target-identification task. On the other hand, Cognitive Load did not significantly interact with any factor in the error data (all  $p$  values  $> 0.100$ ).

### **4.3.3 Discussion**

First, the low-cognitive-load condition of Experiment 9 generated a Mexican-hat interference function of separation similar to those obtained in the comparable conditions of previous experiments (namely, in the conditions that were low in both perceptual and cognitive load).

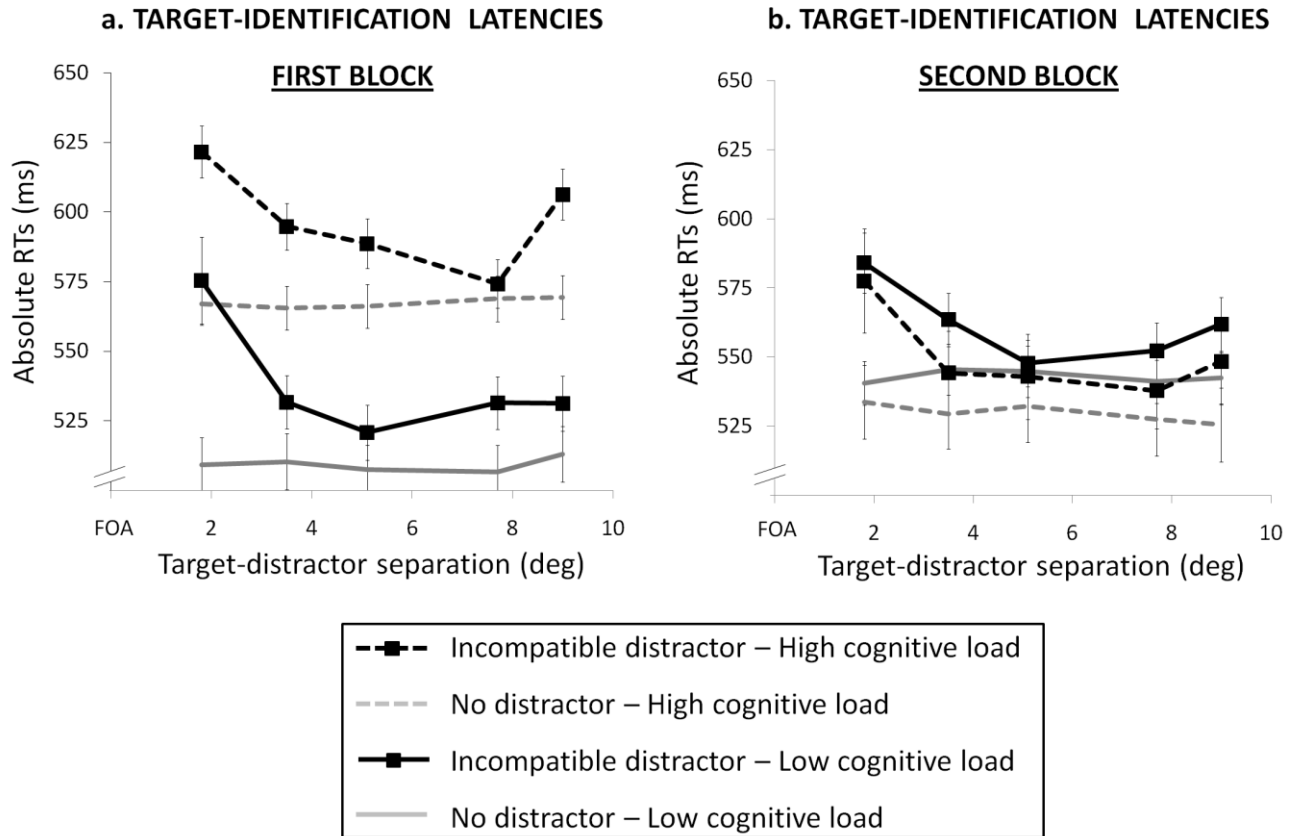
Second, the findings of Experiment 9 suggest that increasing the load on cognitive-control mechanisms caused the profile of perceptual resources to spatially *defocus* (as indexed by the shifting *out* of the bottom of the Mexican-hat function). While the increase in cognitive load had an effect on the spatial profile of distractor interference, it did not show the main effect on distractor interference expressed in Experiment 8 (namely, it did not show an increase in the *amplitude* of distractor interference across separations with increasing cognitive load). Consequently, it did not support the suggestion of Experiment 8 that the availability of cognitive resources affects post-perceptual levels of selection; nevertheless, the defocusing of perceptual resources

observed in Experiment 9 under high cognitive load arguably entailed a redistribution, where perceptual resources increased at certain separations but decreased at others, possibly masking any overall increase in the amplitude of distractor interference across separations. Nevertheless, distractors did appear to interfere *more* in conditions of high than low cognitive load at *some* spatial separations (notably the separation 5.1 deg). The latter observation is therefore consistent with previous suggestions that cognitive load increases distractor interference (e.g., Lavie et al., 2004; Lavie & de Fockert, 2005, 2006).

In sum, the findings of Experiment 9 suggest that increasing cognitive load defocuses the profile of perceptual resources. However, the statistical significance of the defocusing effect of load on the profile of perceptual resources (namely, the statistical significance of the interaction between Cognitive Load, Presence of Incompatible Distractor, and Separation) was not highly significant ( $p = 0.039$ ). This might have been due to an effect of *experimental practice* (i.e., a decreasing influence of load and/or distractor interference with increasing practice; see Experiment 1). This possibility was investigated by running further analyses in which we added the factor ‘Order’ (to distinguish between participants who performed the high-cognitive-load condition first or second). The effect of Order did not reach significance (i.e., all  $p$  values involving this factor exceeded 0.100). Nevertheless, when only the data obtained from the condition performed first were included in the analysis, the effect of Cognitive Load became stronger ( $p = 0.011$ ; see Figure 30). It is therefore possible that practice weakened the cognitive-load manipulation. With this in mind, future experiments manipulated cognitive load across participants.



## EXPERIMENT 9: EFFECT OF PRACTICE



**Figure 30**

*Experiment 9 – Latencies. The figure shows: (1) incompatible-distractor mean latencies (in ms) as a function of target-distractor separation (in deg), cognitive load (high or low), and block of trials (first or second) – see black lines; and (2) no-distractor mean latencies (in ms) as a function of cognitive load (high or low), and block of trials (first or second) – see grey lines. Error bars depict +/- 0.5 SEM. (FOA) = attended location.*

Given the novelty of our finding that cognitive factors can affect the focus of perceptual resources and the importance of the theoretical implications that follow from it, Experiment 10 was an attempt to replicate it using a different cognitive-load manipulation. A neutral-distractor condition was included in Experiment 10 in order to be in a position to discriminate between effects of cognitive load on salience-related and response-related distractor interference.

## **4.4 EXPERIMENT 10: Cognitive load (replication)**

Experiment 10 used a method similar to that used in Experiment 9, except for the following changes: (i) neutral as well as incompatible distractors were included; (ii) the secondary cognitive-load task that was intercalated between blocks of trials involved performing easy or difficult mental calculations rather than memorizing one or six digits; and (iii) cognitive load was manipulated in different groups of participants.

In this experiment, distractor interference was measured in three ways: (1) using *incompatible-distractor total interference* (obtained by comparing no-distractor with incompatible-distractor performance); (2) using *incompatible-distractor response-related interference* (obtained by comparing neutral-distractor with incompatible-distractor performance); and (3) using *saliency-related interference* (obtained by comparing no-distractor with neutral-distractor performance). The first measure was used in an attempt to replicate the findings of Experiment 9. The last two measures arguably allowed us to test whether the effect of cognitive load was apparent using both *response-related* and *saliency-related interference*: given that the stimuli were modelled on those in Experiment 5, stimulus-driven effects on saliency were expected to be high; by implication, comparing neutral-distractor with incompatible-distractor performance should largely isolate response-related interference.

### **4.4.1 Method**

#### **4.4.1.1 Design**

A repeated-measures design was used in which distractor compatibility (incompatible or neutral), target-distractor separation (at controlled stimulus eccentricity) and cognitive load were manipulated.

#### ***4.4.1.2 Participants***

40 participants from Goldsmiths College (25 females; 3 left-handed; mean age 25.6 yr; age range 19 to 50 yr; see Appendix 11) with normal or corrected-to-normal vision took part in the experiment in exchange for £10. They were all naïve as to the aims of the study.

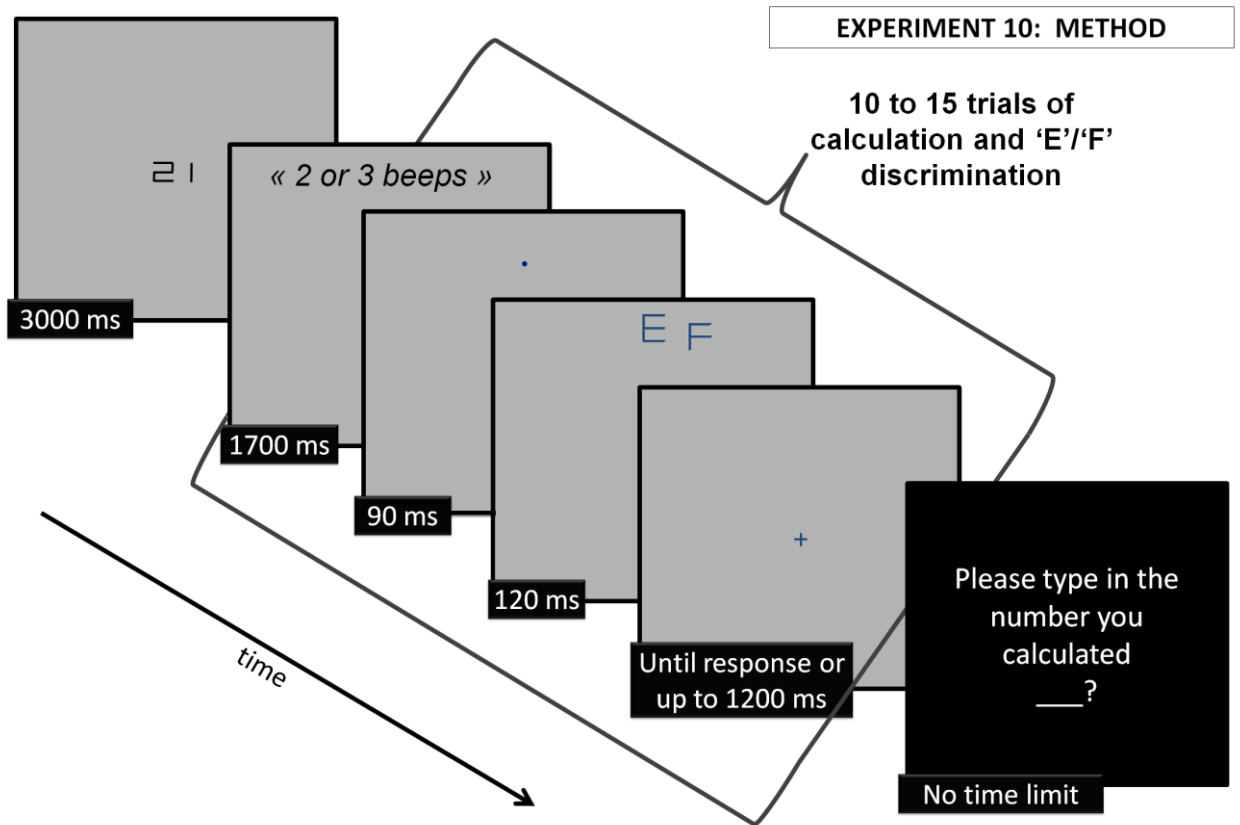
#### ***4.4.1.3 Stimuli and procedure for the target-identification task***

The method was as in Experiment 5 (see Chapter 3). The target was always the letter 'E' or 'F' and the distractor the letters 'E', 'F' or 'X'. The distractor, when present (in 80% of the trials), was equally often response-incompatible (e.g., if the target was 'E', the distractor was 'F') or response-neutral (e.g., the letter 'X'). On 20% of trials, no distractor was presented and the target appeared on its own. The latter constituted the no-distractor baseline condition. Only four target-distractor separations were tested in order to reduce the number of trials and the amount of practice participants acquired with the load tasks. Unlike in Experiments 1 to 9, there was no auditory feedback when target-identification responses were incorrect as this would have interfered with the cognitive task (see below).

#### ***4.4.1.4 Stimuli and procedure for the cognitive task***

A calculation task was interleaved between all target-identification trials in order to manipulate cognitive load (see Figure 31). Each block of 10 to 15 target-identification

trials was preceded by the presentation of a two-digit reference number (between 21 and 59) displayed at the centre of the screen for 2000 ms. 1000 ms after the disappearance of this reference number, the first trial of the target-identification block began. At the beginning of each trial, the computer emitted two or three beeps for 500 ms. These beeps signalled different things in the two load conditions. In the low-cognitive-load condition, the participants had mentally to add *one* to the reference number, irrespective of whether the computer had emitted two or three beeps, and to keep the outcome in their mind. In the high-cognitive-load condition, the participants had mentally to add two to the reference number if the computer had emitted two beeps, or three if the computer had emitted three beeps, and they had to keep the outcome in their mind. The participants only had 1200 ms to perform the calculation. After this time had elapsed, the next target-identification trial in the block was presented. Just 400 ms after the participants had made their target-identification response, they heard again two or three beeps and had again to add *one* (in the low-cognitive-condition), or *two* or *three* respectively (in the high-cognitive-load condition), to the running total from the previous trial. After repeating this procedure for between 10 and 15 trials, participants were asked to type in the final total they had arrived at (there was no time limit and no feedback was given).



**Figure 31**

*Experiment 10 – Method. A schematic representation of one block of ten to fifteen trials. Each block of trials started with the presentation of a two-digit reference number. At the beginning of each trial, the computer emitted two or three beeps. In the low-cognitive-load condition, the participants had mentally to add one to the reference number, irrespective of whether the computer had emitted two or three beeps, and to keep the outcome in their mind. In the high-cognitive-load condition, the participants had mentally to add two to the reference number if the computer had emitted two beeps, or three if the computer had emitted three beeps, and to keep the outcome in their mind. They then performed an ‘E’/‘F’ target identification. Immediately after they gave their response to the target, the computer again emitted two or three beeps and they had to add one (low cognitive load) or two or three (high cognitive load) to the running total from the previous trial. After ten to fifteen trials of calculation and target identification, the participants were asked to type in the final total they had arrived at and the next block of trials started.*

Experiment 10 lasted 40 minutes. It consisted of two load conditions (low- and high-cognitive-load) performed by separate groups of participants. Each load condition comprised 480 target-identification trials (in 50 blocks each of 10 to 15 trials), preceded by 60 practice trials (in 1 block of 20 trials where the participants performed just the target-identification task and 3 blocks of 10 to 15 trials where they performed both the target-identification and the cognitive task).

#### **4.4.2 Results**

The cognitive-load task involved 39 blocks of easy calculations (low-cognitive-load condition) for one group of participants and 39 blocks of difficult calculations (high-cognitive-load condition) for the other group of participants. The calculations were well performed by all participants. In average, the participants responded within +/- 1.2 of the correct answer in the low-cognitive-load condition and within +/- 3.0 of the correct answer in the high-cognitive-load condition.

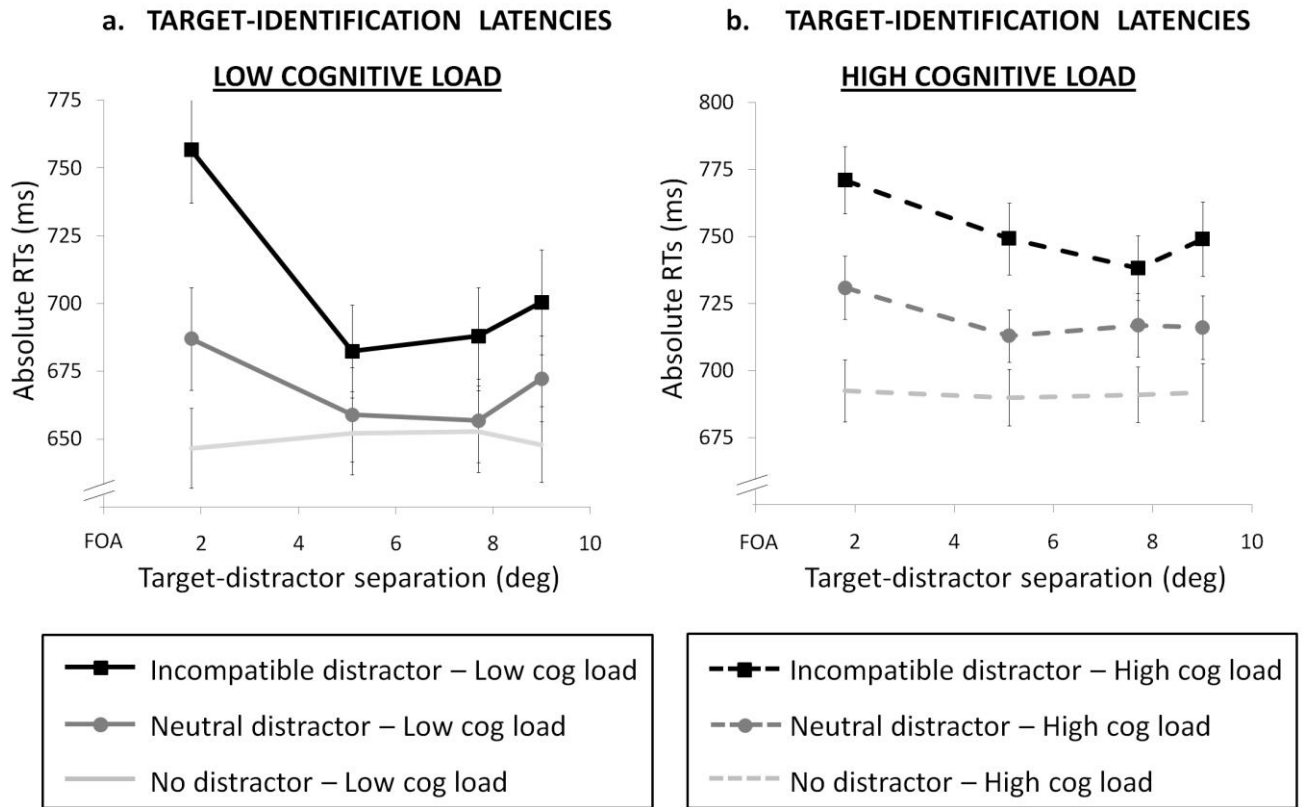
We analyzed both the speed and accuracy of forced-choice target-identification responses. Response latencies (RTs) were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, which represented 91.4% of the latencies overall.

For each participant, mean RTs (and error percentages) were calculated for incompatible- and neutral-distractor trials at the four target-distractor separations (1.8, 5.1, 7.7 and 9.0 deg; see Figure 32). Moreover, for each participant, no-distractor RTs (and errors) were each randomly separated into four bins and mean RTs (and error

percentages) were calculated for each bin. The bins were used as baselines to match the four target-distractor separations.

Three analyses were performed on mean RTs (and error percentages). Each of them compared performance obtained with one type of distractor with that obtained with another type of distractor, or with no distractor, as a function of separation and cognitive load. Specifically, the first analysis compared *incompatible*-distractor with *no*-distractor performance as a function of separation and cognitive load; the second analysis compared *incompatible*-distractor with *neutral*-distractor performance as a function of separation and cognitive load; and the third analysis compared *neutral*-distractor with *no*-distractor performance as a function of separation and cognitive load. These three comparisons allowed us to isolate, respectively, *incompatible-distractor total interference*, *incompatible-distractor response-related interference*, and *salience-related interference*, and to test whether each type of interference as a function of separation was modulated by cognitive load. A difference in the shape of the interference function between the two cognitive-load conditions would emerge if (1) the function in one load condition was *more focused* than the function in the other load condition or (2) the function in one load condition was *steeper* than the function in the other load condition while being *similarly focused*. These two possibilities can be discriminated using interpolation analyses on the interference functions of separation (see Results of Experiment 2, Chapter 2).

EXPERIMENT 10: EFFECT OF COGNITIVE LOAD



**Figure 32**

*Experiment 10 – Latencies. The figure shows: (1) distractor-present mean latencies (in ms) as a function of target-distractor separation (in deg), target-distractor compatibility (incompatible or neutral) and cognitive load (high or low) – see black and dark-grey lines; and (2) no-distractor mean latencies (in ms) as a function of cognitive load (high or low) – see light-grey lines. Error bars depict +/- 0.5 SEM. (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location.*



#### ***4.4.2.1 Comparison of incompatible- with no-distractor RTs as a function of separation and cognitive load***

##### **Reaction times**

This analysis tested for the effects of three factors, namely, Presence of Incompatible Distractor, Separation and Cognitive Load on target-identification RTs using a mixed-design ANOVA. Where there was a significant interaction, additional analyses, namely, ANOVAs and interpolation analyses, were performed to understand the origin of the interaction.

##### *Effects of Presence of Incompatible Distractor, and Separation*

The main effects of both Presence of Incompatible Distractor, and Separation were significant (respectively,  $F(1,38) = 65.72, p < 0.001, \eta_p^2 = 0.634$  and  $F(3,114) = 11.14, p < 0.001, \eta_p^2 = 0.227$ ) and the interaction between Presence of Incompatible Distractor, and Separation was also significant ( $F(3,114) = 12.04, p < 0.001, \eta_p^2 = 0.241$ ). In other words, there was evidence for significant *incompatible-distractor total interference* and the latter varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear and quadratic trends ( $F(1,38) = 12.34, p = 0.001, \eta_p^2 = 0.245$  and  $F(1,38) = 19.19, p < 0.001, \eta_p^2 = 0.336$ ; the cubic trend had a  $p$  value  $> 0.100$ ), consistent with a Mexican-hat profile.

##### *Effect of Cognitive Load*

The main effect of Cognitive Load was not significant ( $F(1,38) = 1.18, p = 0.284, \eta_p^2 = 0.030$ ): overall, the cognitive-load manipulation did not affect performance at target identification. Similarly, Cognitive Load was not found to interact with Presence of

Incompatible Distractor ( $F(1,38) = 0.06, p = 0.811, \eta_p^2 = 0.002$ ), suggesting that *incompatible-distractor total interference* pooled across separations was similar in both load conditions. On the other hand, while the two-way interaction between Cognitive Load and Separation was not significant ( $F(3,114) = 2.01, p = 0.117, \eta_p^2 = 0.227$ ), the three-way interaction between Cognitive Load, Presence of Incompatible Distractor, and Separation was significant ( $F(3,114) = 3.13, p = 0.029, \eta_p^2 = 0.101$ ). The significance of this three-way interaction suggests that, like in Experiment 9, *incompatible-distractor total interference* as a function of separation was different in conditions of low and high cognitive load.

Given the significance of the three-way interaction, the effects of Presence of Incompatible Distractor, and Separation were investigated separately for each condition of Cognitive Load. In the low-load condition, the interaction between Presence of Incompatible Distractor, and Separation was significant ( $F(3,57) = 16.20, p < 0.001, \eta_p^2 = 0.460$ ). Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear, quadratic and cubic trends (respectively:  $F(1,19) = 10.83, p = 0.004, \eta_p^2 = 0.363$ ;  $F(1,19) = 37.89, p < 0.001, \eta_p^2 = 0.666$ ; and  $F(1,19) = 4.59, p = 0.045, \eta_p^2 = 0.195$ ), once again consistent with a Mexican-hat profile. On the other hand, in the high-load condition, while the effect of Presence of Incompatible Distractor was highly significant ( $F(1,19) = 99.51, p < 0.001, \eta_p^2 = 0.840$ ), the interaction between Presence of Incompatible Distractor, and Separation was *not* significant ( $F(3,57) = 1.47, p = 0.233, \eta_p^2 = 0.072$ ). This suggests that, while *incompatible-distractor total interference* was large, the function of separation was almost *flat* in the high-load condition (see Figure 32). This finding is arguably consistent with a *defocusing* of the profile of perceptual

resources, suggesting that the bottom of the interference function of separation occurred further out in the high- than in the low-cognitive-load condition (see Figure 32). This hypothesis was tested using polynomial-interpolation analyses.

#### *Comparison of the locations of the bottoms of the functions of separation*

Interpolation analyses were performed on *incompatible-distractor total interference* as a function of separation in each cognitive-load condition (see Results of Experiment 2, Chapter 2, for details on the methodology used). The local minima derived from the interpolation analyses were compared across load conditions.

The group-mean local minimum of the total interference as a function of separation occurred at 5.70 deg (SEM = 0.32) in the low-cognitive-load condition and at 6.67 deg (SEM = 0.38) in the high-cognitive-load condition. This difference was significant ( $t(38) = 2.04$ ,  $p = 0.048$ ,  $d = 0.642$ ). In other words, *incompatible-distractor total interference* produced evidence that the bottom of the profile of perceptual resources occurred closer to the attended location in the low- than in the high-cognitive-load condition.

#### **Errors**

This analysis tested for the effects of three factors, namely, Presence of Incompatible Distractor, Separation and Cognitive Load on target-identification errors using a mixed-design ANOVA.

