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# The spatial focus of attention is controlled at perceptual and cognitive levels

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## **ABSTRACT**

Selective attention has been hypothesised to reduce distractor interference at both perceptual and post-perceptual levels (Lavie, 2005), respectively by focusing perceptual resources on the attended location and by blocking at post-perceptual levels distractors that survive perceptual selection. This study measured the impact of load on these two levels of selection using a flanker paradigm (Eriksen & St. James, 1986) and indexing distractor interference as a function of separation. It distinguished changes in the *extent of focus* of the distractor-interference function of separation (reflecting the perceptual level of selection) from changes in the amplitude of distractor interference *not accompanied* by changes in focus (reflecting the post-perceptual level of selection). It showed that: (1) the spatial profile of perceptual resources is shaped like a ‘Mexican hat’ (Müller et al., 2005); (2) increasing perceptual load causes perceptual resources to *focus* (Caparos & Linnell, 2009); (3) increasing cognitive load causes perceptual resources to *defocus*; and (4) participants with reduced working-memory span show reduced post-perceptual blocking of distractors. While these findings are consistent with two levels of selective attention, they show that the first perceptual level is affected not only by perceptual but also by cognitive-control mechanisms.

(192 words)

Key words: Selective attention; spatial attention; perceptual load; cognitive load

## INTRODUCTION

To ensure efficient functioning, the brain must exclude irrelevant, distracting information. Distractor processing has implications in everyday-life situations (e.g. educational achievement; driving safety; advertising strategies) and disproportionate distractor processing is associated with several pathologies (e.g. AD/HD, schizophrenia). The question of how we cope with distraction is therefore central to psychological research, and much progress in understanding the mechanisms involved has been made in the field of attention research.

### Selective attention as a two-level process

Selective attention is the umbrella term given to the mechanisms thought to be involved in the exclusion of distracting information. It has been widely studied using the flanker paradigm (Eriksen & Hoffman, 1972, 1973) in which participants must selectively attend to a target spatially flanked by task-relevant distractors. Work with this paradigm has suggested that selective attention is a two-level process involving two independent mechanisms (Lavie, Hirst, de Fockert, & Viding, 2004; MacDonald & Lavie, 2008). 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., Boudreau, Williford, & Maunsell, 2006; Eriksen & St James, 1986; LaBerge, 1983; Yantis & Johnston, 1990). The second level of selection in the two-level model 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).

### Effects of load on selective attention and a common limitation of previous studies

Either of the two levels of attentional selection can reduce distractor interference and manipulations of load have been assumed to isolate which level is responsible. Thus, 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 an increase in the effectiveness of the perceptual level of selection (Kahneman & Chajczyk, 1983; Forster & Lavie, 2007; LaBerge, Brown, Carter, Bash, & Hartley, 1991; Lavie, 1995; Lavie et al., 2004; Lavie & Tsai, 1994; Madden & Langley, 2003; Maylor & Lavie, 1998). 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 effectiveness of the post-perceptual level of selection (de Fockert et al., 2001; Lavie & de Fockert, 2005, 2006; Lavie et al., 2004; MacDonald & Lavie, 2008; Maylor & Lavie, 1998). Below we summarise the results of these

perceptual- and cognitive-load studies and describe a limitation that they all suffer from and a new approach to tackling this limitation.

Studies combining the flanker paradigm with perceptual-load manipulations have typically suggested that perceptual load determines the effectiveness of perceptual selection by changing the focus of perceptual resources (LaBerge et al., 1991; Kahneman & Chajczyk, 1983; Lavie, 1995; 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 effectiveness 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).

### Aim of the current study

The aim of the current study 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). Distinguishing these levels should make it possible to test whether perceptual load does indeed determine the effectiveness of perceptual levels of selection and cognitive load just the effectiveness of post-perceptual levels of selection. The current study capitalised on the inherently spatial nature of the perceptual level of selection (i.e., of the perceptual-resource-allocation mechanisms) 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) and the other non-spatial (the amplitude of distractor interference across separations). The spatial dependent variable was obtained by mapping distractor interference as a function of distractor separation from the attended location. Since the interference generated by a distractor indexes the perceptual resources allocated to the distractor location (e.g., Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1973; Cohen & Shoup, 1997; Hazeltine, Poldrack, & Gabrieli, 2000; Miller, 1991), the *pattern of interference* generated by distractors *as a function of separation* indexes the extent of focus of the spatial profile of perceptual resources and, therefore, the effectiveness of the perceptual level of selection. The non-spatial dependent variable, namely, the *amplitude* of distractor interference across separations, was used to index the effectiveness 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 unambiguously indexed variations in the effectiveness 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 effectiveness of perceptual and/or post-perceptual selection.

Both the amplitude of distractor interference across separations and the extent of focus can be extracted by adapting previous studies to include a manipulation of distractor separation. 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>1</sup>, one 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

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<sup>1</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 *spatial cueing paradigm* (Posner, 1980). Indeed, the findings of some of these studies (e.g., 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.

load caused 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.

In this study then we mapped distractor interference as a function of separation - distinguishing changes in the extent of focus of the separation function from changes in the amplitude of distractor interference *not* accompanied by changes in focus - while manipulating perceptual and cognitive load. We tested whether (i) increasing perceptual load does indeed focus perceptual resources and (ii) increasing cognitive load, or decreasing the effectiveness of cognitive control, penetrates perceptual processing and defocuses perceptual resources rather than just affecting post-perceptual levels of selection.