### *Effects of Presence of Incompatible Distractor, and Separation*

The main effect of Presence of Incompatible Distractor was significant ( $F(1,38) = 13.74, p = 0.001, \eta_p^2 = 0.266$ ): errors were higher (by 3.3%) in the incompatible- than in the no-distractor condition, showing that there was significant *incompatible-distractor total interference* in the error data. Moreover, both the main effect of Separation and the interaction between Presence of Incompatible Distractor, and Separation were significant (respectively,  $F(3,114) = 3.89, p = 0.011, \eta_p^2 = 0.093$  and  $F(3,114) = 4.13, p = 0.008, \eta_p^2 = 0.098$ ). The significance of the latter interaction showed that *incompatible-distractor total interference* varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear and quadratic trends (respectively,  $F(1,38) = 4.71, p = 0.036, \eta_p^2 = 0.148$  and  $F(1,38) = 4.70, p = 0.037, \eta_p^2 = 0.110$ ; the cubic trend had a  $p$  value  $> 0.100$ ), consistent with a Mexican-hat profile.

### *Effect of Cognitive Load*

The main effect of Cognitive Load was marginally significant (participants made 5.1% more errors in the high-cognitive-load condition;  $F(1,38) = 2.88, p = 0.099, \eta_p^2 = 0.081$ ): the cognitive-load manipulation marginally affected participant's performance at identifying the target on errors. On the other hand, none of the interactions involving Cognitive Load was significant (all  $p$  values  $> 0.100$ ).

#### ***4.4.2.2 Comparison of incompatible- with neutral-distractor RTs as a function of separation and cognitive load***

##### **Reaction times**

This analysis tested for the effects of three factors, namely, Compatibility (I. vs. N.), Separation and Cognitive Load on target-identification RTs using a mixed-design ANOVA.

##### *Effects of Compatibility (I. vs. N.) and Separation*

The main effects of both Compatibility (I. vs. N.) and Separation were significant (respectively,  $F(1,38) = 53.66$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.585$  and  $F(3,114) = 13.35$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.260$ ) and the interaction between Compatibility (I. vs. N.) and Separation was marginally significant ( $F(3,114) = 2.51$ ,  $p = 0.063$ ,  $\eta_p^2 = 0.062$ ). In other words, there was evidence for significant *incompatible-distractor response-related interference* and the latter varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor response-related interference* as a function of separation was explained by a combination of linear and quadratic trends ( $F(1,38) = 3.68$ ,  $p = 0.063$ ,  $\eta_p^2 = 0.088$  and  $F(1,38) = 3.90$ ,  $p = 0.056$ ,  $\eta_p^2 = 0.093$ ; the cubic trend had a  $p$  value  $> 0.100$ ), consistent with a Mexican-hat profile.

##### *Effect of Cognitive Load*

The main effect of Cognitive Load was not significant ( $F(1,38) = 1.24$ ,  $p = 0.272$ ,  $\eta_p^2 = 0.032$ ). Similarly, Cognitive Load and Compatibility (I. vs. N.) did not significantly interact ( $F(1,38) = 0.07$ ,  $p = 0.800$ ,  $\eta_p^2 = 0.002$ ), suggesting that *incompatible-distractor response-related interference* pooled across separations was similar in both

load conditions. On the other hand, while the interaction between Cognitive Load and Separation was not significant ( $F(3,114) = 1.30, p = 0.278, \eta_p^2 = 0.033$ ), the three-way interaction between Cognitive Load, Compatibility (I. vs. N.) and Separation was significant ( $F(3,114) = 2.65, p = 0.053, \eta_p^2 = 0.095$ ). The significance of this three-way interaction suggests that *incompatible-distractor response-related interference* as a function of separation was different in conditions of high and low cognitive load.

Given the significance of the three-way interaction, the effects of Compatibility (I. vs. N.) and Separation were investigated separately for each condition of Cognitive Load. In the low-load condition, the interaction between Compatibility (I. vs. N.) and Separation was significant ( $F(3,57) = 5.67, p = 0.002, \eta_p^2 = 0.230$ ). Polynomial trends for the interaction showed that *incompatible-distractor response-related interference* as a function of separation was explained by a combination of linear, quadratic and cubic trends (respectively:  $F(1,19) = 5.00, p = 0.057, \eta_p^2 = 0.177$ ;  $F(1,19) = 10.76, p = 0.004, \eta_p^2 = 0.362$ ; and  $F(1,19) = 5.14, p = 0.035, \eta_p^2 = 0.213$ ), consistent with a Mexican-hat profile. On the other hand, in the high-load condition, while the effect of Compatibility (I. vs. N.) was highly significant ( $F(1,19) = 20.74, p < 0.001, \eta_p^2 = 0.522$ ), the interaction between Compatibility (I. vs. N.) and Separation was *not* significant ( $F(3,57) = 0.62, p = 0.606, \eta_p^2 = 0.032$ ). This suggests that, consistent with the previous analysis, while distractor interference was large, the function of separation was almost *flat* in the high-load condition (see Figure 32). This finding is arguably consistent with a *defocusing* of the profile of perceptual resources, suggesting that the bottom of the interference function of separation occurred further out in the high- than in the low-cognitive-load condition (see Figure 32). This hypothesis was tested using polynomial-interpolation analyses.

### *Comparison of the locations of the bottoms of the functions of separation*

Interpolation analyses were performed on *incompatible-distractor response-related interference* as a function of separation in each cognitive-load condition (see Results of Experiment 2, Chapter 2, for details on the methodology used). The local minima derived from the interpolation analyses were compared across load conditions.

The group-mean local minimum of *incompatible-distractor response-related interference* as a function of separation occurred at 5.56 deg (SEM = 0.23) in the low-cognitive-load condition and 6.35 deg (SEM = 0.30) in the high-cognitive-load condition. This difference was significant ( $t(38) = 2.07$ ,  $p = 0.045$ ,  $d = 0.649$ ). Thus, *incompatible-distractor response-related interference* produced evidence that the bottom of the profile of perceptual resources occurred closer to the attended location in the low- than the high-cognitive-load condition.

### **Errors**

This analysis tested for the effects of three factors, namely, Compatibility (I. vs. N.), Separation and Cognitive Load on target-identification errors using a mixed-design ANOVA.

### *Effects of Compatibility (I. vs. N.) and Separation*

The main effect of Compatibility (I. vs. N.) was significant ( $F(1,38) = 14.60$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.278$ ): errors were higher (by 2.7%) in the incompatible- than in the neutral-distractor condition, showing that there was significant *incompatible-distractor response-related interference* in the error data. Moreover, both the main effect of

Separation and the interaction between Compatibility (I. vs. N.) and Separation were significant (respectively,  $F(3,114) = 3.85$ ,  $p = 0.011$ ,  $\eta_p^2 = 0.092$  and  $F(3,114) = 5.36$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.124$ ). The significance of the latter interaction showed that *incompatible-distractor response-related interference* varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor response-related interference* as a function of separation was explained by a quadratic trend ( $F(1,38) = 6.62$ ,  $p = 0.014$ ,  $\eta_p^2 = 0.148$ ; the linear and cubic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

#### *Effect of Cognitive Load*

Once again, the main effect of Cognitive Load was marginally significant (as already shown in Section 4.4.2.1 above;  $F(1,38) = 3.33$ ,  $p = 0.076$ ,  $\eta_p^2 = 0.081$ ) but none of the interactions involving Cognitive Load were significant (all  $p$  values  $> 0.100$ ).

#### ***4.4.2.3 Comparison of neutral- with no-distractor RTs as a function of separation and cognitive load***

#### **Reaction times**

This analysis tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation and Cognitive Load on target-identification RTs using a mixed-design ANOVA.

#### *Effects of Presence of Neutral Distractor, and Separation*

The main effects of both Presence of Neutral Distractor, and Separation were significant (respectively,  $F(1,38) = 29.83$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.440$  and  $F(3,114) = 4.63$ ,



$p = 0.004$ ,  $\eta_p^2 = 0.109$ ) and the interaction between Presence of Neutral Distractor, and Separation was also significant ( $F(3,114) = 5.57$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.128$ ). In other words, neutral distractors generated significant *saliency-related interference* and the latter varied with separation. Polynomial trends for the interaction showed that *saliency-related interference* as a function of separation was explained by a combination of linear and quadratic trends (respectively,  $F(1,38) = 9.16$ ,  $p = 0.004$ ,  $\eta_p^2 = 0.194$  and  $F(1,38) = 9.09$ ,  $p = 0.005$ ,  $\eta_p^2 = 0.193$ ; the cubic trend had a  $p$  value  $> 0.100$ ), consistent with a Mexican-hat profile.

#### *Effect of Cognitive Load*

Neither the main effect of Cognitive Load nor any of the interactions involving this factor were significant (all  $p$  values  $> 0.100$ ). It appears that *saliency-related interference* was not sensitive enough to reveal the effect of Cognitive Load. No additional analyses were performed on these data.

#### **Errors**

This analysis tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation and Cognitive Load on target-identification errors using a mixed-design ANOVA. None of the main effects or interactions was significant in this analysis (all  $p$  values  $> 0.100$ ).

#### **4.4.3 Discussion**

The findings of Experiment 10 once again did not show an effect of cognitive load on the amplitude of distractor interference (both saliency-related and response-related) across separations (see Discussion of Experiment 9). On the other hand, the findings of

Experiment 10 confirmed that loading cognitive-control mechanisms causes the profile of perceptual resources to spatially *defocus* (as indexed by the shifting *out* of the bottom of the Mexican-hat function). However, this effect could only be measured when using *incompatible-distractor total interference* or *incompatible-distractor response-related interference* and not when using *neutral-distractor salience-related interference*. We conclude that *salience-related interference* was insufficiently sensitive to reveal the effect of cognitive load in Experiment 10.

It was possible that the effect of cognitive load in Experiments 9 and 10 was exerted only indirectly. Cognitive load might have reduced the efficiency of the exogenous cue that was used to orient perceptual resources to the target location with the result that perceptual resources were oriented less well and, only because of this, were less focused. While some findings from the literature are inconsistent with this view (cognitive load has been found not to affect exogenous spatial orienting; Jonides, 1981; Pashler, 1991; Santangelo, Finoia, Raffone, Belardinelli, & Spence, 2008), it was desirable to test this possibility directly. In order to do so, we tested the effect of cognitive load on the profile of perceptual resources using *central* target presentation, thus obviating the need for any orienting of perceptual resources. If cognitive load was still found to defocus perceptual resources in this case, it would suggest that the effects observed in Experiments 9 and 10 were not only due to an effect on the orienting of perceptual resources.

In Experiment 11, the effect of *perceptual load* on the profile of perceptual resources was also tested once again. This is because we wished to replicate the effect of perceptual load observed in Experiment 8 using central-target presentation, as most

perceptual-load studies have used such central presentation (e.g., Kahneman & Chajczyk, 1983; LaBerge et al., 1991; Lavie, 1995; Lavie et al., 2004; Lavie & Fox, 2000).

#### **4.5 EXPERIMENT 11: Effects of perceptual and cognitive load with central target presentation**

Experiment 11 used a flanker paradigm with a perceptual load manipulation and with the same cognitive load manipulation as in Experiment 9. The main difference between Experiment 11 and previous experiments was that, in Experiment 11, the target was presented *centrally*. As a result, the manipulation of target-distractor separation was confounded with a manipulation of distractor eccentricity. Despite this confound with eccentricity, the distractors were not scaled for cortical magnification to avoid the possibility that an increase in interference with increasing separation was an artefact of overscaling. If interference from peripheral and *unscaled* distractors was shown to increase with increasing separation (as predicted over certain separations by the Mexican-hat profile), this would have to be despite the effect of cortical magnification.

On each trial of Experiment 11, the participants had (1) to identify a central target letter, while ignoring a distractor letter occurring at different eccentricities (i.e., perform the flanker task), and *then* (2) to either detect the presence of a gap in the target – in the low-perceptual-load condition – or discriminate the position of this gap – in the high-perceptual-load condition (i.e., perform the perceptual-load task; see Figure 33). Across blocks of trials, a cognitive-load task was added to the two perceptual tasks performed on each trial (thus requiring participants to perform three tasks in all). In the cognitive-

load task, the participants had to memorize either one (low-cognitive-load condition) or six (high-cognitive-load condition) digits before the beginning of each set of twenty trials. We employed the cognitive-load manipulation used in Experiment 9 as it was less difficult than that used in Experiment 10 (participants made 5% less errors and were faster by 120 ms in the high-cognitive-load condition of Experiment 9 compared to the same condition in Experiment 10) and we wanted to ensure that participants could perform the triple task with a sufficient level of accuracy.

The perceptual- and cognitive-load manipulations were performed *between* participants. Thus, we tested three combinations of perceptual- and cognitive-load conditions, each one in a different group of participants: the first group of participants performed a condition of *low* perceptual load and *low* cognitive load; the second group of participants performed a condition of *high* perceptual load and *low* cognitive load; finally, the third group of participants performed a condition of *high* perceptual load and *high* cognitive load. Comparing the results of the first and second groups allowed us to test for the effect of perceptual load on selective attention, whereas comparing the results of the second and third groups allowed us to test for the effect of the cognitive load on selective attention. Note that the *cognitive-load* manipulation was performed under conditions of high perceptual load because the profile of perceptual resources had to be *well focused* for a *defocusing* effect of cognitive load to be detectable.

In Experiment 11, like in Experiment 10, distractor interference was measured in three ways: (1) using *incompatible-distractor total interference* (obtained by comparing no-distractor with incompatible-distractor performance); (2) using *incompatible-distractor response-related interference* (obtained by comparing neutral-distractor with

incompatible-distractor performance); and (3) using *saliency-related interference* (obtained by comparing no-distractor with neutral-distractor performance).

#### **4.5.1 Method**

##### ***4.5.1.1 Design***

A mixed design was used in which compatibility of the distractor (incompatible or neutral) and target-distractor separation (where stimulus eccentricity was *not* controlled) were manipulated within participants, and perceptual and cognitive load were manipulated to be high or low in different groups of participants.

##### ***4.5.1.2 Participants***

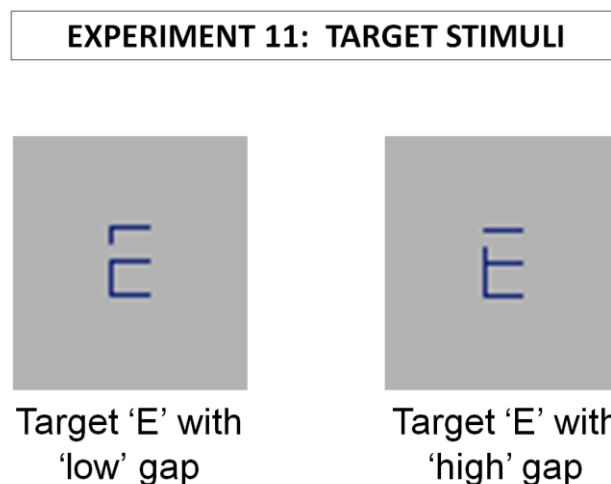
106 participants (84 females; 10 left-handed; mean age 20 yr; age range 16 to 36 yr; see Appendix 12), with reported normal or corrected-to-normal vision, participated in the experiment in exchange for course credits. They were all naïve as to the aims of the study.

##### ***4.5.1.3 Stimuli and procedure for the perceptual tasks***

On each trial, participants performed two perceptual tasks. The primary task was to identify, as quickly but as accurately as possible, a target letter ('E' or 'F') with a two-alternative forced-choice (2-AFC). This primary task (i.e., the flanker task) was used to measure the profile of perceptual resources. The secondary task was used to manipulate perceptual load. It required participants either to detect the presence of a gap in the target – in the low-perceptual-load condition – with a 2-AFC ('present' or 'absent'), or

to discriminate the position of this gap – in the high-perceptual-load condition – with a 2-AFC (‘high’ or ‘low’).

The stimuli on which these perceptual tasks were performed consisted of (1) an ‘E’ or ‘F’ target letter and (2) an ‘E’, ‘F’ or ‘X’ distractor letter. The target letter (subtending 0.48 by 0.64 deg) was presented at the centre of the screen. It had a small gap located either ‘high’ or ‘low’ in the *upper half* of its vertical axis (see Figure 33). The distractor letter (subtending 1.60 by 1.90 deg) was presented along the horizontal midline of the screen, equally often on the left or right of the target. It was removed from the target by 1.8, 3.6, 5.4, 7.2 or 9.0 deg (the five target-distractor separations). It was response-incompatible with the target (e.g., it was ‘F’ if the target was ‘E’) on 46% of trials. On the other 46% of trials, it was the neutral letter ‘X’. In the remaining 8% of trials, no distractor was presented.



**Figure 33**

*Experiment 11 – Method. A schematic representation of an ‘E’ target letter with a low gap (left) and with a high gap (right).*

Each trial started with an empty screen for 700 ms, followed by the presentation of the stimuli for 100 ms. The participants had up to 1500 ms to respond to target identity and, then, up to 10,000 ms to respond to gap presence (low perceptual load) or position (high perceptual load). Auditory feedback was given about incorrect responses for both tasks.

#### ***4.5.1.4 Stimuli and procedure for the cognitive task***

Experiment 11 also required participants to perform a tertiary working-memory task used to manipulate cognitive load. This task was modelled on the working-memory task used in Experiment 9.

Before each block of twenty trials, a vertical array of six digits was presented to the participants (for the cognitive-load task). They had to memorize either (1) the digit with the lowest value within this array (low-cognitive-load condition) or (2) the six digits in their order of presentation (high-cognitive-load condition). After each block of twenty trials, participants were asked to type in the digit(s) they had memorized (there was no time limit, but sequence knowledge was required in the high-cognitive-load condition). No feedback was given for the cognitive-load task.

The experiment consisted of 480 trials, preceded by 80 practice trials. The different conditions of the target-identification task were presented intermixed and in randomized order. The different conditions of the perceptual- and cognitive-load tasks were performed by different groups of participants.

### 4.5.2 Results

In each cognitive-load condition, the working-memory task involved 24 memorisations. Correct memorisation was defined as the recall of the single digit that had to be memorized, in the low-cognitive-load condition, or as the recall in the correct order of at least five out of the six digits that had to be memorized, in the high-cognitive-load condition. None of the participants performed less than 16 memorisations correctly (out of 24 memorisations). On average, the participants performed 22 memorisations out of 24 memorisations correctly in both cognitive-load conditions.

Before analysing target-identification performance on the primary task, we analysed results from the secondary perceptual-load task to ascertain that it was adequately well performed. It was found that (1) in the gap-detection task (low-perceptual-load), the gap was missed in 4.9% of ‘gap-present’ trials and falsely reported in only 11.8% of ‘gap-absent’ trials, and (2) in the gap-discrimination task (high-perceptual-load condition, pooled across low and high cognitive load), the gap was incorrectly reported as ‘high’ in only 13.2% of ‘low-gap’ trials and as ‘low’ in 13.1% of ‘high-gap’ trials.

We analyzed both the speed and accuracy of forced-choice target-identification responses. Target-identification trials were analysed only when they occurred in a block of trials that was followed by a correct memory-task recall *and* when the presence of the gap was accurately reported (low-perceptual-load condition) or when the location of the gap was correctly discriminated (high-perceptual-load condition). In addition, and as usual, response latencies (RTs) were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant. This represented 83.2% of the latencies overall.



For each participant, mean target-identification ('E' or 'F') RTs (and error percentages) were calculated for incompatible- and neutral-distractor trials at each of the five target-distractor separations (1.8, 3.6, 5.4, 7.2 and 9.0 deg; see Figures 34 and 35). Moreover, for each participant, no-distractor RTs (and errors) were randomly separated into five bins, and mean RTs (and error percentages) were calculated for each bin. The bins were used as baselines to match the five target-distractor separations.

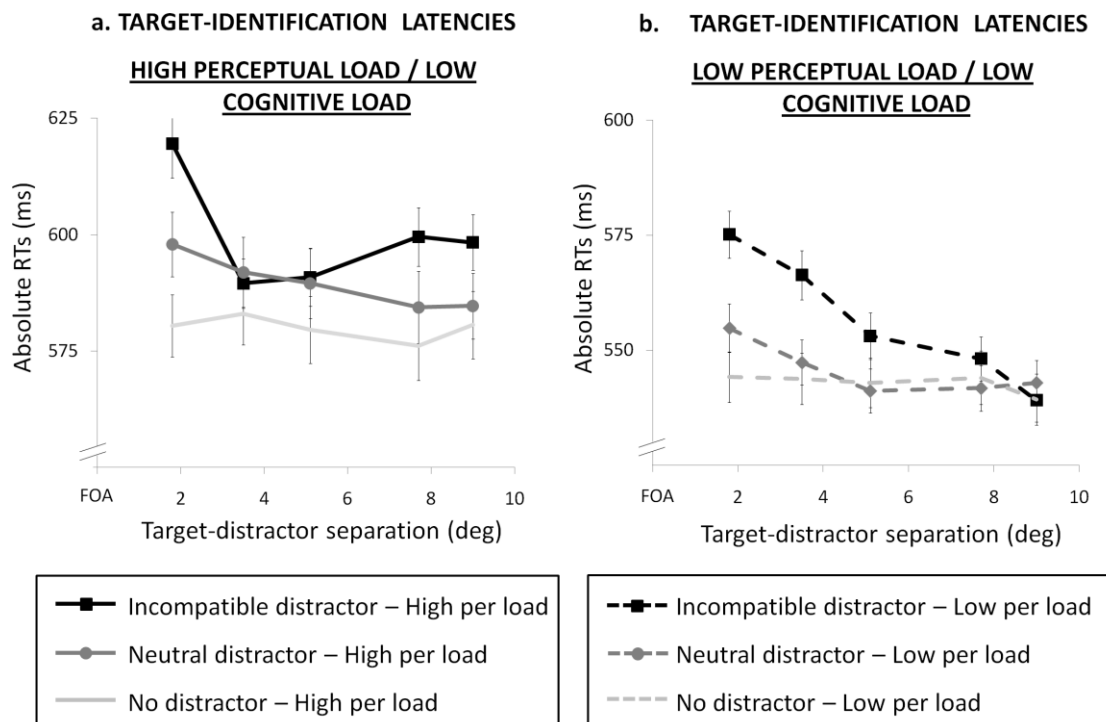
Six analyses were performed on mean RTs (and error percentages). The first three analyses tested for the effect of *perceptual load* by comparing the condition of *low* perceptual load (and low cognitive load) to the condition of *high* perceptual load (and low cognitive load). The following three analyses tested for the effect of *cognitive load*, by comparing the condition of *low* cognitive load (and high perceptual load) to the condition of *high* cognitive load (and high perceptual load).

Specifically, the first analysis compared *incompatible*-distractor with *no*-distractor performance (thus isolating *incompatible-distractor total interference*) as a function of separation and perceptual load; the second analysis compared *incompatible*-distractor with *neutral*-distractor performance (thus isolating *incompatible-distractor response-related interference*) as a function of separation and perceptual load; the third analysis compared *neutral*-distractor with *no*-distractor performance (thus isolating *salience-related interference*) as a function of separation and perceptual load; the fourth analysis compared *incompatible*-distractor with *no*-distractor performance (thus isolating *incompatible-distractor total interference*) as a function of separation and cognitive load; the fifth analysis compared *incompatible*-distractor with *neutral*-distractor

performance (thus isolating *incompatible-distractor response-related interference*) as a function of separation and cognitive load; and, finally, the sixth analysis compared *neutral-distractor* with *no-distractor* performance (thus isolating *salience-related interference*) as a function of separation and cognitive load.

Each of these analyses allowed us to test whether the type of interference isolated was significant *across* separations and whether the shape of the interference function of separation was modulated by perceptual or cognitive load. Where interference as a function of separation was significantly modulated by perceptual or cognitive load, interpolation analyses were applied to determine the separation at which the bottom of the function occurred in each perceptual or cognitive-load condition. This allowed us to determine if the functions of separation were similarly focused in the different perceptual and cognitive-load conditions.

EXPERIMENT 11: EFFECT OF PERCEPTUAL LOAD



**Figure 34**

*Experiment 11 – Latencies. The figure shows: (1) distractor-present mean latencies (in ms) as a function of target-distractor separation (in deg), target-distractor compatibility (incompatible or neutral) and perceptual load (high or low; note that cognitive load was low in both conditions) – see black and dark-grey lines; and (2) no-distractor mean latencies (in ms) as a function of perceptual load (high or low) – see light-grey lines. Error bars depict +/- 0.5 SEM. (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location.*

#### ***4.5.2.1 Comparison of incompatible- with no-distractor RTs as a function of separation and perceptual load***

##### **Reaction times**

This analysis tested for the effects of three factors, namely, Presence of Incompatible Distractor, Separation and Perceptual Load on target-identification RTs using a mixed-design ANOVA. Where there was a significant interaction, additional analyses, namely, ANOVAs and interpolation analyses, were performed to understand the origin of the interaction.