#### Preview of Experiments 1 and 2: the profile of perceptual resources

Given that changes in the spatial focus of the interference function can only be properly indexed when the profile is well defined, Experiments 1 and 2 focused on resolving a controversy that exists in the literature concerning the profile or shape of the distractor-interference function of separation. Up until recently, it has been widely held that the profile describes a simple gradient, with distractor interference decreasing steadily with increasing separation (e.g., Cave & Bichot, 1999; Eimer, 1997; Kramer & Jacobson, 1991; Shepherd & Müller, 1989; Starreveld, Theeuwes, & Mortier, 2004; Yantis & Johnston, 1990). However, recent studies have suggested that the profile is more complex and best modelled by a 'Mexican-hat' function, in which distractor interference does indeed first decrease but then *increases* (before tailing off) with increasing separation (Bahcall & Kowler, 1999; Caparos & Linnell, 2009; Cave & Zimmerman, 1997; Cutzu & Tsotos, 2003; Hodgson, Müller, & O'Leary, 1999; Hopf, Boehler, Luck, Tsotsos, Heinze, & Schoenfeld, 2006; Kristjansson & Nakayama, 2002; Mounts, 2000; Müller et al., 2005; Pan & Eriksen, 1993; Schwartz, Vuilleumier, Hutton, Maravita, Dolan, & Driver, 2005; Slotnick, Hopfinger, Klein, & Sutter, 2002). Experiments 1 and 2 measured distractor interference as a function of separation and generated findings consistent with a Mexican-hat profile, with distractors at intermediate separations from the attended location being more efficiently ignored than those at nearer *and* further separations.

#### Preview of Experiments 3 to 5: effects of load on the focus of perceptual resources

Given that the profile of perceptual resources describes a Mexican hat, the degree of focus of perceptual resources can be derived from the 'bottom' of the function (the point where

distractor interference stops decreasing and starts increasing with increasing separation and which corresponds to the best ‘ignored’ separation). Thus, when the bottom of the function occurs at *smaller separations*, perceptual resources are more *focused*. Experiment 3 showed that an increase in perceptual load caused the bottom of the Mexican-hat function to move closer to the attended location, confirming that perceptual load focuses perceptual resources in space. It also showed that individual differences in working-memory span, and therefore in the effectiveness of cognitive control (Engle, Cantor, & Carullo, 1992; Engle, 2002; Kane & Engle, 2002), affected the amplitude of distractor interference across separations but not the spatial focus of perceptual resources. The latter finding is consistent with the suggestion that a second, post-perceptual level of selection is involved in blocking distractors from cognitive intrusion when they have been perceptually processed. Finally, Experiments 4 and 5 showed that, when cognitive-control mechanisms were loaded by a concurrent working-memory task, the bottom of the Mexican-hat function of separation moved away from the attended location, showing that cognitive-control mechanisms can after all also affect the spatial focusing of perceptual resources and thus what we perceive.

## EXPERIMENT 1

Experiment 1 tested whether the spatial profile of perceptual resources, as indexed from flanker interference in Eriksen’s flanker paradigm (Eriksen & Hoffman, 1972, 1973), is shaped like a gradient or a Mexican hat. In this experiment, several measures of flanker interference were tested and compared with a view to deciding which was the best to index the profile of perceptual resources.

In Eriksen’s flanker paradigm, the participants perform a target-identification task (using a two-alternative forced-choice response; see Figure 1) whilst ignoring a concurrently presented distractor stimulus. The distractor can be compatible (with its identity mapped to the same response as the target), incompatible (with its identity mapped to the opposite response to the target), or neutral (with its identity not mapped to any response). To the extent that the distractors are processed, it is possible for these three types of distractors to affect performance<sup>2</sup> through one, or both, of two types of interference, namely, *response-related* interference and what we will henceforth refer to as *salience-related* (singleton-type) interference. The former is assumed to reflect a competition for response selection (e.g., Eriksen & St. James, 1986; Lavie, 1995; Yantis & Johnston, 1990) and the latter a competition for perceptual representation in the visual system (Björk & Murray, 1977; Forster & Lavie, 2008; McCarley, Mounts, & Kramer, 2004, 2007). 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). In Experiment 1 (and also in Experiment 2), two different measures of *response-related* interference and one measure of *salience-related* interference were used to index the profile of perceptual resources.

### *Response-related interference*

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<sup>2</sup> Performance can be indexed using both latencies and errors. In the present study, latencies were found to be a better measure of performance than errors, although error and latency measures always agreed.



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. Incompatible distractors have been shown to *increase* latencies and errors for target-identification (e.g., Cohen & Shoup, 1997; Miller, 1991; Pan & Eriksen, 1993; 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; Miller, 1991; 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 *incompatible*-distractor performance with *compatible*-distractor performance (e.g., Anderson & Kramer, 1993; Forster & Lavie, 2007; Kramer & Jacobson, 1991; LaBerge et al., 1991; Lavie et al., 2004; Müller et al., 2005) or by comparing *incompatible*-distractor performance with *neutral*-distractor performance (e.g., Eriksen & St. James, 1986; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Lavie, 1995; Lavie & de Fockert, 2003; Yantis & Johnston, 1990). These comparisons have been proposed to isolate *response-related* interference and to exclude *salience-related* interference. 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 experiment, we used *both* these indices to determine whether the profile of perceptual resources described a gradient (Yantis & Johnston, 1990) or a Mexican hat (Müller et al., 2005). The profiles extracted using the two types of measures were compared. A concern was to test whether the shapes of the two profiles agreed and whether the bottoms of the two profiles - provided the profiles described Mexican-hat patterns - occurred at similar separations.