##### *Effects of Presence of Incompatible Distractor, and Separation*

The main effects of both Presence of Incompatible Distractor, and Separation were significant (respectively,  $F(1,70) = 28.43, p < 0.001, \eta_p^2 = 0.289$  and  $F(4,280) = 15.06, p < 0.001, \eta_p^2 = 0.177$ ) and the interaction between Presence of Incompatible Distractor, and Separation was also significant ( $F(4,280) = 11.30, p < 0.001, \eta_p^2 = 0.139$ ). In other words, there was significant *incompatible-distractor total interference* and the latter varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear and quadratic trends (respectively  $F(1,70) = 30.87, p < 0.001, \eta_p^2 = 0.306$  and  $F(1,70) = 12.82, p = 0.001, \eta_p^2 = 0.155$ ; the cubic and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

##### *Effect of Perceptual Load*

First, the main effect of Perceptual Load was significant (participants were slower of around 40 ms in the high-perceptual-load condition;  $F(1,70) = 4.53, p = 0.037, \eta_p^2 =$

0.061), showing that the perceptual-load manipulation affected participants' performance at the target-identification task (see Figure 34). Second, Perceptual Load did not interact significantly with Presence of Incompatible Distractor ( $F(1,70) = 0.98$ ,  $p = 0.325$ ,  $\eta_p^2 = 0.014$ ). This suggests that *incompatible-distractor total interference* pooled across separations was similar in both perceptual-load conditions. Third, both the two-way interaction between Perceptual Load and Separation and the three-way interaction between Perceptual Load, Presence of Incompatible Distractor, and Separation were significant (respectively  $F(4,280) = 6.05$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.080$ , and  $F(4,280) = 3.68$ ,  $p = 0.006$ ,  $\eta_p^2 = 0.085$ ). The significance of the three-way interaction suggests that *incompatible-distractor total interference as a function of separation* was different in conditions of high and low perceptual load.

Given the significant of the three-way interaction, the effects of Presence of Incompatible Distractor, and Separation were investigated separately for each condition of Perceptual Load. In both load conditions, the interaction between Presence of Incompatible Distractor, and Separation was significant (respectively, for low and high load:  $F(4,140) = 10.20$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.226$  and  $F(4,140) = 5.83$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.143$ ). Polynomial trends for the interactions showed that, in the low-perceptual-load condition, *incompatible-distractor total interference* as a function of separation was explained by a linear trend ( $F(1,35) = 33.69$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.490$ ; the quadratic, cubic and quartic trends had  $p$  values  $> 0.100$ ) whereas, in the high-perceptual-load condition, it was explained by a combination of quadratic and cubic trends (respectively:  $F(1,35) = 10.17$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.225$  and  $F(1,35) = 12.41$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.262$ ; the linear and quartic trends had  $p$  values  $> 0.100$ ). Thus, *incompatible-distractor total interference* described a gradient pattern in the low-perceptual-load condition but it described a

Mexican-hat pattern in the high-perceptual-load condition. This change in the *qualitative* shape of the function may have been due to an inward shift of the bottom of the Mexican hat with increasing perceptual load (see Figure 34). This possibility was tested using interpolation analyses.

#### *Comparison of the locations of the bottoms of the functions of separation*

Interpolation analyses were performed on the *incompatible-distractor total interference* as a function of separation in each perceptual-load condition (see Results of Experiment 2, Chapter 2, for details on the methodology used). The local minima derived from the interpolation analyses were compared across load conditions.

The group-mean local minimum of *incompatible-distractor total interference* as a function of separation occurred at 6.59 deg (SEM = 0.36) in the low-perceptual-load condition and at 5.01 deg (SEM = 0.28) in the high-perceptual-load condition. This difference was significant ( $t(70) = 3.49$ ,  $p = 0.001$ ,  $d = 0.862$ ). In other words, there was significant evidence that the bottom of the profile of perceptual resources occurred closer to the attended location in the high- than the low-perceptual-load condition.

#### **Errors**

For all comparisons, none of the main effects or interactions in errors was significant (all  $p$  values > 0.100).

#### ***4.5.2.2 Comparison of incompatible- with neutral-distractor RTs as a function of separation and perceptual load***

##### **Reaction times**

This analysis tested for the effects of three factors, namely, Compatibility (I. vs. N.), Separation and Perceptual Load on target-identification RTs using a mixed-design ANOVA.

##### *Effects of Compatibility (I. vs. N.) and Separation*

The main effects of both Compatibility (I. vs. N.) and Separation were significant (respectively,  $F(1,70) = 26.64$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.276$  and  $F(4,280) = 12.90$ ,  $MSE = 773.5$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.156$ ) and the interaction between Compatibility (I. vs. N.) and Separation was also significant ( $F(4,280) = 2.50$ ,  $p = 0.043$ ,  $\eta_p^2 = 0.034$ ). In other words, there was significant *incompatible-distractor response-related interference* and the latter varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor response-related interference* as a function of separation was explained by a combination of linear and cubic trends (respectively  $F(1,70) = 5.08$ ,  $p = 0.027$ ,  $\eta_p^2 = 0.068$  and  $F(1,70) = 3.31$ ,  $p = 0.073$ ,  $\eta_p^2 = 0.050$ ; the quadratic and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

##### *Effect of Perceptual Load*

First, once again (see Section 4.5.2.1 above), the main effect of Perceptual Load was significant ( $F(1,70) = 5.60$ ,  $p = 0.021$ ,  $\eta_p^2 = 0.074$ ). Second, Perceptual Load did not interact significantly with Compatibility (I. vs. N.) ( $F(1,70) = 0.047$ ,  $p = 0.829$ ,  $\eta_p^2 = 0.001$ ). This suggests that *incompatible-distractor response-related interference* pooled

across separations was similar in both perceptual-load conditions. Third, while the two-way interaction between Perceptual Load and Separation was not significant ( $F(4,280) = 1.78, p = 0.132, \eta_p^2 = 0.025$ ), the three-way interaction between Perceptual Load, Compatibility (I. vs. N.) and Separation was significant ( $F(4,280) = 3.69, p = 0.006, \eta_p^2 = 0.050$ ). The significance of the three-way interaction suggests that *incompatible-distractor response-related interference* as a function of separation was different in conditions of high and low perceptual load.

Given the significance of the three-way interaction, the effects of Compatibility (I. vs. N.) and Separation were investigated separately for each condition of Perceptual Load. In both load conditions, the interaction between Compatibility (I. vs. N.) and Separation was significant (respectively, for low and high load:  $F(4,140) = 3.02, p = 0.020, \eta_p^2 = 0.079$  and  $F(4,140) = 3.16, p = 0.016, \eta_p^2 = 0.083$ ). Polynomial trends for the interactions showed that, in the low-perceptual-load condition, *incompatible-distractor response-related interference* as a function of separation was explained by a linear trend ( $F(1,35) = 9.89, p = 0.003, \eta_p^2 = 0.220$ ; the quadratic, cubic and quartic trends had  $p$  values  $> 0.100$ ) whereas, in the high-perceptual-load condition, it was explained by a combination of quadratic and cubic trends (respectively:  $F(1,35) = 5.75, p = 0.022, \eta_p^2 = 0.141$  and  $F(1,35) = 7.65, p = 0.009, \eta_p^2 = 0.179$ ; the linear and quartic trends had  $p$  values  $> 0.100$ ). Thus, *incompatible-distractor response-related interference* described a gradient pattern in the low-perceptual-load condition but it described a Mexican-hat pattern in the high-perceptual-load condition. This change in the *qualitative* shape of the function may have been due to an inward shift of the bottom of the Mexican hat with increasing perceptual load. This possibility was tested using interpolation analyses.



### *Comparison of the locations of the bottoms of the functions of separation*

Interpolation analyses were performed on the *incompatible-distractor response-related interference* as a function of separation in each perceptual-load condition. The local minima derived from the interpolation analyses were compared across load conditions.

The group-mean local minimum of *incompatible-distractor response-related interference* as a function of separation occurred at 5.46 deg (SEM = 0.42) in the low-perceptual-load condition and at 4.43 deg (SEM = 0.28) in the high-perceptual-load condition. This difference was significant ( $t(70) = 2.04$ ,  $p = 0.044$ ,  $d = 0.515$ ). In other words, there was once again significant evidence that the bottom of the profile of perceptual resources occurred closer to the attended location in the high- than in the low-perceptual-load condition.

### **Errors**

For all comparisons, none of the main effects or interactions in errors was significant (all  $p$  values  $> 0.100$ ).

### ***4.5.2.3 Comparison of neutral- with no-distractor RTs as a function of separation and perceptual load***

#### **Reaction times**

This analysis tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation and Perceptual Load on target-identification RTs using a mixed-design ANOVA.

### *Effects of Presence of Neutral Distractor, and Separation*

The main effects of Presence of Neutral Distractor was marginally significant ( $F(1,70) = 3.70, p = 0.059, \eta_p^2 = 0.050$ ), the effect of Separation was significant ( $F(4,280) = 3.33, p = 0.011, \eta_p^2 = 0.045$ ), and the interaction between Presence of Neutral Distractor, and Separation was marginally significant ( $F(4,280) = 2.30, p = 0.059, \eta_p^2 = 0.032$ ). In other words, neutral distractors generated marginally significant *salience-related interference* and the latter marginally varied with separation. Polynomial trends for the interaction showed that *salience-related interference* as a function of separation was best explained by a linear trend ( $F(1,70) = 5.60, p = 0.021, \eta_p^2 = 0.074$ ; all other trends had  $p$  values  $> 0.100$ ), thus describing a gradient rather than a Mexican-hat pattern.

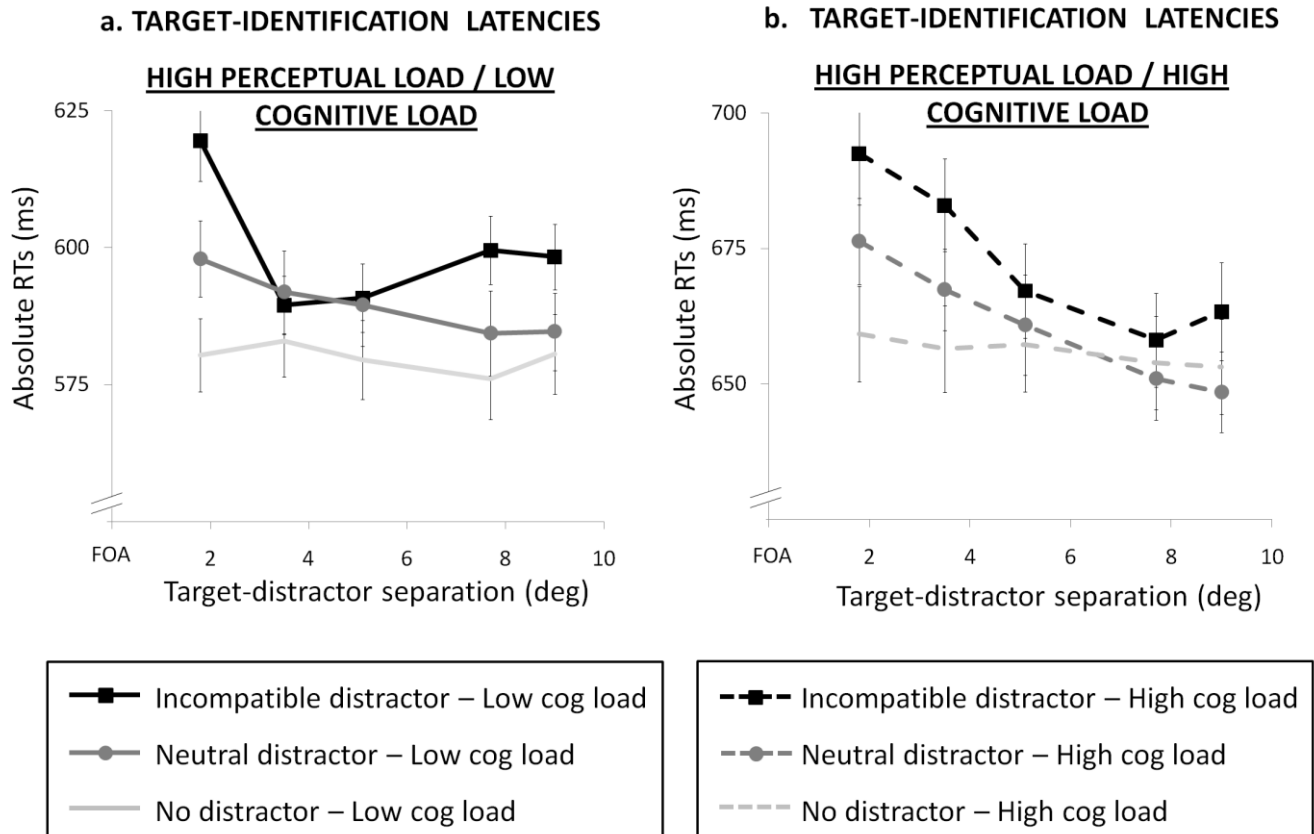
### *Effect of Perceptual load*

The main effect of Perceptual Load was significant (as already shown in Section 4.5.2.1 above;  $F(1,70) = 4.72, p = 0.033, \eta_p^2 = 0.063$ ), but Perceptual Load did not interact with any other factor (all  $p$  values  $> 0.100$ ).

### **Errors**

For all comparisons, none of the main effects or interactions in errors was significant (all  $p$  values  $> 0.100$ ).

EXPERIMENT 11: EFFECT OF COGNITIVE LOAD



**Figure 35**

*Experiment 11 – Latencies. The figure shows: (1) distractor-present mean latencies (in ms) as a function of target-distractor separation (in deg), target-distractor compatibility (incompatible or neutral) and cognitive load (high or low; note that perceptual load was high in both conditions) – see black and dark-grey lines; and (2) no-distractor mean latencies (in ms) as a function of cognitive load (high or low) – see light-grey lines. Error bars depict +/- 0.5 SEM. (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location.*

#### ***4.5.2.4 Comparison of incompatible- with no-distractor RTs as a function of separation and cognitive load***

##### **Reaction times**

This analysis tested for the effects of three factors, namely, Presence of Incompatible Distractor, Separation and Cognitive Load on target-identification RTs using a mixed-design ANOVA.

##### *Effects of Presence of Incompatible Distractor, and Separation*

The main effects of both Presence of Incompatible Distractor, and Separation were significant (respectively,  $F(1,68) = 16.95$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.200$  and  $F(4,272) = 7.01$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.093$ ) and the interaction between Presence of Incompatible Distractor, and Separation was also significant ( $F(4,272) = 5.98$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.108$ ). In other words, there was significant *incompatible-distractor total interference* and the latter varied with separation. Polynomial trends for the interaction showed that *incompatible-distractor total interference* as a function of separation was explained by a combination of linear and quadratic trends (respectively  $F(1,68) = 13.56$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.166$  and  $F(1,68) = 9.12$ ,  $p = 0.004$ ,  $\eta_p^2 = 0.118$ ; the cubic and quartic trends had  $p$  values  $> 0.100$ ), consistent with a Mexican-hat profile.

##### *Effect of Cognitive load*

First, the main effect of Cognitive Load was significant (participants were slower of around 80 ms in the high-cognitive-load condition;  $F(1,68) = 10.04$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.129$ ), showing that the cognitive-load manipulation affected participants' performance at the target-identification task (see Figure 35). Second, Cognitive Load did not interact

significantly with Presence of Incompatible Distractor ( $F(1,68) = 0.90, p = 0.346, \eta_p^2 = 0.013$ ). This suggests that *incompatible-distractor total interference* pooled across separations was similar in both cognitive-load conditions. Third, while the two-way interaction between Cognitive Load and Separation did not reach significance ( $F(4,272) = 1.64, p = 0.163, \eta_p^2 = 0.024$ ), the three-way interaction between Cognitive Load, Presence of Incompatible Distractor, and Separation was significant ( $F(4,272) = 3.05, p = 0.018, \eta_p^2 = 0.084$ ). The significance of this three-way interaction suggests that *incompatible-distractor total interference* as a function of separation was different in conditions of high and low cognitive load.

Given the significance of the three-way interaction, the effects of Presence of Incompatible Distractor, and Separation were investigated separately for each condition of Cognitive Load. In both load conditions, the interaction between Presence of Incompatible Distractor, and Separation was significant (respectively, for low and high load:  $F(4,140) = 5.83, p < 0.001, \eta_p^2 = 0.143$  and  $F(4,132) = 3.72, p = 0.007, \eta_p^2 = 0.101$ ). Polynomial trends for the interactions showed that, in the low-cognitive-load condition, *incompatible-distractor total interference* as a function of separation was explained by a combination of quadratic and cubic trends (respectively:  $F(1,35) = 10.17, p = 0.003, \eta_p^2 = 0.225$  and  $F(1,35) = 12.41, p = 0.001, \eta_p^2 = 0.262$ ; the linear and quartic trends had  $p$  values  $> 0.100$ ) whereas, in the high-cognitive-load condition, it was explained by a linear trend ( $F(1,33) = 10.70, p = 0.003, \eta_p^2 = 0.245$ ; the quadratic, cubic and quartic trends had  $p$  values  $> 0.100$ ). Thus, *incompatible-distractor total interference* described a Mexican-hat pattern in the low-cognitive-load condition but it described a gradient pattern in the high-cognitive-load condition. This change in the

*qualitative* shape of the function may have been due to an outward shift of the bottom of the Mexican hat (see Figure 35). This was tested using interpolation analyses.

#### *Comparison of the locations of the bottoms of the functions of separation*

Interpolation analyses were performed on the *incompatible-distractor total interference* as a function of separation in each cognitive-load condition. The local minima derived from the interpolation analyses were compared across load conditions.

The group-mean local minimum of the total interference as a function of separation occurred at 5.01 deg (SEM = 0.28) in the low-cognitive-load condition and at 6.52 deg (SEM = 0.36) in the high-cognitive-load condition. This difference was significant ( $t(68) = 3.33, p = 0.001, d = 0.837$ ). In other words, there was significant evidence that the bottom of the profile of perceptual resources occurred closer to the attended location in the low- than in the high-cognitive-load condition.

#### **Errors**

For all comparisons, none of the main effects or interactions in errors was significant (all  $p$  values > 0.100).

#### ***4.5.2.5 Comparison of incompatible- with neutral-distractor RTs as a function of separation and cognitive load***

##### **Reaction times**

This analysis tested for the effects of three factors, namely, Compatibility (I. vs. N.), Separation and Cognitive Load on target-identification RTs using a mixed-design ANOVA.

##### *Effects of Compatibility (I. vs. N.) and Separation*

The main effects of both Compatibility (I. vs. N.) and Separation were significant (respectively,  $F(1,68) = 20.46$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.231$  and  $F(4,272) = 12.89$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.159$ ) but the interaction between Compatibility (I. vs. N.) and Separation was not significant ( $F(4,272) = 1.33$ ,  $p = 0.260$ ,  $\eta_p^2 = 0.019$ ). In other words, *incompatible-distractor response-related interference* was significant but, overall, did not vary with separation.

##### *Effect of Cognitive load*

First, the main effect of Cognitive Load was significant (as already shown in Section 4.5.2.4 above;  $F(1,68) = 11.16$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.141$ ). Second, the interaction between Cognitive Load and Compatibility (I. vs. N.) was not significant ( $F(1,68) = 0.19$ ,  $p = 0.661$ ,  $\eta_p^2 = 0.003$ ). This showed that *incompatible-distractor response-related interference* pooled across separations was similar in both cognitive-load conditions. Third, while the two-way interaction between Cognitive Load and Separation was significant ( $F(4,272) = 2.74$ ,  $p = 0.029$ ,  $\eta_p^2 = 0.086$ ), the three-way interaction between Cognitive Load, Compatibility and Separation was not significant ( $F(4,272) = 0.97$ ,

$p = 0.425$ ,  $\eta_p^2 = 0.014$ ). The absence of significance of the three-way interaction shows that *incompatible-distractor response-related interference* as a function of separation was not significantly affected by cognitive load. No further analyses were thus performed on these data.

### **Errors**

For all comparisons, none of the main effects or interactions in errors was significant (all  $p$  values  $> 0.100$ ).

#### ***4.5.2.6 Comparison of neutral- with no-distractor RTs as a function of separation and cognitive load***

### **Reaction times**

This analysis tested for the effects of three factors, namely, Presence of Neutral Distractor, Separation and Cognitive Load on target-identification RTs using a mixed-design ANOVA.

#### *Effects of Presence of Neutral Distractor, and Separation*

The main effects of both Presence of Neutral Distractor, and Separation were significant (respectively,  $F(1,68) = 6.70$ ,  $p = 0.012$ ,  $\eta_p^2 = 0.090$  and  $F(4,272) = 4.60$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.063$ ) and the interaction between Presence of Neutral Distractor, and Separation was also significant ( $F(4,272) = 3.04$ ,  $p = 0.018$ ,  $\eta_p^2 = 0.043$ ). In other words, neutral distractors generated significant *saliency-related interference* and the latter varied with separation. Polynomial trends for the interaction showed that *saliency-related interference* as a function of separation was best explained by a linear trend



( $F(1,68) = 12.07, p = 0.001, \eta_p^2 = 0.151$ ; all other trends had  $p$  values  $> 0.100$ ), thus describing a gradient rather than a Mexican-hat pattern.

#### *Effect of Cognitive load*

The main effect of Cognitive Load was significant (as already shown in Section 4.5.2.4 above;  $F(1,68) = 10.27, p = 0.002, \eta_p^2 = 0.131$ ) but Cognitive Load did not interact with any other factor (all  $p$  values  $> 0.100$ ).

#### **Errors**

For all comparisons, none of the main effects or interactions in errors was significant (all  $p$  values  $> 0.100$ ).

#### **4.5.3 Discussion**

First, when perceptual load was *high* and cognitive load was *low*, we observed a Mexican-hat profile of perceptual resources. This finding provides an important generalisation of previous findings of Mexican-hat profiles around peripheral targets (Müller et al., 2005; Experiments 3 to 6 and 8 to 10); central target presentation is arguably a more ecologically valid scenario since sustained covert attention to peripheral locations with fixed eyes is an exception rather than the rule: in everyday life, our eyes closely follow our attention.

Second, when perceptual load was *low* and cognitive load was *low*, we observed a gradient profile of perceptual resources. This finding suggests that, in the low-perceptual-load (and low-cognitive-load) condition, the profile of perceptual resources was *defocused*; it was too spread for the increasing arm of the Mexican-hat function to

be sampled, especially *against* the effect of cortical magnification. Differences in the perceptual load employed in past studies may thus explain why some studies have reported gradient profiles and others Mexican-hat ones (see Chapters 2 and 3). While it is not feasible precisely to evaluate and compare perceptual loads across published studies, reports of gradient profiles may have involved low-perceptual-load settings, where the target always occurred at the expected location and/or the display was uncrowded (e.g., Henderson & Macquistan, 1993). Equally, reports of Mexican-hat profiles may have involved difficult perceptual tasks, where the target location was unknown and/or the display was crowded (e.g., Cutzu & Tsotsos, 2003).

Third, when perceptual load was *high* and cognitive load was *high*, we also observed a gradient profile of perceptual resources. Once again, this finding suggests that, in the high-cognitive-load (and high-perceptual-load) condition, the profile of perceptual resources was *defocused*; it was too spread for the increasing arm of the Mexican-hat function to be sampled. In other words, the findings of Experiment 11, like those of Experiments 9 and 10, suggest that increasing cognitive load causes the profile of perceptual resources to spatially defocus (as indexed by the shifting *out* of the bottom of the Mexican-hat function). Note that this finding was significant only in the analyses of *incompatible-distractor total interference* (i.e., the combination of salience-related and response-related interference). On the whole, it appeared that the sensitivity of the method was increased by using a combination of *salience-related* and *response-related* interference rather than either alone (consistent with the findings of Chapter 3).

In conclusion, the results of Experiments 8 and 11 confirm that perceptual mechanisms (e.g., perceptual load) affect the spatial focusing of perceptual resources, and the results

of Experiments 9, 10 and 11 confirm that cognitive-control mechanisms are involved in the focusing of perceptual resources. When cognitive resources are available, we may be able to focus perceptual resources (to a certain extent at least) simply through cognitive engagement with a task requiring spatial selection.