This concern emerges from the fact that one of the two measures, namely, the one obtained by comparing incompatible-distractor performance with neutral-distractor performance, may contain *salience-related interference* from the incompatible distractor as, in certain circumstances, incompatible (and compatible) distractors can be predicted to be more salient

than neutral distractors, for instance, due to differences in their task-relatedness (Björk & Murray, 1977).<sup>3</sup>

### *Saliency-related interference*

This is no cause for concern, however, 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; Forster & Lavie, 2008; Lavie & de Fockert, 2005, 2006; McCarley & Mounts, 2008). Then the presence of saliency-related interference in the index obtained by comparing incompatible-distractor with neutral-distractor performance is not problematical and indeed makes for a more sensitive measure (see Experiment 5). An important goal of Experiments 1 and 2 was therefore to test whether response-related and saliency-related interference do index the same profile.

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, 2005; Mounts & Gavett, 2004; Mounts & Tomaselli, 2005). Note that, unlike response-related interference, saliency-related interference can only operate in one direction (namely, to increase RTs and errors).

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

## Method

### *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.

### *Participants*

14 healthy participants from Goldsmiths College (5 females; 2 left-handed; mean age 22.3 yr; age range 18 to 39 yr) 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.

### *Experimental setup*

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

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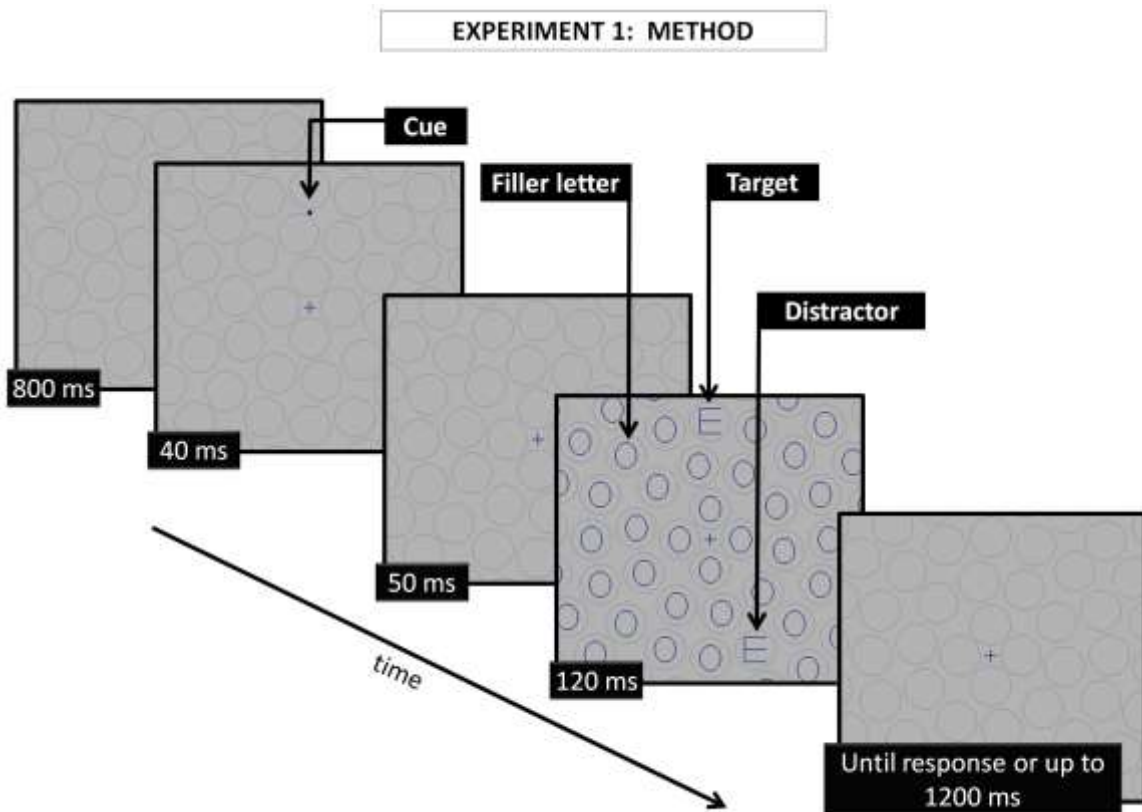
<sup>3</sup> This form of saliency has been labelled ‘contingent’ saliency to emphasize its dependence on the underlying task set (Corbetta & Shulman, 2002; Folk, Remington, & Johnston, 1992).

chin rest was used to maintain a viewing distance of 70 cm. The program used to generate the stimuli and run the experiment was written in Turbo Pascal 7.0.

### *Stimuli and procedure*

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 two fingers of their dominant hand) as quickly but as accurately as possible while ignoring a distractor letter and filler letters. The target was always the letter 'E' or 'F', the distractor was always the letter 'E', 'F' or 'X', and the filler letters were always the letter 'O'. 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.

The stimulus letters (target, distractor and filler letters) were all of the same dark blue (CIE  $x = 0.15$ ,  $y = 0.08$  and  $L = 0.44$   $\text{cd/m}^2$ ) and subtended 0.90 by 1.05 deg. A cross (subtending 0.5 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 1). They were dark grey (CIE  $x = 0.29$ ,  $y = 0.32$  and  $L = 4.67$   $\text{cd/m}^2$ ) against a light grey background (CIE  $x = 0.28$ ,  $y = 0.30$  and  $L = 13.70$   $\text{cd/m}^2$ ). 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 (see Figure 1).