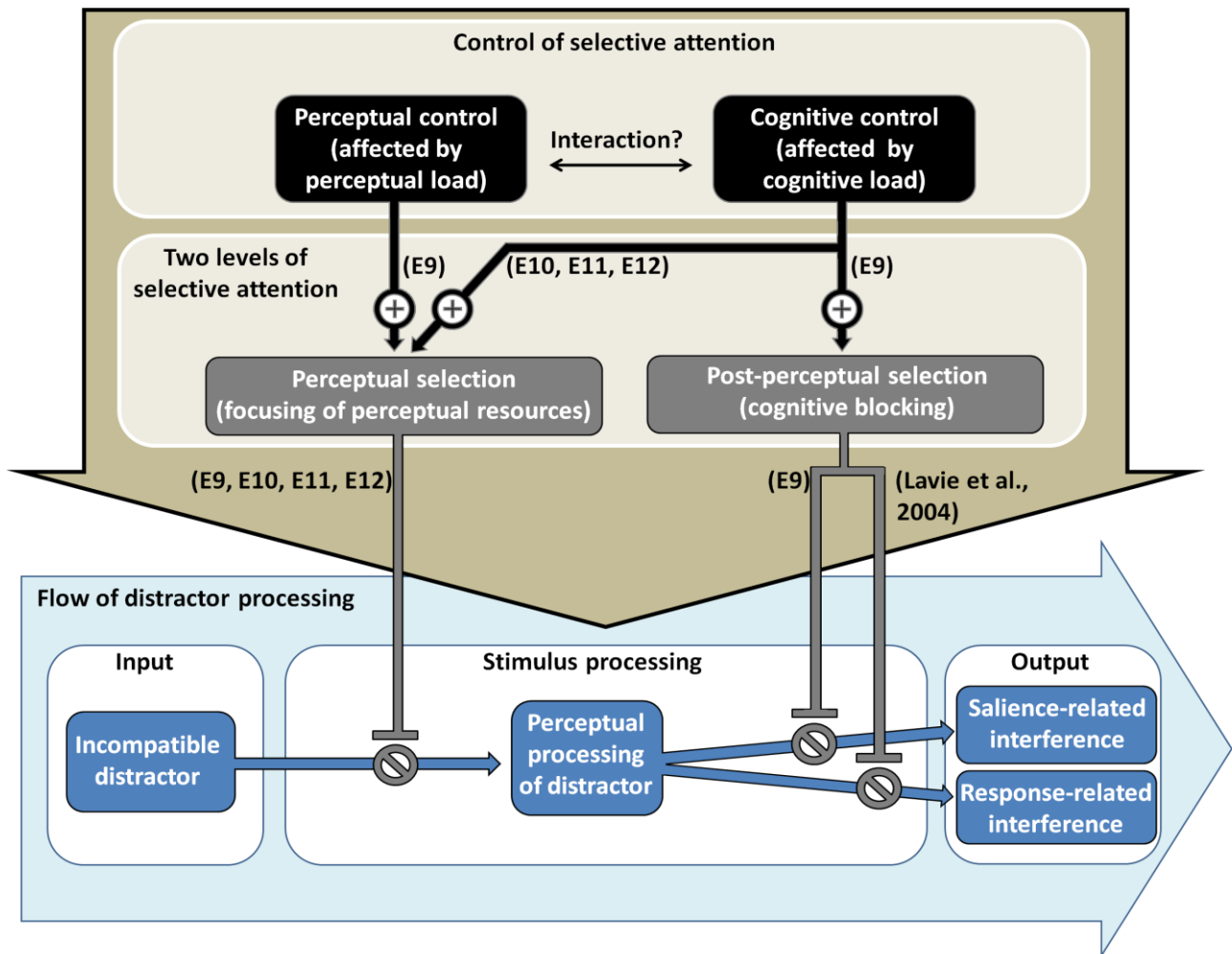
#### **4.6 Discussion of Chapter 4**

The four experiments presented in this chapter produced the following main results:

- (a) distractor interference as a function of separation was found to describe a Mexican-hat pattern with peripheral target presentation (Experiments 8, 9 and 10; see Figures 26, 29, 30, and 32) as well as with central target presentation (Experiment 11; see Figure 34 and 35);
- (b) the interference function of separation became more spatially focused when perceptual load increased (as indexed by the bottom of the interference function of separation occurring at a smaller separation; Experiments 8 and 11; see Figures 26 and 34);
- (c) the interference function of separation became more spatially defocused when cognitive load increased (as indexed by the bottom of the interference function of separation occurring at a larger separation; Experiments 9, 10 and 11; see Figures 29, 30, 32 and 35).
- (d) there was a decrease in the *amplitude of salience-related interference* (not accompanied by changes in the focus of the interference function of separation) when working-memory span increased (Experiment 8; see Figure 27);

Our results have the following four implications. First, the Mexican-hat profile of perceptual resources can be generalized to a more ecologically valid situation where perceptual resources are at fixation. Second, increasing perceptual load does focus perceptual resources in space as shown with cue/probe studies (Downing, 1988; Handy et al., 1996; Williams, 1988) but never directly with flanker studies. Third, the spatial focus of perceptual resources is also affected by cognitive load. This confirms the involvement of cognitive-control mechanisms in the spatial deployment of perceptual resources (Scerif et al., 2006). Fourth, some results of Experiment 8 appear consistent with the view that selective attention operates at two different levels (e.g., Lavie et al., 2004). According to this view, selection operates by reducing distractor interference not only at a perceptual level (by variations in the spatial focus of perceptual resources) but also at a later, post-perceptual level (by the cognitive control of the intrusion of perceptually-processed distractors; e.g., de Fockert et al., 2001 ; Lavie, 2000 ; 2005 ; Lavie & Fox, 2000 ; Lavie et al., 2004 ; MacDonald & Lavie, 2008 ; Maylor & Lavie, 1998 ; Paquet, 2001 ; Pashler, 1999; Yi et al., 2004). These four implications are elaborated below (the last three are summarized in Figure 36).

SCHEMATIC REPRESENTATION OF THE DUAL-CONTROL MODEL OF SELECTIVE ATTENTION



**Figure 36**

*A schematic representation of the dual-control model of selective attention.*

**4.6.1 Mexican-hat profile with central target presentation**

The first novel finding of the present experiments was that the profile of perceptual resources around a central target is shaped like a Mexican hat under certain conditions: the interference from peripheral and *unscaled* incompatible distractors was shown first to decrease but then to increase with increasing separation (in the face of decreasing cortical magnification) in the high-perceptual-load/low-cognitive-load condition of Experiment 11 (note that the distractors were not scaled for cortical magnification to

avoid the possibility that the increase in interference with increasing separation was an artefact of overscaling). This finding constitutes an important generalisation of previous reports of Mexican-hat profiles around peripheral targets (e.g., Müller et al., 2005; Chapters 2 and 3). Using central target presentation is arguably a more ecologically valid scenario since sustained covert attention to peripheral locations with fixed eyes is an exception rather than the rule: in everyday life, our eyes closely follow our attention.

#### **4.6.2 Effect of perceptual load on the focus of perceptual resources**

Experiments 8 and 11 confirmed using the flanker task that, under conditions of high perceptual load, perceptual resources become more spatially focused (see Figures 26 and 34; Downing, 1988; Handy et al., 1996; Williams, 1988). The focusing effect of perceptual load has been demonstrated using the cue/probe paradigm (Downing, 1988; Handy et al., 1996; Williams, 1988) but only *inferred* by flanker studies using a distractor at a single fixed separation from the attended location (Forster & Lavie, 2008 ; Lavie, 1995, 2000, 2005; Lavie & Fox, 2000 ; Lavie et al., 2004 ; LaBerge et al., 1991). In fact, in Experiments 8 and 11, it was confirmed that, because the profile of perceptual resources follows a Mexican-hat pattern, drawing conclusions about the focus of perceptual resources using data from a single separation can be misleading (see Chapter 1). Indeed, it was shown that the effect of perceptual load depends on the separation sampled: while nearer separations showed a decrease in interference with increasing perceptual load (consistent with previous findings), larger separations showed an *increase* in interference with increasing perceptual load (see Figures 26 and 34). This finding is currently not predicted by the widely cited load model (e.g., Lavie, 1995), according to which increases in perceptual load always cause a decrease in distractor interference. If separation is not considered in load studies, between-study

comparisons and generalisations may be compromised, since the effect of perceptual load *depends* on separation.

Equally, if load is not considered in studies of the profile of perceptual resources, between-study comparisons and generalisations about the characteristics of this profile are compromised. For instance, in our hands, the bottom of the Mexican-hat function falls at a separation no smaller than 3.5 deg, when, in other hands (e.g., Hopf et al., 2006), it falls at a separation as small as 1.4 deg to the attended location. This difference in the spatial extent of the focus between our study and the study of Hopf et al. (2006) possibly arose because the latter study used a paradigm different from ours that may have entailed higher perceptual load. Likewise, there are many studies in the literature arguing for a gradient profile that used stimuli with arguably lower perceptual load. With lower load, perceptual resources would be considerably less well focused and it would only be possible to sample the ‘decreasing’ arm of the interference function of separation (see Chapters 2 and 3). As a result, a Mexican-hat function would present as a gradient function. In fact, in Experiment 11, the interference function of separation obtained under low perceptual load described a simple gradient pattern. If we had not shown that the same function described a Mexican hat when perceptual load was high, we would have had to argue that the profile of perceptual resources described a gradient in this experiment. This adds load to the other factors that have been proposed (see Chapter 2) to explain why some studies have concluded that the profile describes a gradient while others, like ours, have concluded that it describes a Mexican hat.

In summary, in Experiments 8 and 11 of this chapter, it was shown that perceptual load focuses perceptual resources in space. This highlights the necessity of sampling more than one spatial separation since sampling from only a single separation can be misleading as to the direction of the effect of load. Finally, experiments in this chapter may help in resolving the longstanding debate about the shape of the spatial profile of perceptual resources: we suggest that it is always shaped like a Mexican-hat, but that, under some perceptual-load conditions, it may be mistaken for a gradient.

#### **4.6.3 Cognitive control of the focus of perceptual resources**

It has been suggested that cognitive-control mechanisms are not involved in controlling the focus of perceptual resources (de Fockert et al., 2001 ; Lavie et al., 2004 ; Lavie, 2005 ; Lavie & de Fockert, 2005 ; 2006 ; MacDonald & Lavie, 2008 ; Yi et al., 2004). This suggestion has been supported by fMRI findings that cognitive load did not change the BOLD signal in perceptual areas to visual scenes presented in the background of attended stimuli (Yi et al., 2004) and that there was no effect of cognitive load on the phenomenological awareness or detectability of a peripheral irrelevant stimulus (MacDonald & Lavie, 2008). The results of Experiment 8 appear consistent with this suggestion: while individual differences in working-memory span (i.e., in the efficiency of cognitive-control mechanisms; Engle et al., 1992; Engle, 2002; Kane & Engle, 2002; Lépine et al., 2005) affected the amplitude of distractor interference across separations, they had no effect on the spatial focus of perceptual resources (i.e., they did not induce any shift in the bottom of the interference function of separation; see Figure 27).

Nevertheless, none of these findings rule out the possibility that cognitive control is also involved in focusing perceptual resources. In Yi et al. (2004), the probe measuring the



effect of cognitive load had no spatial resolution given that it was a background scene sampling all separations. Therefore any defocusing due to increasing cognitive load would not have been measurable. In MacDonald & Lavie (2008), a single fixed separation was used to index the allocation of perceptual resources. Thus any variation in this focusing might have been missed due to insufficient separation sampling. Finally, in Experiment 8 reported here, the absence of an effect of working-memory span on the focus of perceptual resources may have resulted from a lack of power of the manipulation of span. Thus, even participants with poor cognitive control (i.e., low working-memory span) may not have had their cognitive-control resources exhausted by the arguably low cognitive load involved in performing the experiment (in Experiment 8, all participants had to do was to keep in mind the target template and task instructions).

Experiments 9, 10 and 11 sought to overcome the above limitations by exerting strong demands on cognitive control with a difficult memory task (Experiments 9 and 11; as in MacDonald & Lavie, 2008, and Yi et al., 2004), or a calculation task (Experiment 10), and simultaneously measuring the spatial profile of perceptual resources. It showed that, under conditions of high cognitive load, the bottom of the Mexican-hat interference function of separation moved away from the attended location (see Figures 29, 30, 32 and 35), thus providing evidence that cognitive-control mechanisms are after all involved in the focusing of perceptual resources and lending support to the findings of Scerif et al. (2006; see Figure 36).

This effect of cognitive load on the focus of perceptual resources has the same implication as the effect of perceptual load, namely, it may explain why some studies

have generated gradient rather than Mexican-hat findings (if cognitive load was higher in these studies, perceptual resources would have been more defocused and these studies would have revealed a gradient rather than a Mexican hat).

#### **4.6.4 Visual selective attention operates at two different levels**

Experiments 8 to 11 have provided evidence that distractors can be excluded at a perceptual level, by spatially focusing perceptual resources on the attended location. In addition, the result of the working-memory-span manipulation in Experiment 8 (i.e., an increase in distractor interference across separation not accompanied by a change in focus when memory span decreased) appears consistent with the existence of a second post-perceptual level of selection, which is non-spatial in nature and blocks perceptually processed distractors from further intrusion (when they have been poorly filtered at the perceptual level; see Figure 36; de Fockert et al., 2001; Lavie et al., 2004; Lavie & Fox, 2000; Lavie, 2005; Maylor & Lavie, 1998; Paquet, 2001).

Given that the post-perceptual level of selection is assumed to operate on the output of the perceptual level of selection, it can be expected that it will exert a smaller impact on performance when distractors have been more efficiently excluded at the perceptual level. Indeed, the results of Experiment 8 suggest that the increase in distractor interference with decreasing working-memory span was smaller at the bottom of the Mexican-hat where distractors had been excluded the most efficiently at a perceptual level (see Figure 27; note that this interpretation must be taken with caution as there was no significant interaction between the amplitude of distractor interference and separation). Other studies have provided evidence in favour of this idea. For instance, Lavie and Fox (2000) showed that the negative priming of distractor stimuli

disappeared for distractors that did not cause interference (i.e., that had not been perceptually processed). On the other hand, when distractors caused interference (i.e., when they had been perceptually processed), they produced negative priming, which suggested an inhibition at a post-perceptual level of perceptually processed distractors. Similar results were reported by Paquet (2001).

It is noteworthy that, overall, there was not much evidence in Experiments 9, 10 and 11 that the manipulations of cognitive load impacted on post-perceptual levels of selection (i.e., there was no general increase in distractor interference across separations under conditions of increased cognitive load). This may have been due to a change in the focus of perceptual resources that made the amplitude effect more difficult to observe.

#### **4.7 Conclusions**

In summary, in this chapter, we have used Eriksen's flanker paradigm (Eriksen & Hoffman, 1972, 1973) to test the effect of perceptual and cognitive load on distractor interference. Two dependent variables were used, namely, the distractor-interference function of separation and the amplitude of distractor interference, in order to discriminate between effects of load on, respectively, perceptual levels of attentional selection (i.e., the focusing of perceptual resources) and post-perceptual levels of attentional selection (i.e., the post-perceptual blocking of processed distractors). The following four important results were produced: (1) the spatial profile of perceptual resources is shaped like a Mexican hat even with central target presentation (Müller et al., 2005; Chapters 2 and 3); (2) increasing *perceptual* load causes an *increase* in the spatial focus of perceptual resources; (3) increasing *cognitive* load causes a *decrease* in

the spatial focus of perceptual resources; and (4) decreasing working-memory span reduces post-perceptual selection. These findings are consistent with a dual-control model of selective attention (see Figure 36). According to this model, the focus of perceptual resources (the perceptual level of selective attention) and what we see is modulated not only by perceptual but also by cognitive-control mechanisms.

In the following chapter, we test the effect of two other factors on the extent of focus of perceptual resources, namely, individual differences in cognitive failure (or the *deployment* of cognitive resources) and trait anxiety.

# CHAPTER 5 - COGNITIVE FAILURE AND TRAIT

## ANXIETY

### **5.1 Introduction: Effects of cognitive failure and trait anxiety on the profile of perceptual resources**

In Chapter 4, we have shown that previous flanker studies that have tested the effects of perceptual and cognitive load on selective attention did not manipulate target-distractor separation and, therefore, could not distinguish between effects originating at perceptual versus post-perceptual levels of selection. Moreover, when load affected perceptual levels of selection, previous studies could not isolate the direction of this effect (i.e., whether it involved a focusing or a defocusing of perceptual resources).

Numerous studies on the effects of individual differences on selective attention suffer from the same limitation, namely, they did not manipulate separation. In this chapter, we focused on two kinds of individual differences, namely, the deployment of cognitive resources, or *cognitive failure* (Broadbent, Cooper, FitzGerald, & Parkes, 1982), and *trait anxiety* (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983), that have been suggested to affect selective attention. We used a flanker task with a manipulation of target-distractor separation (see Chapters 2, 3 and 4) and tested whether cognitive failure really affects post-perceptual levels of selection (as proposed by Forster and Lavie, 2007, but not directly shown) or, instead/also, affects the perceptual level of selection (i.e., the extent of focus of perceptual resources). In addition, we tested

whether trait anxiety really affects perceptual levels of selection (as proposed, for instance, by Weltman, Smith and Egstrom, 1971, but not directly shown) or, instead/also, the efficiency of post-perceptual levels of selection. If anxiety really *does* affect the perceptual level of selection, we investigated the direction of this effect (i.e., whether it involved a focusing or defocusing of perceptual resources) as previous studies have argued for both. Below, we review the literature that exists on the effect of cognitive failure and on the effect of trait anxiety on selective attention.

### **5.1.1 Cognitive failure**

*Cognitive failure* indexes individuals' self-reported everyday absent-mindedness and failures of attention (Forster & Lavie, 2007; Tipper & Baylis, 1987). It is measured using a questionnaire developed by Broadbent et al. (1982; see Appendix 13). In this questionnaire, individuals are asked to provide information about the frequency during the last six months of 25 everyday errors (such as forgetting where one put one's keys, failing to see a road sign or dropping something). The measure extracted from this questionnaire has been found to be reliable over time, suggesting that it reflects a personality trait rather than just a state (Broadbent et al., 1982; Smith, Chappelow, & Belyavin, 1995).

In several studies in the literature, participants with high cognitive-failure scores have been found to be more impaired by the presence of peripheral distractors than participants with low cognitive-failure scores (Forster & Lavie, 2007; Kramer et al., 1994; Martin & Jones, 1983; Tipper & Baylis, 1987). This finding has been interpreted as evidence that post-perceptual levels of selective attention are less efficient in

participants with high cognitive failure (Forster & Lavie, 2007). As we have discussed in Chapters 1 and 4, however, this finding may equally well reflect a decrease in the efficiency of perceptual levels of selective attention (i.e., defocused perceptual resources).<sup>17</sup> If cognitive failure reflects a decrease in the deployment of cognitive resources, both these interpretations could be true (see Chapter 4).

If the first possibility is true (i.e., post-perceptual levels of selective attention are less efficient in participants with high cognitive failure) then, when distractor interference is indexed as a function of separation (see Experiments 1 to 11), the amplitude of distractor interference across separations should be higher in participants with high than with low cognitive failure but the extent of focus of the interference functions should be the same in both groups (see the effect of working-memory span in Experiment 8, Chapter 4). On the other hand, if the second possibility is true (i.e., perceptual levels of selective attention are less efficient in participants with high cognitive failure), the interference function of separation should be more *defocused* in participants with high than with low cognitive failure.

In Experiment 12, we used the data collected in Experiment 8 to test these two hypotheses.<sup>18</sup> The cognitive-failure score of all the participants who participated in

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<sup>17</sup> Note that the finding of an increase in distractor interference could also reflect a *focusing*, rather than a *defocusing*, of perceptual resources (see Figures 26 and 34, Experiments 9 and 12, Chapter 4) but this possibility is not considered as there is arguably no theoretical justification for why participants with high cognitive failure should display more *focused* perceptual resources.

<sup>18</sup> We used these data because we tested a high number of participants in Experiment 8, which allowed us to test for the effect of individual differences.

Experiment 8 was measured using Broadbent's Cognitive Failure Questionnaire (Broadbent et al., 1982) and distractor interference as a function of separation was compared across groups of low and high cognitive failure. The effect of Perceptual Load (measured in Experiment 8) was also included in the analysis of Experiment 12 as Forster and Lavie (2007) have found that cognitive failure affects distractor interference *only* in conditions of low perceptual load.

In Experiment 12, it was tested whether participants with high cognitive failure showed (1) overall higher distractor interference than participants with low cognitive failure but no change in the focus of the function of separation, or (2) a more defocused interference function of separation.

### **5.1.2 Trait anxiety**

Just like cognitive failure, trait anxiety is a lasting personality trait. An individual's level of trait anxiety predicts how likely it is for this individual to experience state anxiety, namely, to experience stress or worry, in a stressful condition (Eysenck, 1992 ; Eysenck, Derakshan, Santos, & Calvo, 2007). It is argued that the more an experimental task is difficult (e.g., when perceptual load is high) and/or stressful, the more individuals with high trait anxiety will experience state anxiety and differ in their performance from individuals with low trait anxiety (Eysenck & Graydon, 1989; Markowitz, 1969; Murray & Janelle, 2003).

Both the effects of trait and state anxiety on selective attention have been addressed in the literature. We review below findings first of studies measuring the effect of state



anxiety and then of studies measuring the effect of trait anxiety. The studies reviewed all assumed an effect on the focus of perceptual resources (i.e., an effect at the perceptual level of selection rather than at a post-perceptual level of selection) but disagreed about the direction of this effect.

Several results published in the literature have been argued to be compatible with the idea that state anxiety affects the *focus* of perceptual resources (Braunstein-Bercovitz, 2003; Dusek, Kermis, & Mergler, 1975; Dusek, Mergler, & Kermis, 1976; Easterbrook, 1959; Janelle, Singer, & Williams, 1999; Shapiro & Johnson, 1987; Shapiro & Lim, 1989; Solso, Johnson, & Schatz, 1968; Weltman, Smith & Egstrom, 1971; Williams, Tonymon, & Anderson, 1990, 1991). However, there exists a controversy with regard to the *direction* of this effect. Namely, some authors have proposed that an increase in state anxiety *focuses* perceptual resources, creating ‘tunnel vision’ that results in improved performance on the task in hand (Easterbrook, 1959; Staal, 2004), whereas other authors have proposed that state anxiety *defocuses* perceptual resources, creating ‘broad vision’ that allows the early detection of threatening stimuli (Eysenck, 1992 ; Rachman, 1988). We report below instances of the evidence that has been used to argue for each view.

Several authors have shown that, in conditions of high state anxiety, individuals are less able to respond to stimuli occurring removed from the attended location. On the basis of this finding, these authors have argued that state anxiety *focuses* perceptual resources (Easterbrook, 1959; Janelle, Singer, & Williams, 1999; Williams, Tonymon, & Anderson, 1990, 1991). For instance, in Weltman, Smith and Egstrom (1971), the participants carried out a dual visual task that consisted in (1) a central acuity task and

(2) a peripheral detection of a flashing light. State anxiety was created by having the participants perform this dual task in a copy of a pressure altitude chamber (i.e., a simulation of a dangerous situation). Half the participants were lead to believe that they were performing a 60ft dive (high-anxiety condition; the increase in anxiety was established through a questionnaire and an increase in heart rate). The other half of the participants thought that they remained at sea level (non-dangerous low-anxiety condition). It was found that the high-state-anxiety group only detected half as many peripheral flashing lights as the low-anxiety group, leading the authors to suggest that the participants in the high-state-anxiety group displayed a spatial *focusing* of perceptual resources.

In contrast with these findings, some authors have shown that, under increased state anxiety, (1) participants' performance at responding to stimuli removed from the attended location improves (Dusek et al., 1975, 1976; Shapiro & Johnson, 1987; Solso, Johnson, & Schatz, 1968) and (2) the interference generated by distractors removed from the attended location increases (Braunstein-Bercovitz, 2003). On the basis of these findings, it has been argued that state anxiety *defocuses* perceptual resources. For instance, this view was expressed in the study of Shapiro and Lim (1989), in which two groups of participants were tested under different state-anxiety conditions. State anxiety was manipulated by having each group listen to a different piece of music during the performance of a visual task: one piece of music was intended to induce anxiety ('The Rite of Spring' from Stravinsky) while the other was intended not to induce anxiety ('Ballad for piano and orchestra', from Faure; the effect of these pieces of music on state anxiety was reported by Albersnagel, in 1988). The visual task consisted in deciding whether a stimulus had appeared at fixation or in the periphery. On some

‘dual’ trials, a stimulus occurred simultaneously at fixation and in the periphery. On those trials, the participant had to decide which stimulus they had seen *first*. It was found that, on dual trials, participants in the low-state-anxiety condition responded more often that they had seen the central stimulus first, whereas participants in the high-state-anxiety condition responded more often that they had seen the peripheral stimulus first. Shapiro and Lim (1989) argued that perceptual resources were more *defocused* in the high-state-anxiety condition.

The above findings were all obtained in studies that have manipulated *state* anxiety. Fewer studies have tested the effect of *trait* anxiety on selective attention. Nevertheless, just like the studies of state anxiety, studies of trait anxiety have made contradictory conclusions. Thus, Derryberry and Reed (1998) and Murray and Janelle (2003) have argued that, in stressful conditions, perceptual resources are more *focused* in individuals with high trait anxiety whereas Markowitz (1969) and Eysenck and Graydon (1989) have argued just the opposite, namely that, in stressful conditions, perceptual resources are more *defocused* in individuals with high trait anxiety.

Nevertheless, all the conclusions about the effect of state and trait anxiety on the focus of perceptual resources are undersupported by the data as the above studies tested the effect of anxiety by sampling just one spatial separation from the attended location. They assumed that an increase in performance at detecting a peripheral probe or in the interference from a peripheral distractor meant that perceptual resources were more defocused (and vice versa). Yet, as was shown in Experiments 8 to 11, this is not always true: the focusing of perceptual resources may be accompanied by an increase in distractor interference at some (large) separations. This is because focusing the

Mexican-hat profile of perceptual resources causes perceptual resources to decrease at some separations but *increase* at other ones (see Figures 26 and 34).

A further limitation of previous studies is that they did not address the possibility that anxiety might affect post-perceptual levels of selection, instead of (or in addition to) perceptual levels of selection. This is all the more remarkable given that, to our knowledge, theories of anxiety all suggest that the effect of anxiety occurs at cognitive levels, by increasing cognitive effort or decreasing the availability of cognitive resources (see Discussion of this chapter). Similarly, given that the effects of anxiety have typically been suggested to take place at a perceptual level (i.e., by focusing or defocusing perceptual resources), it is surprising that anxiety theorists have not suggested that anxiety may affect the availability of *perceptual* resources, by increasing or decreasing the size of the pool of perceptual resources. In other words, the anxiety literature has historically not applied the reasoning of load theory (e.g., Lavie et al., 2004) that post-perceptual effects are modulated by cognitive processes and perceptual effects by perceptual processes.