**Figure 1**

**Figure 1.** Experiment 1. A schematic representation of an experimental trial. In each trial, the presentation of an exogenous cue indicated the location of the upcoming target ('E' or 'F') with 100% validity. Participants signalled target identity (with a two-alternative forced choice or 2-AFC response) while ignoring the distractor letter ('E', 'F' or 'X' in an uncued location) and filler letters ('O's). The figure illustrates a target-distractor separation of 9.0 deg (out of the four possible separations: 1.8, 5.1, 7.7 or 9.0 deg).

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 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 1).

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. 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 1 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.

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

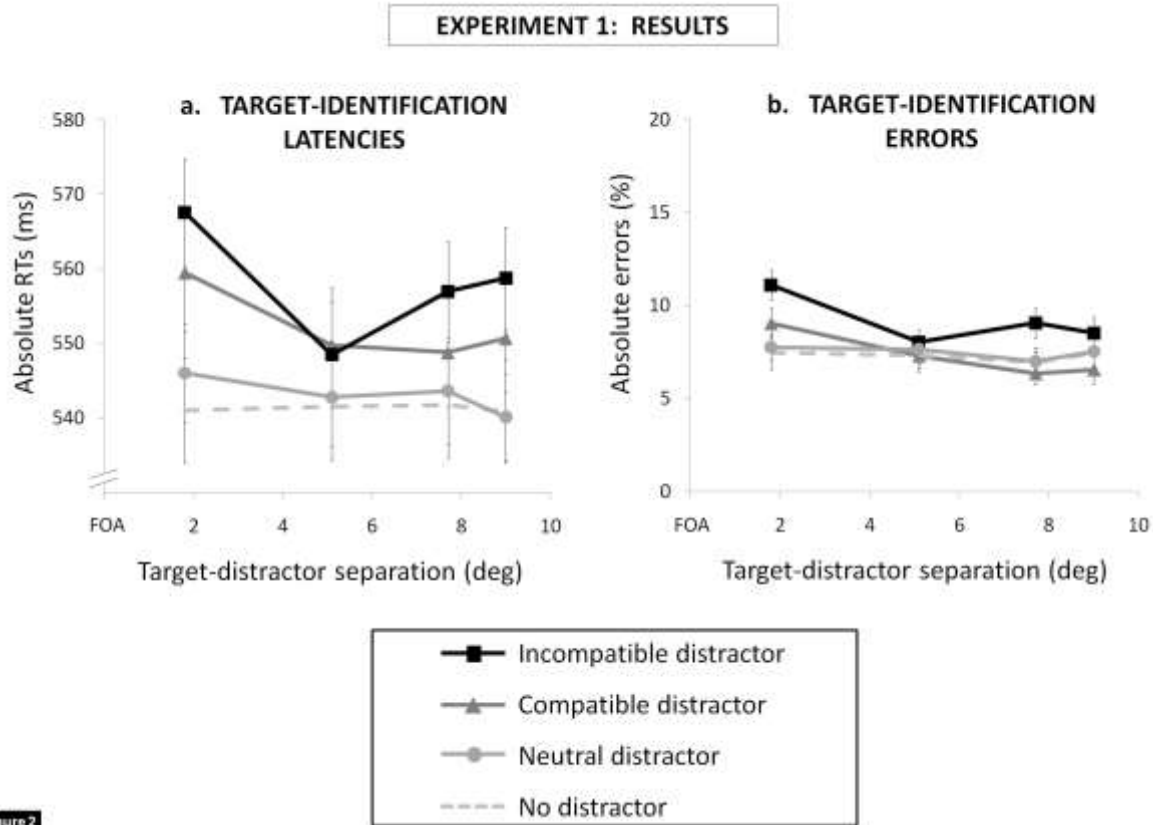
The effect of Target Location was tested but is not reported as Target Location did not interact with any other factor (all  $p$  values  $> 0.100$ ; note that the main effect of Target Location was significant at  $p < 0.010$  as participants were overall slower to respond to North targets than to South, East or West targets). The effect of Target Location was not included in the analyses of subsequent experiments.

Three analyses were performed on mean RTs and errors. These analyses all compared the performance obtained with one type of distractor with that obtained with another type (which equated to subtracting the performance obtained with one type of distractor from that obtained with another type) as a function of separation. Specifically, the first analysis compared *incompatible*-distractor with *compatible*-distractor performance as a function of separation; the second analysis compared *incompatible*-distractor with *neutral*-distractor performance as a function of separation; and the third analysis compared *neutral*-distractor with *no*-distractor performance as a function of separation. 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 Introduction to this experiment), and to testing whether the interference isolated was significant *across* separations, *and* whether this interference was significantly *modulated* with target-distractor separation. Where interference was modulated with separation, polynomial trends were applied to determine the shape of the interference function of separation.<sup>4</sup>

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<sup>4</sup> The interference functions of separation are not explicitly illustrated in this paper (except in Experiment 3, Figure 8) but they can be derived from differencing the absolute RTs as a function of separation in the relevant distractor conditions (see Figure 2).

While all analyses were conducted on errors as well as latencies, the results of the error analyses are not reported (for this or any other experiment) as they were largely insignificant. In the few cases where significant effects were found, these were always in the same direction as the effects in latencies (compare graphs of RTs and errors for each experiment).



**Figure 2**

**Figure 2.** Experiment 1. Absolute incompatible-, compatible- and neutral-distractor latencies and errors (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor latencies and errors. (■) = incompatible distractors; (▲) = compatible distractors; (●) = neutral distractors; (FOA) = attended location. Error bars show +/- 0.5 SEM.

### 1. Comparison of incompatible- with compatible-distractor RTs as a function of separation

This analysis compared *incompatible*-distractor and *compatible*-distractor RTs as a function of separation using a repeated-measures ANOVA<sup>5</sup>. It tested for the effects of two factors, namely, Compatibility (Incompatible vs. Compatible distractor, or I. vs. C.) and Separation (between target and distractor; 1.8, 5.1, 7.7 or 9.0 deg of separation) on target-identification RTs.

The repeated-measures ANOVA showed that: (1) the effect of Compatibility (I. vs. C.) was significant ( $F(1,13) = 5.06, p = 0.042, \eta_p^2 = 0.280$ ), showing that there was significant *combined response-related interference*; (2) the effect of Separation was significant ( $F(3,39)$

<sup>5</sup> The level of significance was set at 0.05 and the 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  $d.f. > 1$ .

= 9.62,  $p < 0.001$ ,  $\eta_p^2 = 0.425$ ), 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 marginally significant ( $F(3,39) = 2.54$ ,  $p = 0.070$ ,  $\eta_p^2 = 0.164$ ), suggesting 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 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 (Müller et al., 2005; see Figure 2) and not with a gradient profile.

## 2. Comparison of incompatible- with neutral-distractor RTs as a function of separation

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

The repeated-measures ANOVA showed that: (1) the effect of Compatibility (I. vs. N.) was significant ( $F(1,13) = 47.71$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.786$ ), showing that there was significant *incompatible-distractor response-related interference*; (2) the effect of Separation was also significant ( $F(3,39) = 6.30$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.326$ ), showing that RTs (pooled across incompatible- and neutral-distractor conditions) varied with separation; and (3) the interaction between Compatibility (I. vs. N.) and Separation was significant ( $F(3,39) = 3.27$ ,  $p = 0.031$ ,  $\eta_p^2 = 0.201$ ), showing 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 ( $F(1,13) = 14.24$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.523$ ; 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.

## 3. Comparison of neutral- with no-distractor RTs as a function of separation

This analysis compared *neutral*-distractor and *no*-distractor RTs as a function of separation using a repeated-measures ANOVA and tested for the effects of two factors, namely, Presence of Neutral Distractor, and Separation on target-identification RTs. The repeated-measures ANOVA showed no significant effect (all  $p$  values  $> 0.100$ ). In other words, there was no evidence that neutral distractors generated *salience-related interference*, nor that *salience-related interference* could be used to measure the profile of perceptual resources.

## 4. Comparison of the interference functions of separation

A final and fourth analysis compared the interference measured in the previous three 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 and second analyses were 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 and were similarly focused.

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.

## Discussion

In Experiment 1, participants were tested on an adaptation of Eriksen's flanker task (Eriksen & Hoffman, 1972, 1973). In order to measure the shape of the profile of perceptual resources, distractor interference was sampled at four different separations from the attended location, using (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 response-related interference* was significant and this interference first decreased but then increased with increasing separation, describing a Mexican-hat pattern (see Figure 2). The control of distractor eccentricity across target-distractor separations ensured that the Mexican-hat pattern was not an artefact of differences in cortical magnification. Moreover, the presence of placeholder and filler letters ensured that the Mexican hat was not a result of masking. Instead, this Mexican-hat pattern must reflect only the spatial profile of perceptual resources given that it is widely accepted in these circumstances that *combined response-related interference* indexes the allocation of perceptual resources at the distractor location. (e.g., Anderson & Kramer, 1993; Kramer & Jacobson, 1991; LaBerge et al., 1991; Lavie et al., 2004). Experiment 1 therefore confirmed Müller et al.'s result (2005) that the profile of perceptual resources is shaped like a Mexican hat. Note that Müller et al. (2005) obtained a Mexican-hat profile with an endogenously defined target location and with a target and distractors that always occurred in the same (right) hemifield. In Experiment 1, the Mexican-hat profile was obtained with exogenous cueing and irrespective of whether target and distractors occurred in the same or in different hemifields (there was no effect of Target Location). Experiment 1 therefore extends Müller et al.'s results.



Another important finding of Experiment 1 was that the same function of separation was obtained with *incompatible-distractor response-related interference* as with *combined response-related interference* (for incompatible and compatible distractors). In fact, *incompatible-distractor response-related interference* was overall larger than *combined response-related interference*. This finding is explained by compatible distractors having generated salience-related interference in a way that neutral distractors did not (see Figure 2). This was probably the result of the presence of *task-driven* salience in compatible distractors compared to neutral distractors;<sup>6</sup> given that task-relevant compatible distractors generated substantial salience-related interference, incompatible distractors should also have done so. This being the case, the comparison between incompatible-distractor and neutral-distractor performance should have produced a measure combining response-related and salience-related interference whereas the comparison between incompatible-distractor and compatible-distractor performance should have isolated a pure measure of response-related interference. The fact that these two measures nevertheless agreed suggests that (1) salience-related interference, just like response-related interference, indexes the allocation of perceptual resources and (2) *incompatible-distractor response-related interference*, as well as *combined response-related interference*, can be used to index perceptual resources (Eriksen & St. James, 1986; Kramer et al., 1994; Lavie, 1995; Lavie & de Fockert, 2003; Yantis & Johnston, 1990).