In the present experiment, we measured the effect of trait anxiety<sup>19</sup> on distractor interference as a function of separation in order to be in a position to distinguish between effects of anxiety at perceptual and post-perceptual levels of selection and, if there are effects at perceptual levels, in order to be able to isolate the *direction* of these effects. This was done in Experiment 12, a re-analysis of Experiment 8 (see Chapter 4). Trait anxiety was measured using Spielberger's Trait Anxiety Inventory (Spielberger et

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<sup>19</sup> Trait rather than state anxiety was used for methodological reason, as the measures of anxiety were collected on a different day from the flanker data.

al., 1983; see Appendix 14). We did not make any hypothesis about the nature of the effect of trait anxiety (see above). We nevertheless predicted that, if trait anxiety was found to have an effect, this effect would be stronger in the high-perceptual-load condition of Experiment 8, simply because this condition should have generated more *state* anxiety as it was arguably more stressful (Smith & Jones, 1992).

## **5.2 EXPERIMENT 12: Cognitive failure and trait anxiety**

### **5.2.1 Method**

#### ***5.2.1.1 Design***

A mixed design was used in which target-distractor separation (at fixed stimulus eccentricity) and perceptual load were manipulated within participants and trait anxiety and cognitive failure were measured across participants.

#### ***5.2.1.2 Participants***

The data obtained in Experiment 8 from 54 participants from Goldsmiths College (47 females; 6 left-handed; mean age 22.8 yr; age range 18 to 29 yr; see Appendix 9) with normal or corrected-to-normal vision were used. The scores for trait anxiety and cognitive failure of these participants were collected.

### **5.2.1.3 Procedure**

#### **5.2.1.3.1 Cognitive Failure**

Cognitive Failure was measured using Broadbent's Cognitive Failure Questionnaire (Broadbent et al., 1982; see Appendix 13). This questionnaire required the participants to answer 25 questions such as "Do you fail to notice signposts on the road?" or "Do you start doing something at home and then get distracted into doing something else (unintentionally)?" using one of the five qualifiers: (1) very often; (2) quite often; (3) occasionally; (4) very rarely; or (5) never. Each response was scored from 0 to 4 where response '1' ('very often') was always scored '4', response '2' ('quite often') was always scored '3', etc. As a result, each participant was given a score from 0 to 100, where 0 represented the lowest possible cognitive failure and 100 the highest possible. The participants filled in the questionnaire after the completion of Experiment 8.

#### **5.2.1.3.2 Trait Anxiety**

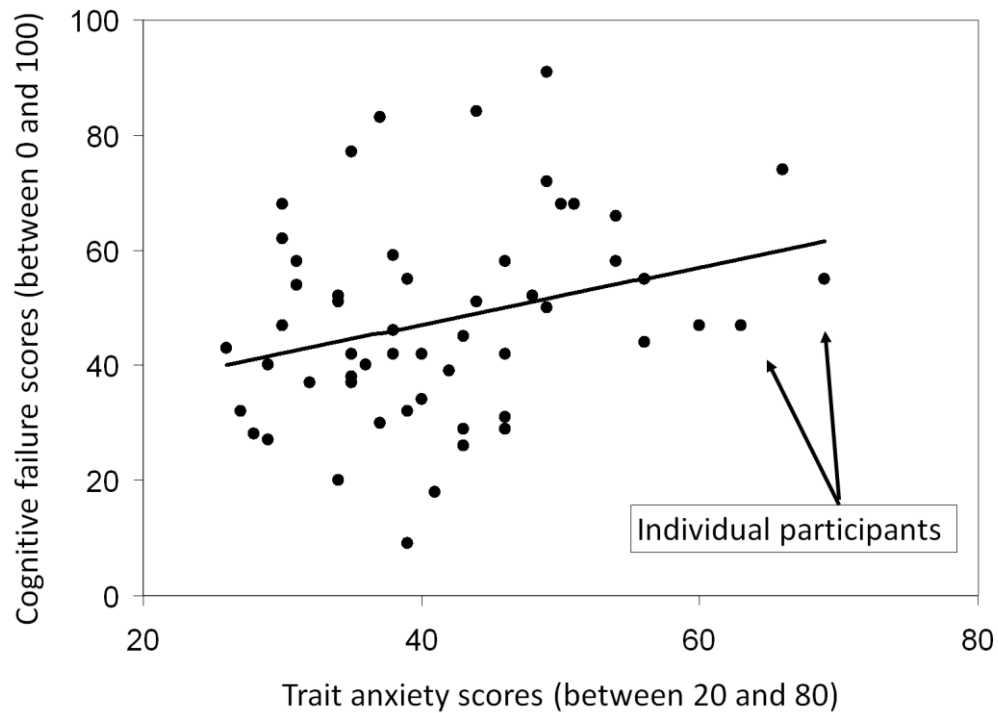
Trait anxiety was measured using Spielberger's Trait Anxiety Inventory (Spielberger et al., 1983; see Appendix 14). This questionnaire required the participants to assess how twenty statements applied to them *in general*. For instance, they had to say whether the statement "I feel nervous and restless" applied to them: (1) almost never; (2) sometimes; (3) often; or (4) almost always. Each response was scored from 1 to 4. A scoring sheet was used to score each answer. Each participant was given a score from 20 to 80, where 20 represented the lowest possible trait anxiety and 80 the highest possible. Most of the participants filled in the questionnaire during a questionnaire session at the beginning of the university year. Those who had not yet filled in the questionnaire at the time of the experiment did so after completion of Experiment 8.

## 5.2.2 Results

First, the participants' questionnaires were analysed. For Spielberger's Trait Anxiety Inventory, the average score was 41.6 and the median score 39.5. The participants were median split into two groups of 27 participants each (with scores ranging from 26 to 39 in the 'low-trait-anxiety' group and from 40 to 69 in the 'high-trait-anxiety' group). For Broadbent's Cognitive Failure Questionnaire, the average score was 47.9 and the median score 46.5. The participants were median split into two different groups of 27 participants each (with scores ranging from 9 to 46 in the 'low-cognitive-failure' group and from 46 to 91 in the 'high-cognitive-failure' group).

A statistical analysis then compared participants' distractor-present RTs (and errors) with no-distractor RTs (and errors) as a function of target-distractor separation (1.8, 3.5, 5.1, 7.7 or 9.0 deg), perceptual load (low or high), trait anxiety (low or high) and cognitive failure (low or high) using a mixed-design ANOVA. Because there was a correlation between the scores of trait anxiety and cognitive failure (participants with higher trait anxiety also tended to have higher cognitive failure:  $r = 0.290$ ,  $p = 0.033$ ; see Figure 37), there were more participants in the groups high both in trait anxiety and cognitive failure (16 participants), or low both in trait anxiety and cognitive failure (16 participants), than in the group high in trait anxiety and low in cognitive failure (11 participants) or in the group low in trait anxiety and high in cognitive failure (11 participants).

## EXPERIMENT 12: REPARTITION OF TRAIT ANXIETY AND COGNITIVE FAILURE SCORES



**Figure 37**

*Scatter plot showing the relation between trait anxiety and cognitive failure scores.*

As in Experiment 8, the statistical analysis tested for the significance of distractor *saliency-related interference* (isolated by comparing distractor-present with no-distractor performance) and it extracted *saliency-related interference* as a function of target-distractor separation (see Results of Experiment 8). Critically, the analysis tested whether the extent of *saliency-related interference*, and *saliency-related interference* as a function of separation, were affected by trait anxiety and cognitive failure.



### ***5.2.2.1 Comparison of neutral-distractor with no-distractor RTs as a function of separation, perceptual load, trait anxiety and cognitive failure***

#### **Reaction times**

##### *Effects of Presence of Neutral Distractor, Separation and Perceptual Load*

The results of the mixed-design ANOVA repeated the effects shown in Experiment 8. It was found that: (1) neutral distractors generated significant *salience-related interference* (i.e., the main effect of Presence of Neutral Distractor was significant:  $F(1,50) = 53.90, p < 0.001, \eta_p^2 = 0.519$ ); (2) this interference varied with separation (i.e., the interaction between Presence of Neutral Distractor and Separation was significant:  $F(4,200) = 3.92, p = 0.004, \eta_p^2 = 0.073$ ) describing a Mexican-hat pattern; (3) participants were slower with high than with low perceptual load (i.e., the main effect of Perceptual Load was significant:  $F(1,50) = 153.53, p < 0.001, \eta_p^2 = 0.754$ ); and (4) the interference function of separation was different in the two load conditions (the interaction between Presence of Neutral Distractor, Separation and Perceptual Load was significant:  $F(4,200) = 3.04, p = 0.018, \eta_p^2 = 0.057$ ) as the bottom of the Mexican hat occurred closer to the attended location with high than with low perceptual load.

##### *Effects of Trait Anxiety and Cognitive Failure<sup>20</sup>*

The novel finding of this experiment was one involving Trait Anxiety: the interaction between Trait Anxiety, Presence of Neutral Distractor and Separation was significant ( $F(4,200) = 2.48, p = 0.045, \eta_p^2 = 0.147$ ), showing that *salience-related interference* as

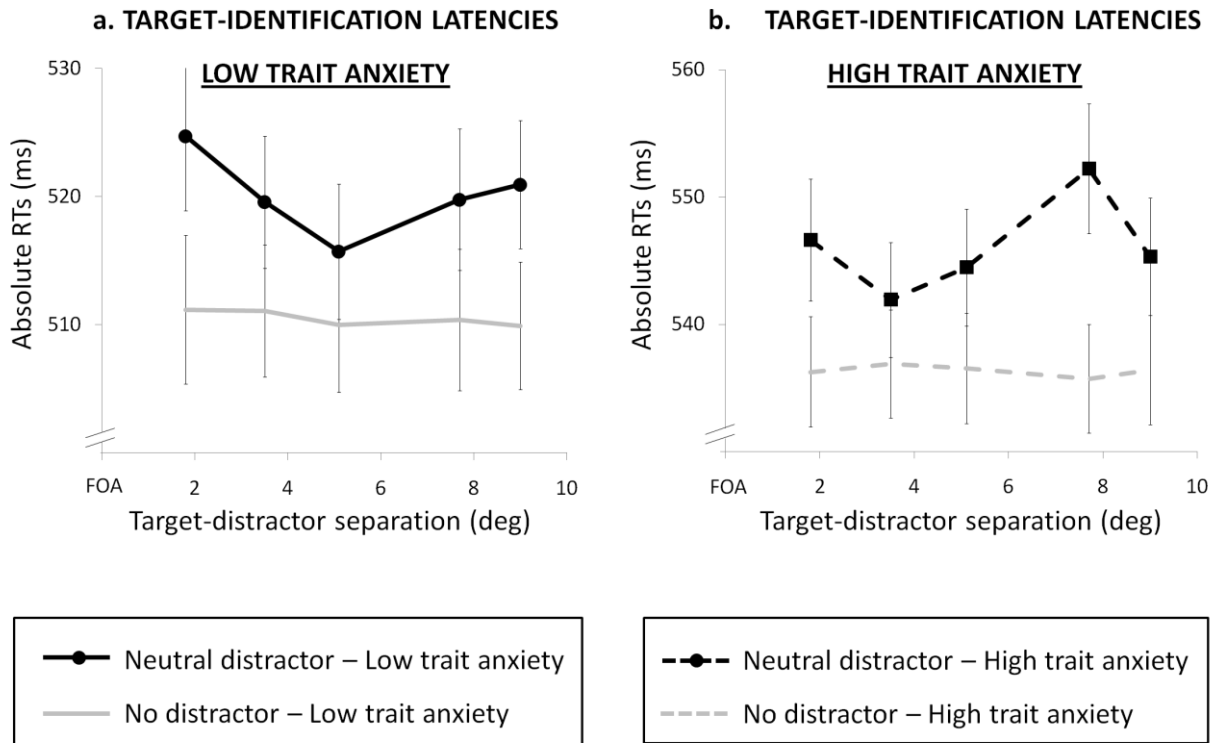
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<sup>20</sup> In this section, unlike in previous ones, significant results are presented first due to the large number of main effects and interactions to be reported.

a function of separation was *different* in high- and low-trait-anxiety participants (see Figure 38). Given the significance of this interaction, the effect of Separation and Presence of Neutral Distractor was investigated separately for each level of Trait Anxiety.

When Trait Anxiety was low, the interaction between Presence of Neutral Distractor and Separation was significant ( $F(4,104) = 2.65$ ,  $p = 0.037$ ,  $\eta_p^2 = 0.193$ ). Polynomial trends for the interaction showed that *salience-related interference* as a function of separation was best explained by a quadratic trend ( $F(1,26) = 8.34$ ,  $p = 0.008$ ,  $\eta_p^2 = 0.243$ ; the  $p$  values for all other trends were above 0.100). When Trait Anxiety was high, the interaction between Presence of Neutral Distractor and Separation was also significant ( $F(4,104) = 3.77$ ,  $p = 0.007$ ,  $\eta_p^2 = 0.127$ ). Polynomial trends for the interaction showed that *salience-related interference* as a function of separation was best explained by a cubic trend ( $F(1,26) = 9.22$ ,  $p = 0.005$ ,  $\eta_p^2 = 0.262$ ; the  $p$  values for all other trends were above 0.100). Therefore, in both low- and high-trait-anxiety participants, the profile of perceptual resources was shaped like a Mexican hat. Nevertheless, it appeared that the profile was more focused in the high than in the low trait-anxiety condition (see Figure 38). This was tested using interpolation analyses (see Results section of Experiment 2 for more details on the methodology used for these interpolations).

EXPERIMENT 12: EFFECT OF TRAIT ANXIETY



**Figure 38**

*Experiment 12 – Latencies. The figure shows: (1) neutral-distractor mean latencies (in ms) as a function of target-distractor separation (in deg) and trait anxiety (low or high) – see black lines; and (2) no-distractor mean latencies (in ms) as a function of trait anxiety (low or high) – see grey lines. Error bars depict +/- 0.5 SEM. (FOA) = attended location.*

In each condition of Trait Anxiety, and for each participant, the separation at which the ‘local minimum’ or bottom of the interference function occurred (i.e., the point where distractor interference stopped decreasing and started increasing) was estimated by calculating the derivative of the cubic function. The local minima so derived were compared across the two Trait Anxiety conditions. The group-mean local minimum occurred at 5.38 deg (SEM = 0.34) in low-trait-anxiety participants and at 4.31 deg (SEM = 0.36) in high-trait-anxiety participants. The difference between the two

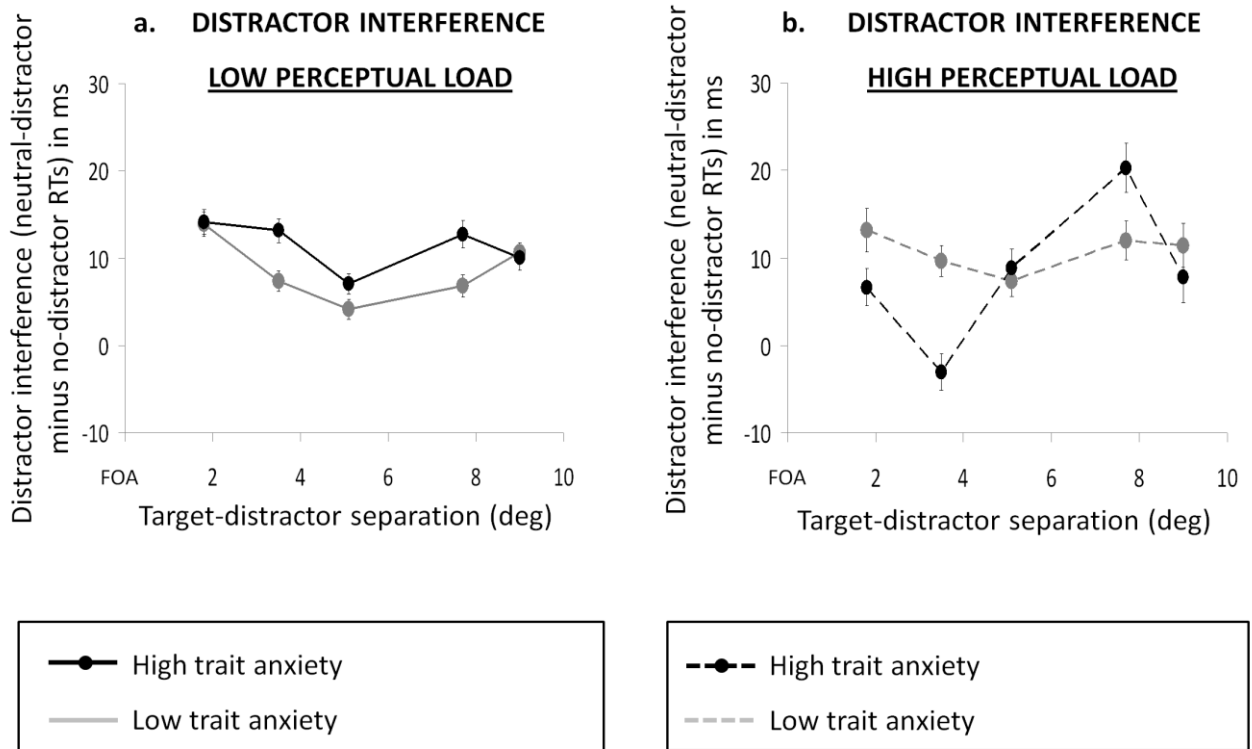
conditions was significant ( $t(52) = 2.17, p = 0.035, d = 0.594$ ): the local minimum of the interference function of separation was closer to the attended location in participants with high trait anxiety than in participants with low trait anxiety (see Figure 38).<sup>21</sup> This finding suggests that the profile of perceptual resources became *more focused* as trait anxiety increased.

In sum, both perceptual load and trait anxiety were shown to focus the profile of perceptual resources (see respectively results of Experiment 8 and the results above). In this context, the question of whether the effects of perceptual load and trait anxiety on the focus of perceptual resources are independent is particularly relevant. The repeated-measures ANOVA showed that the interaction between Presence of Neutral Distractor, Separation, Perceptual Load and Trait Anxiety, was not significant ( $F(4,200) = 1.68, p = 0.157, \eta_p^2 = 0.032$ ). This finding suggests that the effects of Perceptual Load (see Experiment 8) and Trait Anxiety (see above) on the interference function of separation were *independent* even though the data appears to suggest that the effect of trait anxiety was apparent only in the high-perceptual-load condition or, alternatively, that the effect of perceptual load was apparent only in the high-trait-anxiety condition (see Figure 39).

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<sup>21</sup> The location of the bottom of the function was also found to be inversely correlated with participants' trait-anxiety scores ( $r(54) = -0.275, p = 0.045$ )

EXPERIMENT 12: EFFECT OF TRAIT ANXIETY AS A FUNCTION OF PERCEPTUAL LOAD



**Figure 39**

*Experiment 12 – Latencies. The figure shows: (1) distractor interference (neutral-minus no-distractor RTs; in ms) as a function of target-distractor separation (in deg), trait anxiety (low or high) and perceptual load (low or high). Error bars depict +/- 0.5 SEM. (FOA) = attended location.*

None of the other effects involving Trait Anxiety and no effect involving Cognitive Failure were significant, as detailed below.

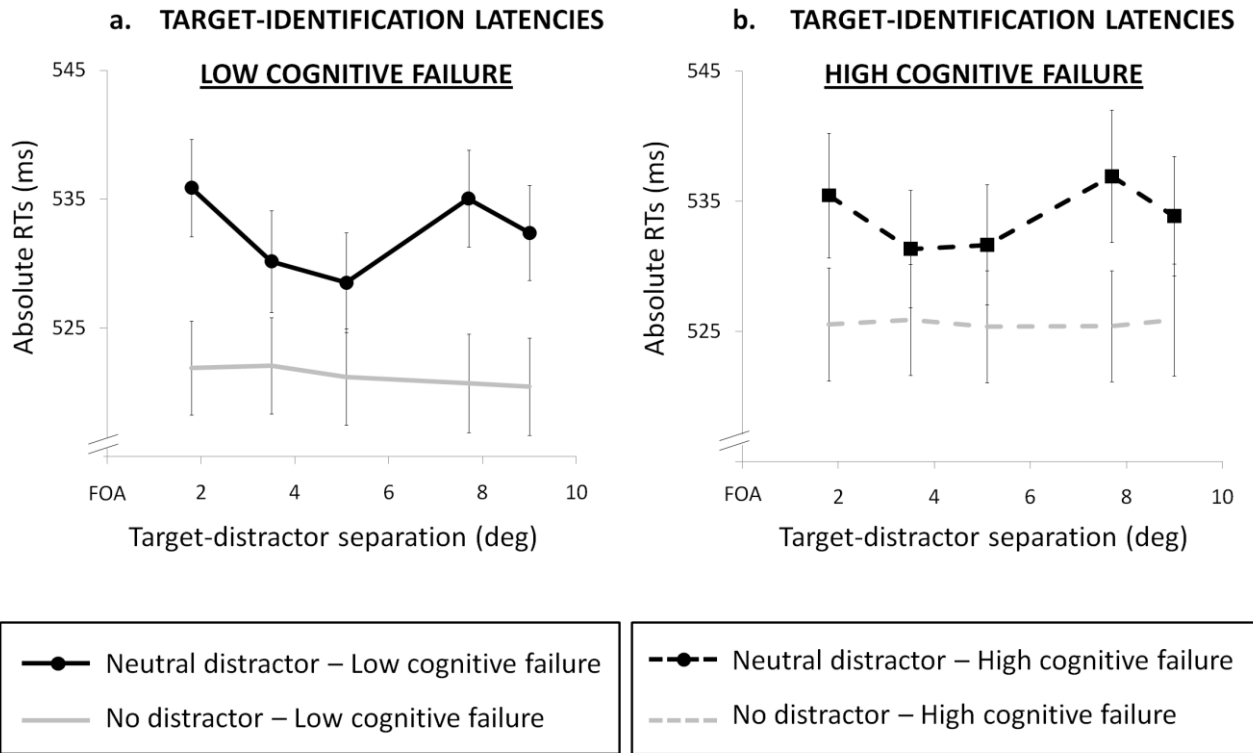
First, neither the main effect of Trait Anxiety nor that of Cognitive Failure were significant (respectively  $F(1,50) = 2.54, p = 0.117, \eta_p^2 = 0.048$  and  $F(1,50) = 0.14, p = 0.906, \eta_p^2 = 0.000$ ); absolute RTs were similar for high and low Trait Anxiety and for high and low Cognitive Failure.

Second, neither Trait Anxiety nor Cognitive Failure interacted significantly with Perceptual Load (respectively  $F(1,50) = 0.10$ ,  $p = 0.757$ ,  $\eta_p^2 = 0.002$  and  $F(1,50) = 0.01$ ,  $p = 0.936$ ,  $\eta_p^2 = 0.000$ ), showing that Trait Anxiety and Cognitive Failure did not change the effect of Perceptual Load on overall performance. The three-way interaction between Trait Anxiety, Cognitive Failure and Perceptual Load was not significant either ( $F(1,50) = 0.67$ ,  $p = 0.416$ ,  $\eta_p^2 = 0.013$ ).

Third, neither Trait Anxiety nor Cognitive Failure interacted significantly with Presence of Neutral Distractor (respectively  $F(1,50) = 0.06$ ,  $p = 0.802$ ,  $\eta_p^2 = 0.001$  and  $F(1,50) = 1.26$ ,  $p = 0.267$ ,  $\eta_p^2 = 0.025$ ), showing that neither Trait Anxiety nor Cognitive Failure affected *saliency-related interference* across separations. In other words, neither Trait Anxiety nor Cognitive Failure had an effect on post-perceptual levels of selection in this experiment. The three-way interaction between Trait Anxiety, Cognitive Failure and Presence of Neutral Distractor was not significant either ( $F(1,50) = 0.91$ ,  $p = 0.346$ ,  $\eta_p^2 = 0.018$ ).

Fourth, the interaction between Cognitive Failure, Presence of Neutral Distractor and Separation was not significant ( $F(4,200) = 0.16$ ,  $p = 0.956$ ,  $\eta_p^2 = 0.003$ ), showing that distractor interference as a function of separation was not affected by Cognitive Failure (see Figure 40). The interaction between Trait Anxiety, Cognitive Failure, Presence of Neutral Distractor and Separation was not significant either ( $F(4,200) = 0.58$ ,  $p = 0.679$ ,  $\eta_p^2 = 0.011$ ).

EXPERIMENT 12: EFFECT OF COGNITIVE FAILURE



**Figure 40**

*Experiment 12 – Latencies. The figure shows: (1) neutral-distractor mean latencies (in ms) as a function of target-distractor separation (in deg) and cognitive failure (low or high) – see black lines; and (2) no-distractor mean latencies (in ms) as a function of cognitive failure (low or high) – see grey lines. Error bars depict +/- 0.5 SEM. (FOA) = attended location.*

Fifth, neither the interaction between Trait Anxiety and Separation nor that between Cognitive Failure and Separation was significant (respectively  $F(4,200) = 3.43$ ,  $p = 0.064$ ,  $\eta_p^2 = 0.043$  and  $F(4,200) = 0.16$ ,  $p = 0.960$ ,  $\eta_p^2 = 0.003$ ), showing that RTs (pooled across distractor-present and no-distractor conditions) as a function of separation were not significantly affected by Trait anxiety or Cognitive Failure. The three-way interaction between Trait Anxiety, Cognitive Failure and Separation was not significant either ( $F(4,200) = 0.51$ ,  $p = 0.730$ ,  $\eta_p^2 = 0.010$ ).

Sixth, the interactions between Trait Anxiety, Presence of Neutral Distractor and Perceptual Load, between Cognitive Failure, Presence of Neutral Distractor and Perceptual Load, and between Trait Anxiety, Cognitive Failure, Presence of Neutral Distractor and Perceptual Load were not significant (respectively,  $F(1,50) = 0.88$ ,  $p = 0.353$ ,  $\eta_p^2 = 0.017$ ;  $F(1,50) = 0.33$ ,  $p = 0.566$ ,  $\eta_p^2 = 0.007$ ; and  $F(1,50) = 0.02$ ,  $p = 0.881$ ,  $\eta_p^2 = 0.002$ ). This shows that Trait Anxiety and Cognitive Failure did not affect the effect of Perceptual Load on overall distractor interference.

Seventh, the interactions between Trait Anxiety, Perceptual Load and Separation, between Cognitive Failure, Perceptual Load and Separation, and between Trait Anxiety, Cognitive Failure, Perceptual Load and Separation, were not significant (respectively,  $F(4,200) = 0.45$ ,  $p = 0.769$ ,  $\eta_p^2 = 0.009$ ;  $F(4,200) = 0.25$ ,  $p = 0.909$ ,  $\eta_p^2 = 0.005$ ; and  $F(4,200) = 0.76$ ,  $p = 0.555$ ,  $\eta_p^2 = 0.005$ ). This shows that Trait Anxiety and Cognitive Failure did not change the effect of Perceptual Load on the RT function of separation (obtained by pooling distractor-present and no-distractor RTs at each separation).

Finally, the interaction between Cognitive Failure, Presence of Neutral Distractor, Separation and Perceptual Load was not significant ( $F(4,200) = 0.66$ ,  $p = 0.617$ ,  $\eta_p^2 = 0.013$ ). This suggests that Cognitive Failure did not change the focusing effect of perceptual load. The five-way interaction between Trait Anxiety, Cognitive Failure, Presence of Neutral Distractor, Separation and Perceptual Load was not significant either ( $F(4,200) = 0.80$ ,  $p = 0.525$ ,  $\eta_p^2 = 0.016$ ).



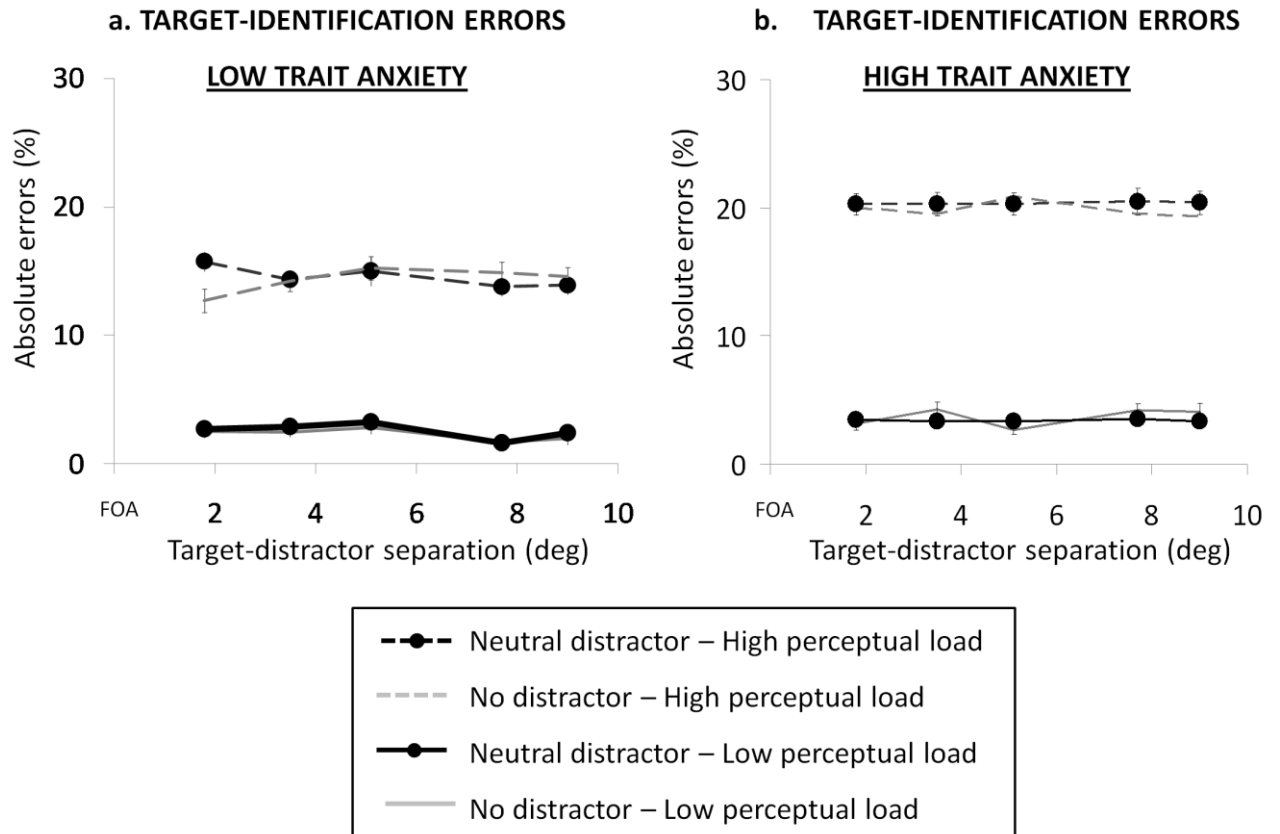
## **Errors**

The results of the repeated-measures ANOVA repeated the effects shown in Experiment 8. It was found that: (1) participants made more errors in the high perceptual-load condition (the main effect of Perceptual Load was significant:  $F(1,50) = 180.54$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.783$ ); but (2) there was no significant *salience-related interference* on errors (the main effect of Presence of Neutral Distractor was not significant:  $F(1,50) = 0.28$ ,  $p = 0.602$ ,  $\eta_p^2 = 0.005$ ); and (3) there was no evidence that *salience-related interference* varied with separation in errors (the interaction between Presence of Neutral Distractor and Separation was not significant:  $F(4,200) = 0.30$ ,  $p = 0.876$ ,  $\eta_p^2 = 0.006$ ).

The novel finding of this experiment was one involving Trait Anxiety, namely, the main effect of Trait Anxiety was significant ( $F(1,50) = 5.56$ ,  $p = 0.022$ ,  $\eta_p^2 = 0.100$ ), showing that errors (obtained by pooling distractor-present and no-distractor errors) were higher in high- than low-trait-anxiety participants. Moreover, the interaction between Trait Anxiety and Perceptual Load was marginally significant ( $F(1,50) = 3.23$ ,  $p = 0.078$ ,  $\eta_p^2 = 0.061$ ), compatible with the fact that the above effect may have originated more from the high-perceptual-load condition (see Figure 41).

No other effects were significant for Trait Anxiety and Cognitive Failure (all other main effects and interactions had  $p$  values  $> 0.100$ ).

EXPERIMENT 12: EFFECT OF TRAIT ANXIETY



**Figure 41**

*Experiment 12 – Errors. The figure shows: (1) neutral-distractor mean errors (in %) as a function of target-distractor separation (in deg), trait anxiety (low or high) and perceptual load (low or high) – see black lines; and (2) no-distractor mean errors (in %) as a function of trait anxiety (low or high) and perceptual load (low or high) – see grey lines. Error bars depict +/- 0.5 SEM. (FOA) = attended location.*

**5.3 Discussion of Chapter 5**

The findings of the present experiment can be summarized as follows: (i) cognitive failure had no effect on the amplitude of distractor interference or on the extent of focus of the interference function of separation; (ii) high-trait-anxiety participants made more errors than low-trait-anxiety participants and this appeared to be true in the high-

perceptual-load condition but not in the low-perceptual-load condition; (iii) the distractor-interference function of separation (in RTs) was more focused in participants with high trait anxiety than in those with low trait anxiety.

### **5.3.1 Cognitive Failure**

The results of the present experiment did not replicate previous findings showing that participants with high cognitive failure are more sensitive to distractor interference than participants with low cognitive failure (Forster & Lavie, 2007; Kramer et al., 1994; Martin & Jones, 1983; Tipper & Baylis, 1987), neither in the low- nor in the high-perceptual-load condition. Note that our experiment is not the only one that has failed to correlate cognitive-failure scores with objective measures of performance at attentional tasks (see Smith et al., 1995). For instance, Kane, Hasher, Stoltzfus, Zacks and Connelly (1994) found no significant correlation between scores of cognitive failure and distractor interference. Additionally, Martin (1983) found no significant correlation between scores of cognitive failure and performance at the Stroop task.

In this experiment, the null effect of cognitive failure suggests that there was no difference between low- and high-cognitive-failure participants either in the efficiency of the perceptual level of selective attention (i.e., the focusing of perceptual resources) or in the efficiency of the post-perceptual level of selective attention (i.e., the cognitive blocking of perceptually processed distractors). Alternatively, however, it is possible that the null effect of cognitive failure was caused by confounding factors, as discussed below.

First, our population may have been biased towards high cognitive-failure scores, causing a ceiling effect. Indeed, in Kramer et al. (1994), the *mean* score for cognitive failure was 37.5 (their median score is unknown) whereas it was 47.9 in this experiment (higher by ten points). Moreover, in Forster and Lavie (2007), the *median* score for cognitive failure was 41.0 (their mean score is unknown) whereas it was 46.5 in this experiment (higher by 5.5 points). Nevertheless, note that in Tipper and Baylis (1987), the median score (47.5) was similar to the one in this experiment (46.5), yet they managed to show an effect of cognitive failure on distractor interference. To test this first hypothesis, we performed further analyses only on the third of the participants with the lowest scores and the third of the participants with the highest scores. These post-hoc analyses still failed to show an effect of cognitive failure either on the amplitude of distractor interference or on the extent of focus of the interference function of separation.

A second hypothesis is that, in our experiment, perceptual load was overall too high, even in the condition that we referred to as low perceptual load, thus preventing any effect of cognitive failure from showing itself (as suggested by the findings of Forster & Lavie, 2007). Yet, it is unlikely that load was higher in this experiment than in Forster and Lavie (2007). Indeed, in the low-perceptual-load condition of this experiment, errors were low (about 5%) and RTs were in the same range (around 500 ms) as those from the low-perceptual-load condition in Forster and Lavie (2007). As a result, it is unlikely that this hypothesis can explain the null effect of cognitive failure in the low-perceptual-load condition of this experiment.

Finally, a third hypothesis is that our method was not sufficiently sensitive. Indeed, we measured the effect of cognitive failure using *salience-related interference* (indexed with neutral distractors). On the other hand, Forster and Lavie (2007) and Kramer et al. (1994) measured the effect of cognitive failure using *response-related interference* (indexed using compatible and incompatible distractors). We found, in Experiment 10 (Chapter 4), that salience-related interference is a less sensitive index of changes in the focus of distractor interference as a function of separation than response-related interference (indeed, the effect of cognitive load was not significant when using salience-related interference but it was significant when using response-related interference). As a result, it is possible that, in this experiment, we have *missed* an effect of cognitive failure on the focus of perceptual resources.

### **5.3.2 Trait Anxiety**

The present experiment provided no evidence for an effect of trait anxiety on the amplitude of distractor interference across separations (i.e., it provided no evidence for an effect of trait anxiety on post-perceptual levels of selection). On the other hand, it showed that the distractor-interference function of separation was more focused in participants with high trait anxiety than in those with low trait anxiety. This finding is consistent with the suggestion that anxiety causes perceptual resources to *focus* (Derryberry & Reed, 1998; Easterbrook, 1954; Janelle, Singer, & Williams, 1999; Murray & Janelle, 2003; Smith & Jones, 1992; Staal, 2004; Williams, Tonymon, & Anderson, 1990, 1991; Weltman, Smith, & Egstrom, 1971) but not with the suggestion that it causes perceptual resources to *defocus* (Braunstein-Bercovitz, 2003; Dusek et al., 1975, 1976; Eysenck & Graydon, 1989; Markowitz, 1969; Shapiro & Johnson, 1987; Shapiro & Lim, 1989; Solso, Johnson, & Schatz, 1968).

There are two non-exclusive ways of accounting for the focusing effect of trait anxiety on the profile of perceptual resources: (1) high-trait-anxiety individuals may have a smaller pool of perceptual resources at their disposal (to our knowledge, this possibility has not been considered in the literature)<sup>22</sup> or (2) they may spend more cognitive resources (i.e., more cognitive effort) on focusing their perceptual resources.

According to the first hypothesis (i.e., that high-trait-anxiety individuals have overall fewer perceptual resources at their disposal), high-trait-anxiety individuals would be more sensitive to bottom-up effects of perceptual difficulty: lower increases in perceptual load would be necessary to focus their perceptual resources; this idea is compatible with the observation that the focusing effect of perceptual load (on RTs) seemed to be effective *only* in the high-trait-anxiety condition (see Figure 39).<sup>23</sup> The suggestion that high-trait-anxiety individuals are more sensitive to perceptual difficulty is also supported by the finding that, in this experiment, high-trait-anxiety participants made overall more errors than low-trait-anxiety participants, and this appeared to be true especially in the high-perceptual-load condition.<sup>24</sup>

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<sup>22</sup> Note that fewer perceptual resources could either be the result or the cause of trait anxiety.

<sup>23</sup> This interpretation of the data must be taken with caution since the four-way interaction between Presence of Neutral Distractor, Separation, Perceptual Load and Trait Anxiety in RTs was *not* significant ( $p = 0.157$ ; see Results section).

<sup>24</sup> There was a marginally significant interaction between Trait Anxiety and Perceptual Load in errors ( $p = 0.078$ ).

According to the second hypothesis (which is not exclusive of the first one), high-trait-anxiety individuals would spend *more cognitive effort* on focusing their perceptual resources (Sarter, Gehring, & Kozak, 2006). This hypothesis is consistent with the suggestion that high-trait-anxiety individuals are prone to spend more effort on the task in hand to avoid failure (Staal, 2004). This could explain why high-trait-anxiety participants appeared to have focused their perceptual resources more than low-trait-anxiety participants mainly in the high-perceptual-load condition, namely, when the risk of failure was high (see Figure 39). Any such increase in focus was not however accompanied by an improvement in overall performance, making the present hypothesis compatible with the ‘processing efficiency theory’ described by Eysenck and Calvo (1992). According to this theory, high-trait-anxiety participants are less ‘cognitively efficient’ than low-trait-anxiety participants in that they spend more cognitive resources to achieve a similar level of performance (or of ‘effectiveness’) to low-trait-anxiety participants.

The data obtained in the present experiment does not allow us to decide between the first and the second hypothesis. In fact, the two hypotheses are not exclusive. For instance, it is possible that participants with high trait anxiety have overall fewer perceptual resources at their disposal, causing them to make more errors and, as a result, causing an increase in participants’ fear of failure and in their cognitive effort to perform the task in hand.

Note that the findings of this experiment do not support an hypothesis found in the literature that high-trait-anxiety participants have access to fewer cognitive resources

than low-trait-anxiety participants because worry monopolises some of their available cognitive resources (Derakshan & Eysenck, 1998; Eysenck & Calvo, 1992; Eysenck et al., 2007; Eysenck, Payne, & Derakshan, 2005; Johnson & Gronlund, 2009; Lavric, Rippon, & Gray, 2003) thus causing a defocusing of perceptual resources. Nevertheless, neither do our findings disconfirm this hypothesis. Indeed, it is possible that, because our experiment did not put the participants in a high state of anxiety (and therefore cognitive resources were not significantly monopolised by worry), high-trait-anxiety participants had sufficient cognitive resources to focus perceptual resources.

It would be interesting to test whether, when the level of state anxiety increases, high-trait-anxiety individuals are still not impaired compared to low-trait-anxiety individuals. If it was found that, under conditions of high state anxiety, individuals with high trait anxiety were more *defocused* than individuals with low trait anxiety, this would suggest that the effect of trait anxiety on the extent of focus of perceptual resources goes in opposite directions depending on the level of state anxiety: trait-anxious people may be *more* focused in conditions of low state anxiety, but *less* focused in conditions of high state anxiety. Such finding would parallel the finding that the effect of anxiety on overall performance is U-shaped: moderate increases in state anxiety *improve* performance whereas strong increases in state anxiety *worsen* performance (Smith & Jones, 1992). In itself, this view could account for contrary conclusions in the literature on the effect of anxiety. Note that this scenario of a U-shaped function of the effect of state anxiety is compatible with the cognitive-effort account for the greater focus in high-trait-anxious participants (see Hypothesis 2 above). If on the other hand, increasing state anxiety did not cause a defocusing effect on high-trait-anxious



participants, this would be compatible with the perceptual-resources account for the greater focus in high-trait-anxious participants (see Hypothesis 1 above).

## **5.4 Conclusions**

In sum, cognitive failure was not shown to affect either the perceptual or the post-perceptual level of selective attention. Trait anxiety was also not found to affect the post-perceptual level of selective attention. On the other hand, it was found to affect the perceptual level of selective attention, by *focusing* perceptual resources, possibly more in conditions of high perceptual load. This may be due to the fact that high-trait-anxiety individuals have overall fewer perceptual resources at their disposal. Alternatively, or additionally, it may be due to the fact that, in difficult conditions, high-trait-anxiety individuals spend more cognitive *effort* on the task in hand in order to avoid failure.

It is noteworthy that, in Experiment 12, the bottom of the Mexican hat for the high-trait-anxious individuals occurred closer to the attended location than in any of the other experiments of this thesis, except in the high-perceptual-load conditions, indeed around a similar separation to the one in Müller et al. (2005). We assume that perceptual load cannot account for the difference in focus between Experiment 1 (see Chapter 2) and Müller et al. (2005) given that we modelled our methodology on theirs. However, individual differences like those reported here, if they varied between our sample and that of Müller et al. (2005), could account for this discrepancy.

In conclusion, this chapter confirmed that, by using the methodology introduced in Chapter 4, one can distinguish between perceptual and post-perceptual accounts of

syndromes where previously this was not possible. This methodology could be used in several other instances where extant findings in the literature about deficits in selective attention could be explained either as perceptual or post-perceptual deficits. This point is addressed further in the General Discussion (Chapter 6).

## CHAPTER 6 – GENERAL DISCUSSION

This General Discussion comprises two main sections. In the first section, we summarize the findings of the present thesis. In the second section, we address some implications of these findings for future research.

### **6.1 Summary of findings**

We summarize below the main findings of this thesis and their implications. These findings concern (1) the indices that can be used to measure the profile of perceptual resources (see Sections 6.1.1 below), (2) the pattern described by the profile of perceptual resources (see Section 6.1.2 below), and (3) the factors that affect the relative focus of the profile of perceptual resources (see Section 6.1.3 below). We finish by describing the ‘dual-control model’ that can accommodate the findings of this thesis (see Section 6.1.4 below).

#### **6.1.1 Indexing the profile of perceptual resources**

In this section, we summarize our results regarding the indices that have been classically used to measure the profile of perceptual resources. These indices are extracted in two tasks, namely, the flanker task and the cue/probe task and can be derived from both reaction times and errors.

##### ***6.1.1.1 Indexing the profile of perceptual resources using reaction times and errors***

In this thesis, the profile of perceptual resources was indexed using *both* reaction times and errors and it is noteworthy that, in most experiments (i.e., Experiments 1, 2, 3, 4, 5, 7, 9 and 10), these two indices agreed. Only in three experiments, namely, in Experiments 6, 8 and 11, did the two indices not agree and this was because distractor interference as measured in errors did *not* vary with separation as it *did* in reaction times. Our findings are consistent with the suggestion that reaction times and errors index similar processes but that errors are a less sensitive measure of the shape of the profile of perceptual resources; they do not provide support for the suggestion that reaction times and errors index different processes (Santee & Egeth, 1982).

#### **6.1.1.2 The flanker task**

In all the experiments of this thesis (except in one condition of Experiment 6 and in Experiment 7; see Section 6.1.2 below), the spatial profile of perceptual resources was mapped using Eriksen's flanker task (Eriksen & Hoffman, 1972, 1973) by systematically manipulating the separation between a distractor and the attended (target) location, and recording the variations in distractor interference as a function of separation. This method has been employed in numerous studies from the literature (see Eriksen & St. James, 1986; McCarley & Mounts, 2008; Mounts, 2000a, 2005; Mounts & Gavett, 2004; Müller et al., 2005; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990) that have used three *types* of measures of distractor interference, namely, (1) *combined response-related interference* (Müller et al., 2005; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990), (2) *incompatible-distractor response-related interference* (Eriksen & St. James, 1986), and (3) *saliency-related interference* (McCarley & Mounts, 2008; Mounts, 2000a, 2005; Mounts & Gavett, 2004). The first of these measures, *combined*

*response-related interference*, is obtained by comparing compatible-distractor performance with incompatible-distractor performance; the second of them, *incompatible-distractor response-related interference*, is obtained by comparing neutral-distractor performance with incompatible-distractor performance; and, the third of them, *saliency-related interference*, is obtained by comparing no-distractor performance with neutral-distractor performance (see Chapters 1, 2 and 3).

These three types of measures were compared in Chapter 3 and it was found that the functions of separation obtained with all of them described a similar pattern and were similarly focused in comparable conditions. This finding suggests that all three types of measure of distractor interference can be use to index the profile of perceptual resources. It was also found that measuring the profile of perceptual resources using only one measure was less sensitive than when using a *combination* of measures. Indeed, in Experiment 11 (see Chapter 4), the effect of cognitive load on the focus of the profile of perceptual resources did not reach significance when using only *saliency-related interference* or only *incompatible-distractor response-related interference*, but it did reach significance when using the combination of the two measures (i.e., by using *incompatible-distractor total interference*, namely, by comparing no-distractor performance with incompatible-distractor performance). Using more than one measure of distractor interference therefore makes the flanker task a more sensitive index of the profile of perceptual resources and, therefore, a more powerful tool for the study of selective attention.

### **6.1.1.3 The cue/probe task**

Eriksen's flanker task is not the only task that has been used to index the profile of perceptual resources. The cue/probe task (Posner, 1980) has also frequently been used for this purpose by systematically manipulating the separation between a probe that must be responded to (i.e., that must be detected or identified) and a cued location (the attended location). Performance at responding to the probe as a function of *cue-probe separation* is taken to reflect the profile of perceptual resources (e.g., Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Dori & Henik, 2006; Downing, 1988; Handy et al., 1996; Henderson, 1991; Henderson & Macquistan, 1993; Hodgson et al., 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Mounts 2000b; Shulman et al., 1985; Tsal, 1983; Williams, 1988).

Performance at responding to the probe as a function of separation obtained using the cue/probe task was qualitatively compared to distractor interference as a function of separation measured with the different types of interference in the flanker task (see point 6.1.1.1 above). With all the different measures, the functions of separation described a similar pattern and were similarly focused (see Chapter 3). This finding confirmed that the cue/probe task and the flanker task can be used equally to measure the profile of perceptual resources.

### **6.1.2 The shape of the profile of perceptual resources**

Contrasting findings about the *pattern* described by the profile of perceptual resources have been reported in the literature. Most flanker studies and numerous cue/probe studies have reported findings consistent with a profile of perceptual resources

describing a *gradient* pattern, where perceptual resources simply decrease with increasing separation (e.g., Dori & Henik, 2006; Downing, 1988; Eriksen & St. James, 1986; Handy et al., 1996; Henderson, 1991; Henderson & Macquistan, 1993; McCarley & Mounts, 2008; Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Shulman et al., 1985; Tsai, 1983; Yantis & Johnston, 1990; Williams, 1988). Other cue/probe studies, but no flanker study, have reported findings consistent with a profile of perceptual resources describing an *inverted-gradient* pattern, where perceptual resources simply increase (before reaching a plateau) with increasing separation (Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Downing, 1988; Hodgson et al., 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Mounts 2000b). Finally, a recent flanker study has reported findings consistent with a profile of perceptual resources describing a Mexican-hat pattern, where perceptual resources first decrease but then *increase*, before then tailing off, with increasing separation (Müller et al., 2005).

In most of the experiments of this thesis, we report findings consistent with the latter Mexican-hat pattern rather than with gradient or inverted-gradient patterns. This Mexican-hat finding was obtained with both central and peripheral presentation of the target and could not be explained by irregularities in the visual field (see Experiments 3 and 7). Only in Experiment 1, and in the low-perceptual-load and high-cognitive-load conditions of Experiment 11, did the function of separation describe a gradient pattern. We propose that such a gradient pattern was obtained because of under-sampling in Experiment 1 (we did not sample far enough from the attended location) and because the profile of perceptual resources was defocused in the low-perceptual-load and in the

high-cognitive-load conditions of Experiment 11, thus preventing us from indexing the increasing arm of the Mexican-hat function.

We reason that the profile of perceptual resources is always shaped like a Mexican-hat, but that, under some circumstances, it may be mistaken for a gradient or an inverted gradient. These circumstances occur when the profile of perceptual resources is so strongly focused or so strongly defocused that it becomes difficult (or impossible) to sample the initial decreasing arm or the subsequent increasing arm of the Mexican-hat function (see Experiment 11 in Chapter 4). Perceptual load, cognitive load and trait anxiety are factors that are proposed to cause perceptual resources to be more or less focused. The effect of these factors across studies may therefore contribute to the varying types of profiles obtained in different studies (see Section 6.1.3 below).