Finally, it was found that neutral distractors did not generate significant salience-related interference. It was therefore not possible to index the profile of perceptual resources using response-irrelevant distractors. The absence of salience-related interference from neutral distractors was probably the result of a reduction in the *stimulus-driven* salience of these distractors due to the filler letters that surrounded and masked them.

In conclusion, the findings of Experiment 1 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 1 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 1. Experiment 2 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 1, except omitting placeholders and filler letters.

## EXPERIMENT 2

As well as omitting placeholders and filler letters, Experiment 2 used only two target locations (North and South) and one additional separation to increase the density of sampling of separations.

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<sup>6</sup> This *positive* salience-related interference of compatible distractors cannot however be separated from their *negative* response-related interference and was therefore not tested.

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

## Method

### *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.

### *Participants*

15 healthy participants from Goldsmiths College (11 females; 1 left-handed; mean age 22.5 yr; age range 19 to 30 yr) 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.

### *Stimuli and procedure*

The same stimuli and procedure were used as in Experiment 1, 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 2 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.

## 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 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 five target-distractor separations (1.8, 3.5, 5.1, 7.7 and 9.0 deg; see Figure 3). Moreover, for each participant, no-distractor (i.e. filler-letters-only) RTs and errors were randomly separated into five bins and means were calculated for each bin. The five bins were used as baselines to match the five target-distractor separations. The same four analyses were performed as in Experiment 1.

EXPERIMENT 2: RESULTS

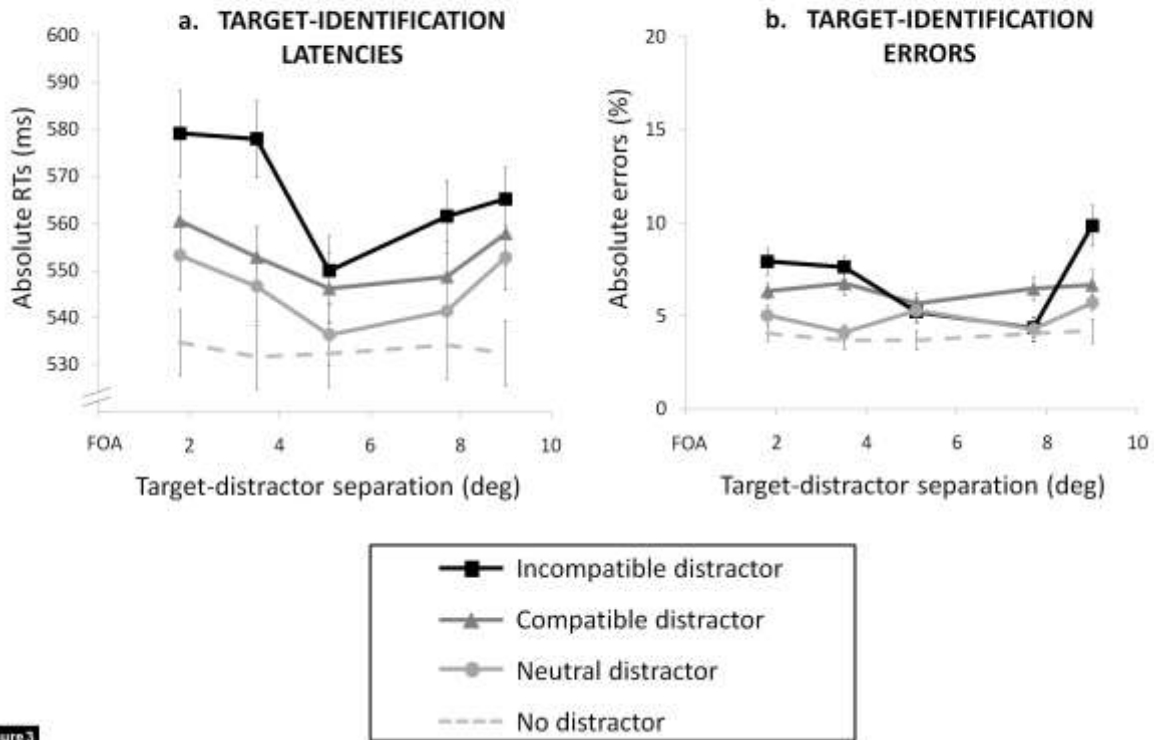


Figure 3

**Figure 3.** Experiment 2. Absolute incompatible-, compatible- and neutral-distractor latencies and errors (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor latencies and errors. (■) = incompatible distractors; (▲) = compatible distractors; (●) = neutral distractors; (FOA) = attended location. Error bars show +/- 0.5 SEM.

1. Comparison of incompatible- with compatible-distractor RTs as a function of separation

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

2. Comparison of incompatible- with neutral-distractor RTs as a function of separation

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

### 3. Comparison of neutral- with no-distractor RTs as a function of separation

This analysis compared *neutral-distractor* and *no-distractor* RTs as a function of separation using a repeated-measures ANOVA. It tested for the effects of two factors, namely, Presence of Neutral Distractor, and Separation on target-identification RTs. 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 2, neutral distractors generated significant *saliency-related interference* and that this interference varied with separation. Polynomial trends for the interaction showed that *saliency-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.

### 4. Comparison of the interference functions of separation

The final analysis used a repeated-measures ANOVA to compare the interference as a function of separation obtained in the previous analyses. 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 *saliency-related interference*) and Separation.

The analysis 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.

## Discussion

First, the findings of Experiment 2 replicated those of Experiment 1 showing that both *combined response-related interference* and *incompatible-distractor response-related interference* as a function of separation describe a Mexican-hat pattern.

Second, the other important finding of Experiment 2 was that neutral distractors can generate saliency-related interference when they are sufficiently salient. *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 means that a more sensitive measure of the profile of perceptual resources can be provided by pooling salience-related and response-related interference from salient distractors (see Experiments 4 and 5).

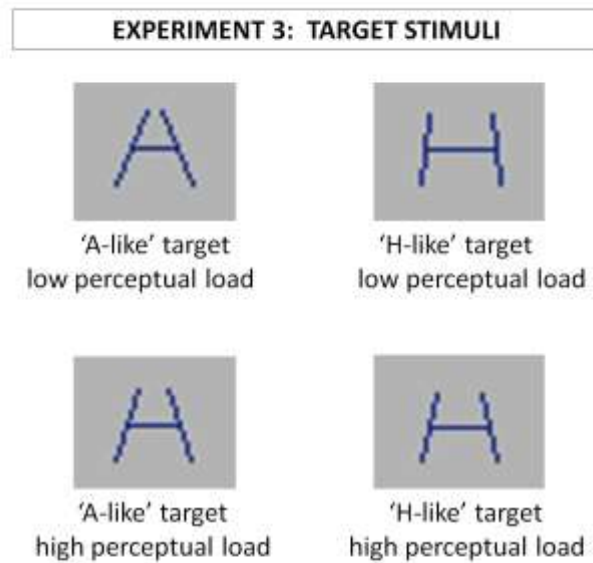
Experiment 3 used an adaptation of the high-salience paradigm introduced in Experiment 2, to measure whether increasing perceptual load *focuses* the Mexican-hat profile of perceptual resources and decreasing the effectiveness of cognitive control *defocuses* the Mexican hat (see General Introduction).

### EXPERIMENT 3

This experiment tested whether perceptual load and the effectiveness of cognitive control only affect the amplitude of distractor interference across separations (as suggested by Müller et al., 2005, for perceptual load and by Lavie et al., 2004, for the effectiveness of cognitive control; see General Introduction) or cause a change in the focus of the interference function of separation (as indexed by a shifting of the bottom of the Mexican-hat function; see General Introduction).

In Experiment 3, the effectiveness of cognitive control was manipulated by selecting groups of participants with different levels of working-memory span (Engle et al., 1992; Kane & Engle, 2002) 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).

On the other hand, in Experiment 3, perceptual load was manipulated within participants. The perceptual-load manipulation was not the typical one that consists in varying the visual noise around a target letter by adding peripheral noise stimuli (e.g., Lavie, 1995; Lavie et al., 2004); indeed, the latter cannot be used when target-distractor separation is varied, since a distractor at small separations will be masked more by noise than a distractor at large separations. In Experiment 3, the manipulation of perceptual load 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 identification was relatively easy (the 'A-like' letter closely resembled 'A' and the 'H-like' letter closely resembled 'H'; see upper half of Figure 4) whereas, in the high-perceptual-load condition, it was difficult (the 'A-like' and 'H-like' letters were much harder to identify; see lower half of Figure 4).



**Figure 4**

**Figure 4.** Experiment 3. A schematic 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 3. This meant that only neutral distractors (that cannot generate response-related interference and can generate only salience-related interference; see Introduction to Experiment 1) could be used. It was hoped that these distractors alone would nevertheless provide a sufficiently sensitive measure to index the profile of perceptual resources (see Experiment 2).

Since Experiment 3 (1) used a distractor that could only generate salience-related interference and (2) investigated individual differences in distractor interference, a larger number of participants was tested than in Experiments 1 and 2.

## Method

### 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.

### Participants

54 participants from Goldsmiths College (47 females; 6 left-handed; mean age 22.8 yr; age range 18 to 29 yr) with normal or corrected-to-normal vision took part in the experiment in exchange for course credits.

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

The method was similar to that used in Experiment 2 except for the differences detailed below (see Figure 5).