In addition, a Mexican-hat profile may be mistaken for a gradient or an inverted gradient when the method used to index the profile of perceptual resources is not sensitive enough. This occurs when an insufficient range of separations is sampled (see Experiment 1 in Chapter 2), when the probe measuring perceptual resources is not powerful enough (see Experiment 1 in Chapter 2), or when the hemifield of stimulus presentation is not taken into account (see Experiment 2 in Chapter 2). In the latter case, if the profile of perceptual resources presents as being differently focused in the two hemifields, averaging the profiles from the two hemifields may result in a gradient. This is precisely what occurred in Experiment 2 (see Chapter 2), where the profile of perceptual resources was more focused in the left than in the right hemifield. This difference in focus may have resulted from receptive fields being larger in the right than in the left hemisphere (Jacobs & Kosslyn, 1994; Kosslyn, Chabris, Marsolek, Koenig,



1992). Alternatively, it may have resulted from a spatial bias towards the right hemifield due to decreased alertness (Manly, Dobler, Dodds, & George, 2005) or due to the direction of reading (McConkie & Rayner, 1976; Rayner, 1998). In Experiments 3 to 11, the focus of the profile of perceptual resources seemed not to be affected by the hemifield factor. The fact that the effect of hemifield could fail to manifest itself (especially in Experiment 11 using central presentation where the effect of hemifield was certainly not confounded with that of target location) seems incompatible with the receptive field hypothesis (a receptive-field effect should occur consistently across experiments).

*Why does the profile of perceptual resources describe a Mexican-hat pattern?*

There is no consensus with regard to the underlying mechanisms accountable for the Mexican-hat shape of the profile of perceptual resources. Nevertheless, two views recurrently appear in the literature. The first of them is that the ignored area (i.e., the bottom of the Mexican hat) reflects a ‘zone of inhibition’ that surrounds the attended location (Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotos, 2003; Hodgson et al., 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Kröse & Julesz, 1989; Mounts, 2000b; Müller et al., 2005; Pan & Eriksen, 1993; Schwartz et al., 2005; Slotnick, Schwarzbach, & Yantis, 2003). This view emphasizes the idea that attentional selection consists in *excluding* irrelevant information that occurs outside the attended location.

The second view that is sometimes found in the literature is that the ignored area around the attended location (i.e., the bottom of the Mexican hat) is indirectly caused by the

borrowing of resources from *around* the attended location and the reallocation of these resources *to* the attended location (Bahcall & Kowler, 1999; Mounts, 2000a; Müller et al., 2005). This view emphasizes the idea that attentional selection consists in enhancing perceptual processing at the attended location by allocating more resources to this location (Carrasco et al., 2000; Pestilli & Carrasco, 2005; Talgar et al., 2001; Henderson & Macquistan, 1993; Lavie, 1995). Note that this view also implies an exclusion of the information in the immediate surroundings of the attended location (as emphasized in the first view; see above).

While the first of these two views is at the centre of two influential models (one computational and one neurophysiological) that have been put forward to account for the Mexican-hat profile of perceptual resources, the second view is less often mentioned in the literature but is consistent with a new neurophysiological model of the Mexican-hat profile of perceptual resources. These models are discussed below.

Cutzu and Tsotsos' (2003) computational *selective tuning* model has been widely cited in order to account for findings of a Mexican-hat profile of perceptual resources. This model is inspired from the architecture of the visual cortex. It proposes that the perceptual processing of visual information involves three main stages. First, the visual information from different stimuli propagates in parallel from *input* to *output* layers in the visual cortex (via feedforward connections). Second, the visual stimulus that received the *largest* response in the output layer (e.g., the stimulus that occurred at the attended location and/or that matched the target templates), also called the 'winner' stimulus, generates a *top-down* signal. This signal propagates backwards towards the input layer and inhibits the connections which do *not* code for the winner stimulus. This

produces an *inhibition* zone around the winner-stimulus location, namely, the bottom of the Mexican hat. In a third stage, the visual information from the winner stimulus re-propagates from *input* to *output* layers but this time *not accompanied* by the information from surrounding stimuli; the latter are inhibited.

Another model is widely referred to when trying to account for Mexican-hat findings. This model suggests that attention causes neuronal receptive fields to *shrink* onto the attended location and this generates a Mexican-hat profile of perceptual resources (e.g., Compte & Wang, 2006; Moran & Desimone, 1985; Pinsk & Kastner, 2004; Womelsdorf, Anton-Erxleben, & Treue, 2008). This idea originated in findings of studies that have used single-cell recordings in monkeys such as the study of Luck et al. (1997). In the latter study, two stimuli were presented simultaneously to the *same* receptive field of a monkey's V4 neuron but only one of them appeared at the attended location. The response of the neuron to these two stimuli was measured. It was shown that the response was biased in favour of the stimulus occurring at the attended location. The other stimulus, which occurred in the same receptive field but *outside* the attended location, was not responded to, as if it had not occurred at all. This finding is compatible with the idea that the receptive field shrank onto the attended locations, away from the other locations covered by the field. This process might generate an ignored area around the attended location, namely, the ignored area, or bottom, of the Mexican hat.

None of the above two models make the prediction that the perceptual processing at the attended location is enhanced. As a result, they are arguably not compatible with the view that the Mexican-hat profile of perceptual resources is caused by the borrowing of

resources from *around* the attended location and the reallocation of these resources *to* the attended location (Bahcall & Kowler, 1999; Mounts, 2000a; Müller et al., 2005). On the other hand, there is a new neurophysiological model that *is* compatible with this view. The model in question suggests that the Mexican hat is the result not only of a shrinkage of receptive fields but also of a *shift* of receptive fields towards the attended location (Connor, Preddie, Gallan, & Essen, 1997; Womelsdorf, 2004; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006; Womelsdorf et al., 2008). This shift of receptive fields would cause both an increase in the amount of receptive fields coding for the attended location and a deficit of receptive fields in areas surrounding the attended location (Womelsdorf et al., 2008).

In any case, it is important to note that any attempt to explain the Mexican-hat profile of perceptual resources (as derived with behavioural measures) using neurophysiological findings must be made with caution. While these attempts are useful because they seek to establish coherent schemas between neurophysiological and psychophysical findings, to our knowledge, no *direct* link has yet been established between neurophysiological findings, on the one hand, and psychophysical findings of a Mexican-hat pattern of perceptual resources, on the other hand.

### **6.1.3 Effects of different factors on the focus of perceptual resources**

In order to explain why many flanker studies and some cue/probe studies that have measured the profile of perceptual resources have revealed *gradient* rather than Mexican-hat functions of separations (e.g., Eriksen & St. James, 1986; Handy et al., 1996; Henderson, 1991; Henderson & Macquistan, 1993; McCarley & Mounts, 2008;

Murphy & Eriksen, 1987; Pan & Eriksen, 1993; Yantis & Johnston, 1990), and why many cue/probe studies have revealed only *inverted-gradient* rather than full Mexican-hat functions of separation (e.g., Bahcall & Kowler, 1999; Caputo & Guerra, 1998; Cave & Zimmerman, 1997; Cutzu & Tsotsos, 2003; Handy et al., 1996; Henderson, 1991; Henderson & Macquistan, 1993; Hodgson et al., 1999; Hopf et al., 2006; Kim & Cave, 1999; Kristjansson & Nakayama, 2002; Mounts 2000b), we suggest that these studies have *missed* part of the Mexican-hat function. Namely, these studies have missed either the initial decreasing arm of the Mexican hat and have therefore reported *inverted-gradient* patterns, or they have missed the subsequent increasing arm of the Mexican hat and have therefore reported *gradient* patterns.

One possible reason why these studies could have missed part of the Mexican-hat function may be that the function was *too focused* or *too defocused* to be fully sampled. In this thesis, we found that three factors (i.e., perceptual load, availability of cognitive resources and trait anxiety) indeed cause a focusing or a defocusing of the profile of perceptual resources and may therefore explain why some studies have revealed a gradient rather than a Mexican hat pattern in the past. We summarize these findings below.

#### **6.1.3.1 Perceptual load**

Increasing perceptual load (i.e., increasing the difficulty of a perceptual task) has been shown to focus perceptual resources (Downing, 1988) using the cue/probe task. Flanker studies, on the other hand, had never directly shown the effect of perceptual load on the profile of perceptual resources. Experiments 8 and 11 (see Chapter 4) tested whether the findings obtained with the cue/probe task can be replicated with the flanker task. This

was found to be the case: the Mexican-hat profile of perceptual resources became more focused under high perceptual load.

One consequence of this finding is that perceptual-load studies need to examine effects of load at *different separations* from across the profile of perceptual resources. Indeed, in both Experiments 8 and 11 (see Chapter 4), an increase in perceptual load caused no main effect across separation; the effect of load reversed between near and far separations (see Figures 26 and 34). This finding is not predicted by the current view of the effect of perceptual load (e.g., LaBerge et al., 1991; Kahneman & Chajczyk, 1983; Lavie, 1995), according to which increases in perceptual load always cause a decrease in distractor interference. If separation is not considered in load studies, between-study comparisons and generalisations may be compromised, since the effect of perceptual load *depends* on separation.

### **6.1.3.2 Availability of cognitive resources**

It has been suggested that cognitive mechanisms are involved in rejecting perceptually-processed distractors at a post-perceptual level but not involved in the control of the spatial focusing of perceptual resources (de Fockert et al., 2001 ; Lavie et al., 2004 ; Lavie & de Fockert, 2005 ; 2006 ; MacDonald & Lavie, 2008 ; Yi et al., 2004). According to this hypothesis, decreasing the availability of cognitive resources should not affect the extent of focus of perceptual resources. This was tested in Experiments 8 to 11 (see Chapter 4). In Experiment 8, while a decrease in working-memory span (in the availability of cognitive resources; Engle et al., 1992; Engle, 2002; Kane & Engle, 2002 ; Lépine et al., 2005) affected the amplitude of distractor interference across separation, it did *not* affect the focus of perceptual resources. This null effect was

consistent with the hypothesis that cognitive-control mechanisms are not involved in the focusing of perceptual resources. Nevertheless, it might have stemmed from a lack of power of the cognitive manipulation. Consequently, Experiments 9 to 11 were designed to put cognitive-control mechanisms under more stress, by increasing *cognitive load*. This was achieved by adding a secondary memory task (in Experiments 9 and 11) or calculation task (in Experiment 10) to the selective-attention task. This cognitive-load manipulation caused the profile of perceptual resources to *defocus*, thus providing evidence that cognitive-control mechanisms are after all involved in the focusing of perceptual resources. This finding is consistent with suggestions in the literature that the focusing of perceptual resources on a given spatial location is internally controlled (Sheperd & Müller, 1989) and modulated by cognitive strategies (see the zoom-lens model; Eriksen & Yeh, 1985; Murphy & Eriksen, 1987). The effect of cognitive load on the focus of perceptual resources (obtained in Experiments 8 to 11) suggests that cognitive load may affect *what we see* (see Section 6.2.3 below).

### **6.1.3.3 Trait anxiety**

Trait anxiety is a lasting personality trait. An individual's level of trait anxiety predicts how likely it is for this individual to experience state anxiety in a stressful condition (Eysenck, 1992; Eysenck et al., 2007). Trait anxiety has been suggested to change the extent of focus of perceptual resources (e.g., Derryberry & Reed, 1998; Calvo & Eysenck, 1996; Eysenck & Calvo, 1992; Eysenck & Graydon, 1989; Markowitz, 1969; Murray & Janelle, 2003). However, there exists a controversy with regard to the *direction* of this effect. Some authors have suggested that increased trait anxiety *focuses* perceptual resources (Derryberry & Reed, 1998; Murray & Janelle, 2003) whereas

others have suggested that it *defocuses* perceptual resources (Markowitz, 1969; Eysenck & Graydon, 1989).

The results of Experiment 12 (see Chapter 5) were consistent with the first hypothesis, namely, the profile of perceptual resources was more focused in participants with high trait anxiety than in participants with low trait anxiety (see Figure 38). There are two non-exclusive ways of accounting for this finding: (1) high-trait-anxiety individuals may have a smaller pool of perceptual resources at their disposal or (2) they may spend more cognitive resources (i.e., more cognitive effort) on focusing their perceptual resources and performing the task.

#### **6.1.4 The dual-control model of selective attention**

The effects of perceptual load, cognitive load and working-memory span on the profile of perceptual resources (see above), as measured using salience-related and/or response-related interference as a function of separation, are consistent with a dual-control model of selective attention (see Figure 42). In line with current thinking, selective attention in this model is a two-level process involving two independent mechanisms. Selective attention to a target location first involves a *perceptual* level of selection that blocks irrelevant stimuli from perceptual processing. This level of selection is inherently spatial in nature; it is thought to involve a pool of perceptual resources that can be allocated to a target location and removed from neighbouring distractor locations (e.g., Boudreau, Williford, & Maunsell, 2006; Eriksen & St James, 1986; LaBerge, 1983; Yantis & Johnston, 1990). The second level of selection occurs at a *post-perceptual*

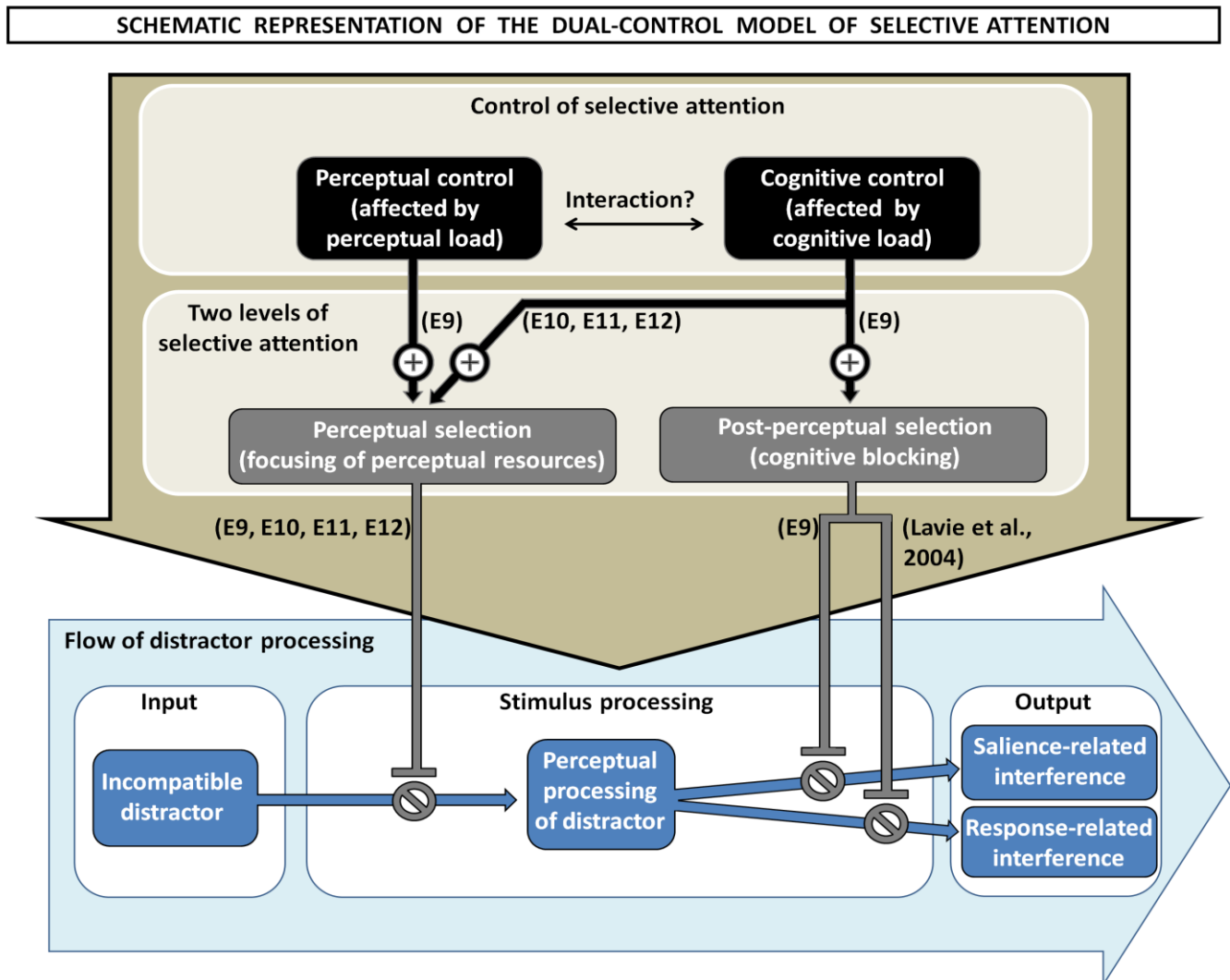


level. It allows distractor stimuli that have been perceptually processed (because they have not been efficiently blocked at the perceptual level) to be blocked from the higher levels of processing that support awareness and response selection (e.g., de Fockert et al., 2001; Lavie et al., 2004; Lavie & de Fockert, 2005; 2006; Pashler, 1999).

The dual-control model of selective attention suggests that these two levels of selective attention are controlled by one or both of two types of mechanisms (see Figure 42). First, and most significantly in this thesis, the perceptual level of selective attention (i.e., the focusing of perceptual resources) is controlled by *both* perceptual mechanisms (affected by perceptual load; see Experiments 8 and 11 in Chapter 4 and see Figure 42) and cognitive mechanisms (affected by cognitive load; see Experiments 9 to 11 in Chapter 4 and see Figure 42). Second, the post-perceptual level of selective attention (i.e., the post-perceptual blocking of perceptually-processed stimuli) is controlled (at least) by cognitive mechanisms (see Experiment 8 in Chapter 4 and see Figure 42; the possibility that perceptual mechanisms can affect the post-perceptual level of selective attention was not tested in the present thesis).

In conclusion, the dual-control model of selective attention can be summarized as follows. The perceptual processing of a distractor is modulated by a first perceptual level of selection (i.e., the relative focus of perceptual resources), itself regulated by *both* perceptual and cognitive-control mechanisms (the possibility that these perceptual and cognitive-control mechanisms exert interacting effects is conceivable but was not tested in this thesis; see Section 6.2.2 below). If the distractor is not efficiently excluded at this first perceptual level of selection, it will be perceptually processed and have a potential for exerting both salience-related and response-related interference. A second

post-perceptual level of selection (i.e., the cognitive blocking of perceptually processed distractors) can intervene to decrease the potential of interference of the distractor. This post-perceptual level of selection is regulated by (at least) cognitive-control mechanisms.



**Figure 42**

*A schematic representation of the dual-control model of selective attention.*

## **6.2 Future studies**

The findings of this thesis will affect several areas of research in psychology. We describe below some of the areas in question.

### **6.2.1 Impact of the findings of this thesis**

The findings of this thesis are directly relevant to researchers interested in selective attention. Indeed, our findings make links between different models of selective attention that have stayed remarkably isolated from each other, namely, studies on the shape of the profile of perceptual resources (e.g., Cutzu & Tsotsos, 2003; Eriksen & StJames, 1986; Henderson & Macquistan, 1993; Mounts, 2000b; Müller et al., 2005; Yantis & Johnston, 1990), studies on the zoom-lens model (e.g., Benso et al., 1998 ; Turatto et al., 2000; Chen, 2003; Castiello & Umilta, 1990; Henderson, 1991 LaBerge, 1983), and studies on the effects of perceptual and cognitive load (e.g., Lavie, 1995; Lavie et al., 2004; MacDonald & Lavie, 2008). The research presented in this thesis should be relevant to researchers interested in any of these topics (e.g., see Section 6.2.2 below). It is also relevant to researchers interested in fundamental processes of selective attention and visual perception (e.g., see Section 6.2.3 below), or in the *differences* in selective attention and perception that have been observed between certain populations but are still not fully understood (e.g., differences in attention observed between control populations and populations with anxiety, schizophrenia, or of cultures other than the Western culture such as the Himba; see Section 6.2.4 below).

### 6.2.2 Do the effects of perceptual and cognitive load interact?

The current view on the effect of perceptual load on the perceptual level of selection (i.e., on the spatial focusing of perceptual resources) is that this effect is completely automatic (Lavie, 2000, 2005; Lavie et al., 2004; MacDonald & Lavie, 2008) with resources being focused independently of any top-down regulation.

Yet, Experiments 9, 10 and 11 questioned this view: they showed that the focusing of perceptual resources is modulated by cognitive-control mechanisms (as indexed by the effect of cognitive load; see the top panel of Figure 42). This finding opens the possibility that perceptual and cognitive-control mechanisms exert interacting effects on the focusing of perceptual resources. Specifically, cognitive control may modulate the responsivity of the spatial focus of perceptual resources to manipulations of perceptual load. The effect of perceptual load would therefore *not* be completely automatic; instead, it would be *gated* by cognitive-control mechanisms.

On the other hand, it is perfectly conceivable that the effects of perceptual load and of cognitive control on the focus of perceptual resources are completely independent of each other so that the extent to which they focus perceptual resources simply *summates*. If this was true, it would suggest that there exists a cognitive mechanism that focuses perceptual resources completely independently of the perceptual mechanisms revealed by the effect of perceptual load. The function of such cognitive mechanism may be to allow one to exclude irrelevant distractors even when perceptual load is *low*.

The possibility that perceptual and cognitive-control mechanisms interact is currently being investigated in the lab. This will lead to a better understanding of the dual-control model of selective attention.

### **6.2.3 Does the extent of focus of perceptual resources affect what we see?**

The effect of cognitive load on the focus of perceptual resources suggests that cognitive load may affect what we see. For instance, it has been proposed that defocusing perceptual resources causes a dilution of resources, causing a decrease in perceptual sensitivity (e.g., Benso et al., 1998; Castiello & Umiltà, 1990; Müller, Bartelt, Donner, Villringer, & Brandt, 2003; Turatto, Benso, Facoetti, Galfano, Mascetti & Umiltà, 2000). Moreover, it has been proposed that when perceptual resources are spatially focused, individuated objects are likely to be perceived, whereas when they are spread, the global properties of the scene will be more readily seen (Chong & Treisman, 2003; Treisman, 2006). Finally, in conditions of spread perceptual resources, objects are less likely to be individuated and accurately perceived, creating ‘illusory conjunctions’ with their neighbours (Treisman & Schmidt, 1982).

What our finding suggests is that variations in cognitive load may influence the extent to which local or global levels of stimulus structure are phenomenologically apprehended. We are currently investigating whether increasing cognitive load increases illusory effects in illusions like the Muller-Lyer that we have evidence depend on global processing but decreases illusory effects in illusions like the Horizontal-vertical that we have evidence depend on local processing (Linnell, Fonteneau, Wakui,

& Davidoff, submitted). We are also investigating whether cognitive load affects attentional resolution using a paradigm adapted from Yeshurun and Carrasco (1998).

#### **6.2.4 The focus of perceptual resources in different populations**

The paradigm introduced in this thesis can be used to understand better the nature of differences in selective attention existing between specific populations and the western student population examined in this thesis (see Chapter 5). This is because the paradigm in question discriminates between differences originating at perceptual levels of selection (in the focus of perceptual resources) and at post-perceptual levels of selection (in the blocking of perceptually processed distractors). Moreover, if a difference occurs at the perceptual level, the paradigm in question isolates the direction of this difference (i.e., whether it consists in a focusing or a defocusing of perceptual resources). We discuss below why it would be interesting to apply this paradigm to understand attentional differences that have been suggested to exist between westerners and a remote population, namely, the Himba population.

The Himba are a semi-nomadic population of animal herders estimated from 20,000 to 50,000 (Namibian Government statistics, 2004) whose territory is spread over some 25,000 square miles in northern Namibia and southern Angola in a region described as the last wilderness in southern Africa. The Himba have been assessed (de Fockert, Davidoff, Fagot, Parron, & Goldstein, 2007) on a size-judgement task where size of a central shape is distorted by a surround of larger or smaller shapes (Ebbinghaus illusion). They did see the illusion but less than other groups (e.g., autistic children) who have been previously recorded as being different to the norm, suggesting that they

experience a strong local bias. The Himba are clearly remarkable in the extent to which they can isolate local parts of figures and therefore be exact in their size judgements. Their local bias was noted in earlier research where they were very attentive to small differences in shape when asked to group geometric figures (Davidoff, Fonteneau, & Fagot, 2008).

It is possible that the local bias observed in the Himba results from an overall more *focused* profile of perceptual resources. If this is the case in the Himba, it could arise from a number of factors: (1) the Himba having *reduced perceptual resources* (see Chapter 5); (2) the Himba having *increased cognitive resources* (see Chapter 4); (3) the Himba deploying their cognitive resources better (a possibility if they are more single-minded and spend fewer cognitive resources in general mental business/multi-tasking; Linnell, Davidoff & Caparos, *in prep*); (4) the Himba having a greater tendency to prepare action plans, even implicitly (recent work has shown that preparation for action focuses perceptual resources on parts of objects rather than whole objects; Linnell, Humphreys, McIntyre, Laitinen & Wing, 2005).<sup>25</sup>

### **6.3 Conclusions**

The experiments presented in this thesis addressed several questions that remained unresolved in the literature to date. These questions were about: (1) the shape of the *profile* of perceptual resources around the attended location, (2) the *indices* that are best

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<sup>25</sup> These four possibilities will be tested on the Himba population in Namibia by the author, under the supervision of J. Davidoff and K. Linnell, in the course of an ESRC-funded project starting in September 2009, using a methodology in part developed from the experiments presented in this thesis.

suiting to studying the shape of this profile, and (3) the effect of perceptual load, cognitive load, cognitive failure and trait anxiety on the extent of *focus* of the profile.

It was found that the profile of perceptual resources describes a Mexican-hat pattern (Müller et al., 2005). This Mexican-hat pattern was obtained whether the profile was indexed using *combined response-related interference* (e.g., Murphy & Eriksen, 1987), *incompatible-distractor response-related interference* (e.g., Eriksen & St. James, 1986), *salience-related interference* (e.g., McCarley & Mounts, 2008), or *probe-detection performance* (e.g., Handy et al., 1996). Finally, while cognitive failure did not affect the extent of focus of the profile of perceptual resources, perceptual load and trait anxiety caused the profile to *focus* and cognitive load caused it to *defocus*.

The present findings have two important implications. First, variations in stimulus and task properties (e.g., load) or in individual characteristics (e.g., anxiety) across studies may explain why some studies have reported gradient rather than Mexican-hat patterns; in some studies, perceptual resources may have been defocused, causing the Mexican-hat profile to be mistaken for a gradient one. Second, contrary to the load theory (Lavie et al., 2004), the focus of perceptual resources is controlled not only at perceptual but also at cognitive levels. Cognitive load may therefore change what we *see*, whether it be an individuated object or the global properties of a scene.



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# **APPENDICES**

## INFORMATION SHEET

Please read the following carefully.

This project contributes to Serge Caparos' (the principal researcher) postgraduate programme of studies at Goldsmiths College. The objective of the research is to investigate the distribution of visual attention in space. Participation will involve completing a computer task that requires keeping concentrated and focused. In total, the experiment will last approximately **[XX minutes]**. If you wish to take a short break, you can do so during any of the many break periods provided within the test. You will receive **[XX pounds or credits]** for your time.

Participation is voluntary and you may withdraw from the study at any time and for any reason without needing to provide an explanation. Data will be held in the strictest of confidence. In the final report the results will be presented in such a way that the individual identity of all participants will remain strictly anonymous. You will receive a written debriefing at the end of the experiment.

If you have any questions, please ask the project researcher, Serge Caparos.

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### **DECLARATION OF CONSENT**

I have read the above information and I understand the procedures involved in this research project. I am willing to take part in the experiment.

NAME (Please print).....

SIGNATURE.....

DATE.....

### **Appendix 1**

*Model for the consent form used in Experiments 1 to 12.*

PARTICIPATN NUMBER	AGE	GENDER	VISION	HANDEDNESS	HAND USED TO ANSWER 'E'
1	19	Female	Normal	Right	Right
2	30	Female	Corrected	Right	Right
3	22	Female	Normal	Right	Right
4	24	Female	Corrected	Right	Left
5	19	Male	Normal	Right	Right
6	18	Female	Normal	Right	Left
7	20	Male	Normal	Right	Left
8	53	Female	Corrected	Right	Left
9	26	Male	Normal	Right	Left
10	55	Female	Normal	Right	Right

## **Appendix 2**

*Participants' information in Experiment 1.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS	HAND USED TO ANSWER 'E'	ORDER
1	18	Female	Corrected	Right	Left	North North South South
2	19	Female	Normal	Right	Right	North North South South
3	36	Female	Normal	Right	Left	South South North North
4	28	Female	Normal	Right	Right	South South North North
5	21	Female	Normal	Right	Right	North North South South
6	20	Female	Normal	Right	Left	North North South South
7	18	Female	Normal	Right	Right	North North South South
8	18	Female	Corrected	Right	Left	South South North North
9	18	Female	Normal	Right	Right	South South North North
10	18	Female	Normal	Left	Left	North North South South
11	18	Female	Normal	Left	Right	North North South South
12	19	Female	Corrected	Right	Left	South South North North
13	17	Female	Corrected	Left	Right	South South North North
14	20	Male	Normal	Right	Left	North North South South

15	19	Female	Normal	Right	Left	South North	South North
16	18	Female	Normal	Right	Left	South North	South North
17	19	Female	Normal	Right	Right	South North	South North
18	26	Male	Normal	Right	Right	North South	North South

### **Appendix 3**

*Participants' information in Experiment 2.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS	HAND USED TO ANSWER 'E'
1	17	Female	Normal	Right	Right
2	20	Male	Normal	Left	Left
3	20	Female	Normal	Right	Left
4	26	Male	Normal	Right	Left
5	28	Male	Corrected	Right	Right
6	16	Male	Normal	Right	Left
7	27	Male	Corrected	Right	Right
8	23	Female	Corrected	Right	Right
9	22	Female	Normal	Right	Right
10	26	Female	Normal	Right	Left
11	26	Female	Corrected	Right	Right
12	28	Female	Normal	Right	Left
13	22	Female	Normal	Right	Left
14	19	Female	Normal	Right	Left
15	18	Female	Corrected	Right	Left
16	39	Female	Normal	Right	Right

### **Appendix 4**

*Participants' information in Experiment 3.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS
1	20	Female	Normal	Right
2	18	Male	Corrected	Right

3	18	Male	Normal	Right
4	20	Male	Normal	Left
5	19	Female	Normal	Right
6	21	Female	Corrected	Right
7	26	Male	Normal	Right
8	23	Male	Normal	Right
9	20	Male	Normal	Right
10	22	Female	Corrected	Left
11	26	Male	Normal	Right
12	21	Male	Normal	Right
13	19	Male	Normal	Right
14	39	Female	Normal	Right

### **Appendix 5**

*Participants' information in Experiment 4.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS
1	24	Female	Normal	Right
2	22	Female	Normal	Right
3	19	Female	Corrected	Right
4	20	Female	Corrected	Right
5	19	Male	Normal	Right
6	21	Female	Normal	Right
7	25	Male	Normal	Right
8	24	Male	Corrected	Right
9	20	Female	Normal	Right
10	19	Female	Normal	Right
11	29	Female	Normal	Right
12	21	Male	Normal	Right
13	30	Female	Normal	Right
14	24	Female	Corrected	Right
15	21	Female	Normal	Left

### **Appendix 6**

*Participants' information in Experiment 5.*



PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS	ORDER
1	19	Female	Normal	Left	Flanker Task Cue/Probe Task
2	24	Female	Normal	Right	Flanker Task Cue/Probe Task
3	18	Female	Normal	Right	Flanker Task Cue/Probe Task
4	18	Female	Corrected	Right	Cue/Probe Task Flanker Task
5	18	Female	Normal	Right	Cue/Probe Task Flanker Task
6	25	Male	Normal	Right	Flanker Task Cue/Probe Task
7	19	Female	Normal	Right	Cue/Probe Task Flanker Task
8	26	Male	Corrected	Right	Flanker Task Cue/Probe Task
9	19	Male	Normal	Right	Flanker Task Cue/Probe Task
10	18	Female	Corrected	Right	Cue/Probe Task Flanker Task
11	23	Male	Normal	Right	Flanker Task Cue/Probe Task
12	20	Female	Normal	Right	Flanker Task Cue/Probe Task
13	18	Female	Normal	Right	Cue/Probe Task Flanker Task
14	20	Female	Corrected	Right	Cue/Probe Task Flanker Task
15	19	Female	Normal	Right	Cue/Probe Task Flanker Task
16	21	Female	Corrected	Right	Cue/Probe Task Flanker Task

### **Appendix 7**

*Participants' information in Experiment 6.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS
1	18	Female	Normal	Right
2	23	Male	Corrected	Right
3	25	Male	Corrected	Right

4	18	Female	Normal	Right
5	18	Female	Normal	Right
6	19	Female	Normal	Left
7	20	Female	Corrected	Right
8	18	Female	Normal	Right
9	20	Female	Corrected	Left
10	19	Male	Normal	Right
11	20	Female	Normal	Right
12	21	Female	Corrected	Right
13	19	Female	Normal	Right
14	26	Male	Normal	Right
15	18	Male	Corrected	Right
16	27	Female	Corrected	Right

### **Appendix 8**

*Participants' information in Experiment 7.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS	ORDER OF PERCEPTUAL-LOAD CONDITIONS	OSPAN SCORE	TRAIT-ANXIETY SCORE	COGNITIVE-FAILURE SCORE
1	18	Female	Corrected	Right	Low High	30	46	42
2	20	Male	Corrected	Left	High Low	58	26	43
3	19	Female	Normal	Right	Low High	39	34	20
4	19	Female	Normal	Right	High Low	48	39	32
5	18	Female	Corrected	Right	Low High	8	30	47
6	18	Female	Normal	Right	Low High	14	37	30
7	29	Female	Normal	Right	High Low	36	46	58
8	19	Male	Normal	Right	Low High	11	44	51
9	18	Female	Normal	Right	High Low	25	32	37
10	19	Female	Normal	Right	Low High	44	34	51
11	18	Female	Normal	Right	High Low	18	50	68
12	19	Female	Corrected	Right	High Low	29	54	58
13	28	Female	Normal	Right	High Low	29	29	27
14	18	Female	Corrected	Right	High Low	28	51	68
15	19	Female	Normal	Right	Low High	43	46	29
16	28	Female	Corrected	Right	High Low	24	40	34
17	23	Female	Normal	Right	High Low	34	35	38
18	18	Female	Normal	Right	Low High	36	49	91
19	18	Female	Normal	Right	High Low	68	35	42
20	22	Female	Corrected	Right	High Low	23	49	50

21	18	Female	Corrected	Left	Low High	45	38	46
22	19	Female	Normal	Right	Low High	14	43	26
23	20	Female	Normal	Right	High Low	28	43	45
24	19	Female	Normal	Right	Low High	37	43	29
25	19	Male	Normal	Left	High Low	57	56	55
26	18	Female	Normal	Right	Low High	32	30	62
27	18	Female	Normal	Right	Low High	7	40	42
28	19	Female	Normal	Right	High Low	7	35	37
29	19	Male	Corrected	Right	High Low	31	54	66
30	18	Female	Normal	Left	Low High	6	30	68
31	24	Female	Normal	Right	High Low	32	34	52
32	18	Female	Normal	Right	High Low	52	46	31
33	18	Female	Normal	Right	High Low	39	27	32
34	18	Female	Normal	Right	Low High	31	69	55
35	19	Female	Normal	Right	High Low	25	38	59
36	21	Female	Normal	Right	High Low	31	39	55
37	18	Female	Normal	Right	High Low	33	49	72
38	25	Female	Normal	Right	Low High	43	38	42
39	18	Female	Normal	Right	Low High	46	44	84
40	20	Male	Normal	Right	High Low	50	28	28
41	20	Female	Normal	Right	Low High	62	41	18
42	29	Female	Normal	Right	Low High	53	39	9
43	21	Female	Corrected	Right	Low High	52	31	58
44	23	Female	Normal	Right	Low High	33	60	47
45	21	Female	Corrected	Right	High Low	27	37	83
46	18	Female	Normal	Right	High Low	36	29	40
47	19	Female	Normal	Left	High Low	10	35	77
48	19	Female	Normal	Right	Low High	24	56	44
49	22	Female	Corrected	Right	Low High	42	36	40
50	25	Female	Corrected	Right	Low High	30	31	54
51	18	Female	Normal	Right	High Low	41	48	52
52	24	Male	Normal	Right	Low High	43	66	74
53	18	Female	Normal	Left	Low High	6	63	47
54	18	Male	Corrected	Right	Low High	61	42	39

## **Appendix 9**

*Participants' information in Experiments 8 and 12.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS	ORDER OF COGNITIVE-LOAD CONDITION
1	21	Female	Normal	Right	High Low
2	18	Female	Corrected	Right	High Low
3	21	Female	Corrected	Left	High Low
4	23	Male	Normal	Right	Low High
5	27	Female	Corrected	Right	Low High
6	21	Female	Normal	Right	Low High
7	19	Female	Corrected	Right	High Low
8	18	Female	Normal	Right	Low High
9	25	Male	Corrected	Right	Low High
10	19	Female	Corrected	Right	Low High
11	18	Female	Normal	Right	High Low
12	19	Female	Normal	Left	Low High
13	18	Female	Corrected	Right	High Low
14	26	Female	Normal	Right	Low High
15	25	Female	Normal	Right	Low High
16	18	Female	Normal	Right	Low High
17	20	Male	Normal	Right	Low High
18	25	Male	Normal	Right	Low High
19	18	Male	Normal	Right	Low High
20	24	Female	Normal	Right	Low High
21	19	Male	Corrected	Right	High Low
22	22	Female	Normal	Right	Low High
23	18	Female	Corrected	Right	High Low
24	21	Female	Normal	Right	High Low
25	21	Male	Normal	Left	High Low
26	18	Female	Corrected	Right	High Low
27	18	Male	Normal	Left	High Low
28	21	Female	Normal	Right	Low High
29	20	Female	Corrected	Right	High Low
30	18	Female	Normal	Right	High Low
31	21	Male	Corrected	Right	High Low

**Appendix 10**

*Participants' information in Experiment 9.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS	COGNITIVE-LOAD CONDITION
1	35	Female	Corrected	Right	High
2	24	Female	Corrected	Right	High
3	20	Female	Corrected	Right	High
4	19	Female	Corrected	Right	High
5	26	Female	Corrected	Right	High
6	21	Female	Normal	Right	High
7	20	Female	Corrected	Right	Low
8	25	Female	Normal	Right	High
9	25	Female	Normal	Left	Low
10	29	Male	Normal	Right	Low
11	48	Male	Corrected	Right	Low
12	20	Female	Normal	Right	High
13	30	Male	Normal	Right	High
14	21	Female	Corrected	Right	High
15	19	Female	Normal	Right	High
16	21	Male	Normal	Right	High
17	33	Male	Normal	Right	High
18	25	Female	Normal	Right	High
19	50	Male	Corrected	Right	High
20	26	Male	Normal	Left	High
21	21	Female	Corrected	Right	High
22	27	Male	Corrected	Right	Low
23	35	Female	Corrected	Right	Low
24	22	Male	Normal	Right	Low
25	22	Female	Corrected	Left	Low
26	28	Female	Normal	Right	Low
27	34	Male	Normal	Right	Low
28	20	Male	Normal	Right	Low
29	22	Female	Normal	Right	Low
30	20	Female	Normal	Right	Low
31	21	Female	Corrected	Right	Low
32	21	Female	Corrected	Right	Low
33	20	Female	Normal	Right	Low
34	23	Female	Normal	Right	Low
35	32	Female	Normal	Right	Low
36	22	Male	Normal	Right	Low
37	25	Male	Normal	Right	Low
38	23	Male	Normal	Right	High
39	26	Male	Normal	Right	High
40	22	Female	Corrected	Right	High

**Appendix 11**

*Participants' information in Experiment 10.*

PARTICIPANT NUMBER	AGE	GENDER	VISION	HANDEDNESS	CONDITION
1	25	Female	Normal	Right	Low PL & Low CL
2	21	Male	Normal	Right	Low PL & Low CL
3	18	Female	Normal	Right	Low PL & Low CL
4	19	Female	Corrected	Right	Low PL & Low CL
5	19	Female	Normal	Right	Low PL & Low CL
6	21	Female	Normal	Right	Low PL & Low CL
7	22	Female	Normal	Right	Low PL & Low CL
8	18	Female	Normal	Left	Low PL & Low CL
9	18	Male	Normal	Right	Low PL & Low CL
10	19	Female	Corrected	Right	Low PL & Low CL
11	20	Female	Corrected	Right	Low PL & Low CL
12	19	Female	Normal	Left	Low PL & Low CL
13	18	Female	Normal	Right	Low PL & Low CL
14	21	Female	Normal	Right	Low PL & Low CL
15	21	Female	Corrected	Right	Low PL & Low CL
16	22	Female	Normal	Right	Low PL & Low CL
17	18	Female	Normal	Right	Low PL & Low CL
18	18	Female	Normal	Left	Low PL & Low CL
19	18	Female	Normal	Right	Low PL & Low CL
20	20	Male	Corrected	Right	Low PL & Low CL
21	19	Female	Normal	Right	Low PL & Low CL
22	21	Female	Normal	Right	Low PL & Low CL
23	18	Female	Corrected	Right	Low PL & Low CL
24	21	Male	Normal	Right	Low PL & Low CL
25	18	Female	Normal	Right	Low PL & Low CL
26	18	Female	Corrected	Right	Low PL & Low CL
27	18	Female	Normal	Right	Low PL & Low CL
28	26	Female	Normal	Right	Low PL & Low CL
29	25	Female	Normal	Right	Low PL & Low CL
30	18	Female	Normal	Right	Low PL & Low CL
31	21	Female	Normal	Right	Low PL & Low CL
32	26	Female	Corrected	Right	Low PL & Low CL
33	18	Female	Normal	Right	Low PL & Low CL
34	18	Male	Normal	Right	Low PL & Low CL
35	18	Female	Normal	Right	Low PL & Low CL
36	18	Male	Corrected	Right	Low PL & Low CL
37	21	Male	Normal	Right	High PL & Low CL

38	21	Female	Normal	Left	High PL & Low CL
39	18	Female	Normal	Right	High PL & Low CL
40	21	Male	Normal	Right	High PL & Low CL
41	19	Female	Corrected	Right	High PL & Low CL
42	20	Female	Normal	Right	High PL & Low CL
43	20	Female	Normal	Right	High PL & Low CL
44	18	Female	Corrected	Right	High PL & Low CL
45	19	Female	Corrected	Right	High PL & Low CL
46	18	Female	Normal	Right	High PL & Low CL
47	18	Female	Corrected	Left	High PL & Low CL
48	20	Female	Corrected	Right	High PL & Low CL
49	18	Female	Corrected	Right	High PL & Low CL
50	18	Male	Corrected	Right	High PL & Low CL
51	18	Female	Normal	Right	High PL & Low CL
52	19	Female	Normal	Right	High PL & Low CL
53	28	Male	Normal	Right	High PL & Low CL
54	22	Female	Corrected	Right	High PL & Low CL
55	21	Female	Normal	Right	High PL & Low CL
56	18	Female	Normal	Right	High PL & Low CL
57	19	Male	Normal	Right	High PL & Low CL
58	18	Female	Normal	Left	High PL & Low CL
59	19	Male	Corrected	Right	High PL & Low CL
60	19	Male	Normal	Right	High PL & Low CL
61	18	Female	Normal	Right	High PL & Low CL
62	18	Female	Corrected	Right	High PL & Low CL
63	31	Male	Normal	Left	High PL & Low CL
64	18	Female	Corrected	Right	High PL & Low CL
65	36	Male	Corrected	Right	High PL & Low CL
66	19	Female	Normal	Right	High PL & Low CL
67	18	Female	Normal	Right	High PL & Low CL
68	18	Female	Normal	Right	High PL & Low CL
69	21	Female	Normal	Left	High PL & Low CL
70	19	Male	Normal	Right	High PL & Low CL
71	21	Male	Corrected	Right	High PL & Low CL
72	20	Female	Normal	Right	High PL & Low CL
73	19	Female	Normal	Right	High PL & High CL
74	19	Female	Corrected	Right	High PL & High CL
75	21	Female	Normal	Right	High PL & High CL
76	20	Female	Normal	Right	High PL & High CL
77	19	Male	Normal	Right	High PL & High CL
78	19	Female	Normal	Right	High PL & High CL
79	16	Female	Corrected	Right	High PL & High CL
80	18	Female	Corrected	Right	High PL & High CL
81	18	Female	Normal	Right	High PL & High CL
82	20	Female	Normal	Left	High PL & High CL

83	18	Female	Corrected	Right	High PL & High CL
84	18	Female	Normal	Right	High PL & High CL
85	22	Female	Normal	Right	High PL & High CL
86	19	Male	Normal	Right	High PL & High CL
87	18	Female	Normal	Right	High PL & High CL
88	18	Female	Corrected	Right	High PL & High CL
89	19	Female	Normal	Right	High PL & High CL
90	18	Female	Normal	Right	High PL & High CL
91	18	Female	Normal	Right	High PL & High CL
92	19	Female	Corrected	Right	High PL & High CL
93	19	Female	Normal	Right	High PL & High CL
94	18	Female	Corrected	Right	High PL & High CL
95	19	Female	Corrected	Right	High PL & High CL
96	20	Female	Normal	Right	High PL & High CL
97	19	Female	Normal	Right	High PL & High CL
98	19	Female	Normal	Right	High PL & High CL
99	20	Female	Normal	Right	High PL & High CL
100	31	Male	Corrected	Right	High PL & High CL
101	21	Female	Normal	Left	High PL & High CL
102	20	Female	Corrected	Right	High PL & High CL
103	29	Male	Normal	Right	High PL & High CL
104	16	Male	Corrected	Right	High PL & High CL
105	18	Female	Normal	Right	High PL & High CL
106	19	Female	Corrected	Right	High PL & High CL

## **Appendix 12**

*Participants' information in Experiment 11.*



**The Cognitive Failures Questionnaire (Broadbent, Cooper, FitzGerald & Parkes, 1982)**

The following questions are about minor mistakes which everyone makes from time to time, but some of which happen more often than others. We want to know how often these things have happened to you in the past 6 months. Please circle the appropriate number.

		Very often	Quite often	Occasionally	Very rarely	Never
1.	Do you read something and find you haven't been thinking about it and must read it again?	4	3	2	1	0
2.	Do you find you forget why you went from one part of the house to the other?	4	3	2	1	0
3.	Do you fail to notice signposts on the road?	4	3	2	1	0
4.	Do you find you confuse right and left when giving directions?	4	3	2	1	0
5.	Do you bump into people?	4	3	2	1	0
6.	Do you find you forget whether you've turned off a light or a fire or locked the door?	4	3	2	1	0
7.	Do you fail to listen to people's names when you are meeting them?	4	3	2	1	0
8.	Do you say something and realize afterwards that it might be taken as insulting?	4	3	2	1	0
9.	Do you fail to hear people speaking to you when you are doing something else?	4	3	2	1	0
10.	Do you lose your temper and regret it?	4	3	2	1	0
11.	Do you leave important letters unanswered for days?	4	3	2	1	0
12.	Do you find you forget which way to turn on a road you know well but rarely use?	4	3	2	1	0
13.	Do you fail to see what you want in a supermarket (although it's there)?	4	3	2	1	0
14.	Do you find yourself suddenly wondering whether you've used a word correctly?	4	3	2	1	0

	Very often	Quite often	Occasionally	Very rarely	Never
15. Do you have trouble making up your mind?	4	3	2	1	0
16. Do you find you forget appointments?	4	3	2	1	0
17. Do you forget where you put something like a newspaper or a book?	4	3	2	1	0
18. Do you find you accidentally throw away the thing you want and keep what you meant to throw away – as in the example of throwing away the matchbox and putting the used match in your pocket?	4	3	2	1	0
19. Do you daydream when you ought to be listening to something?	4	3	2	1	0
20. Do you find you forget people's names?	4	3	2	1	0
21. Do you start doing one thing at home and get distracted into doing something else (unintentionally)?	4	3	2	1	0
22. Do you find you can't quite remember something although it's "on the tip of your tongue"?	4	3	2	1	0
23. Do you find you forget what you came to the shops to buy?	4	3	2	1	0
24. Do you drop things?	4	3	2	1	0
25. Do you find you can't think of anything to say?	4	3	2	1	0

### **Appendix 13**

*The Cognitive Failure Questionnaire. Broadbent et al. (1982).*

## SELF-EVALUATION QUESTIONNAIRE

STAI Form Y-2

Name \_\_\_\_\_ Date \_\_\_\_\_

### DIRECTIONS

A number of statements which people have used to describe themselves are given below. Read each statement and then circle the appropriate value to the right of the statement to indicate how you *generally* feel. There are no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe how you generally feel.

ALMOST NEVER  
SOMETIMES  
OFTEN  
ALMOST ALWAYS

- |   |   |   |   |   |
|---|---|---|---|---|
| 21. I feel pleasant .....   | 1 | 2 | 3 | 4 |
| 22. I feel nervous and restless .....   | 1 | 2 | 3 | 4 |
| 23. I feel satisfied with myself .....  | 1 | 2 | 3 | 4 |
| 24. I wish I could be as happy as others seem to be .....   | 1 | 2 | 3 | 4 |
| 25. I feel like a failure .....   | 1 | 2 | 3 | 4 |
| 26. I feel rested .....   | 1 | 2 | 3 | 4 |
| 27. I am "calm, cool, and collected" .....  | 1 | 2 | 3 | 4 |
| 28. I feel that difficulties are piling up so that I cannot overcome them .....                   | 1 | 2 | 3 | 4 |
| 29. I worry too much over something that really doesn't matter .....                              | 1 | 2 | 3 | 4 |
| 30. I am happy .....  | 1 | 2 | 3 | 4 |
| 31. I have disturbing thoughts .....  | 1 | 2 | 3 | 4 |
| 32. I lack self-confidence .....  | 1 | 2 | 3 | 4 |
| 33. I feel secure .....   | 1 | 2 | 3 | 4 |
| 34. I make decisions easily .....   | 1 | 2 | 3 | 4 |
| 35. I feel inadequate .....   | 1 | 2 | 3 | 4 |
| 36. I am content .....  | 1 | 2 | 3 | 4 |
| 37. Some unimportant thought runs through my mind and bothers me .....                            | 1 | 2 | 3 | 4 |
| 38. I take disappointments so keenly that I can't put them out of my mind .....                   | 1 | 2 | 3 | 4 |
| 39. I am a steady person .....  | 1 | 2 | 3 | 4 |
| 40. I get in a state of tension or turmoil as I think over my recent concerns and interests ..... | 1 | 2 | 3 | 4 |

### **Appendix 14**

*The Trait Anxiety Inventory. Spielberger et al. (1983)*