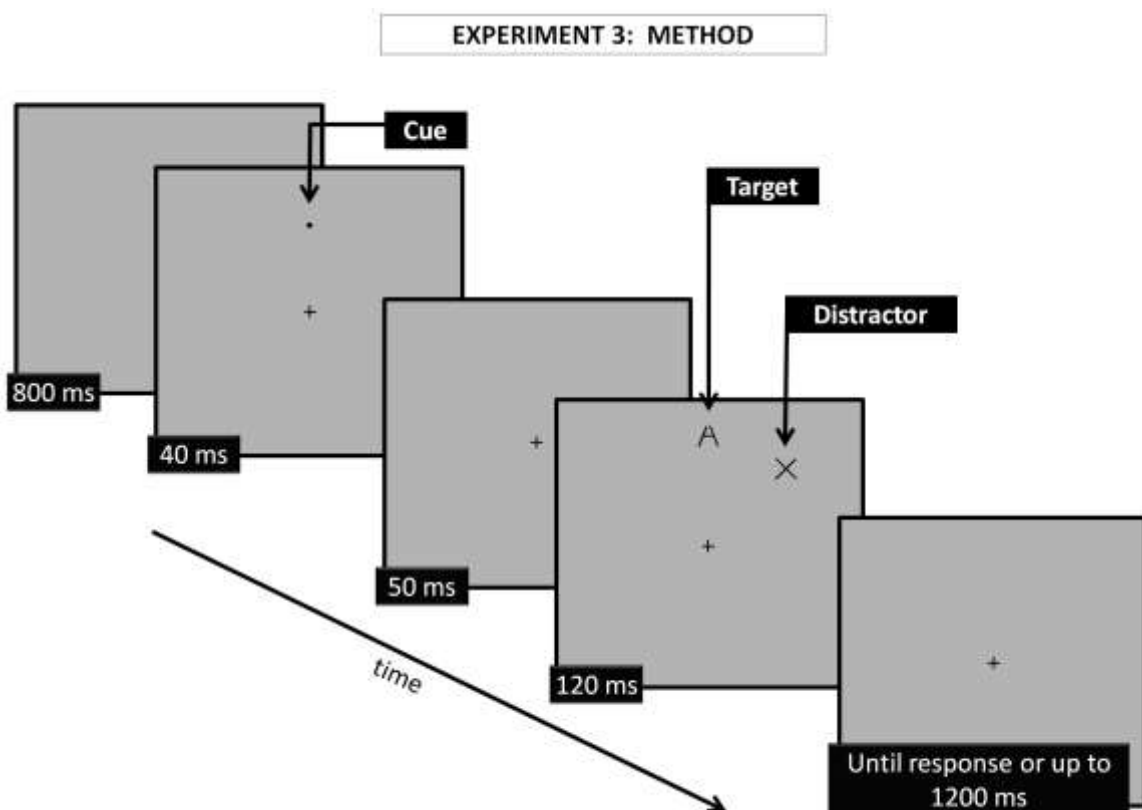


Figure 5

**Figure 5.** Experiment 3. A schematic representation of an experimental trial. In each trial, the presentation of an exogenous cue indicated the location of the upcoming target (‘A-like’ or ‘H-like’) with 100% validity. Participants signalled target identity (with a 2-AFC) while ignoring the distractor letter (‘X’, in an uncued location). The figure illustrates an ‘A-like’ target and a target-distractor separation of 3.5 deg (out of the five possible separations: 1.8, 3.5, 5.1, 7.7 or 9.0 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 4). 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 3 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.

#### *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, generating scores between 0 (low working-memory span) and 75 (high working-memory span; for a description of the task, see Unsworth et al., 2005). It was performed during lab classes on a different day from the target-identification task.

### 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).

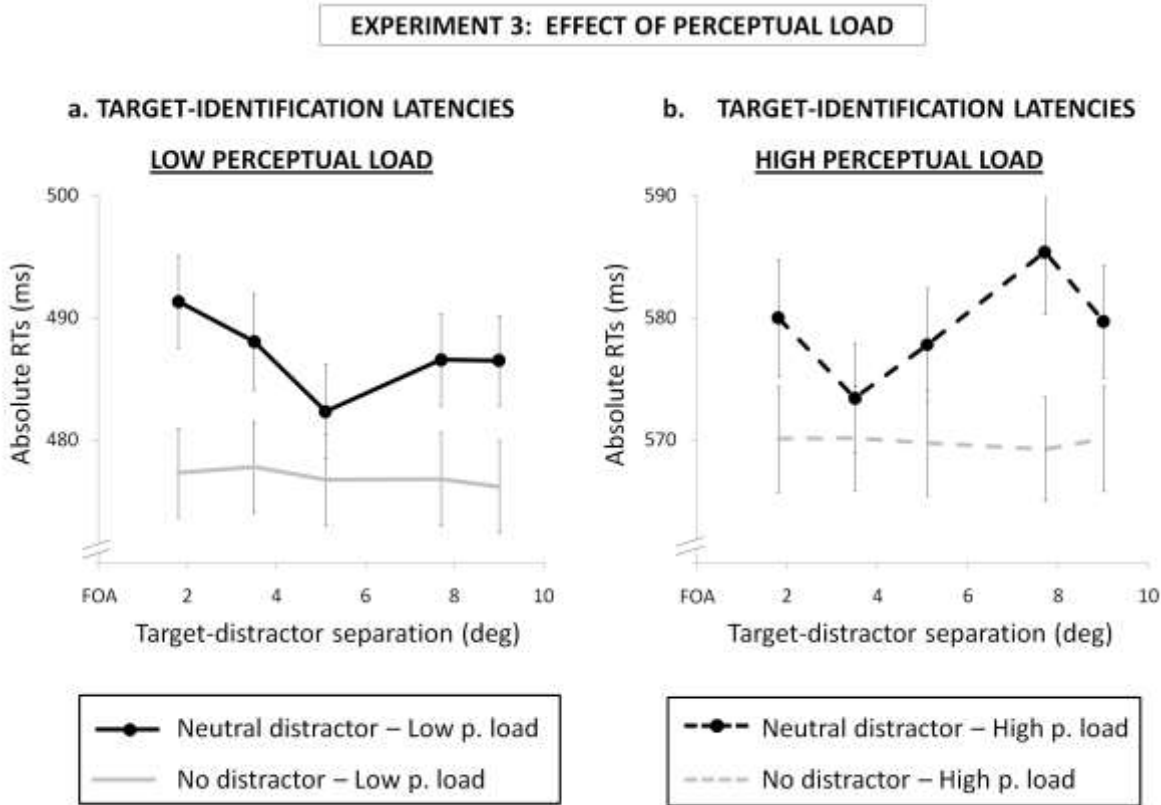
We analyzed both the speed and accuracy of forced-choice target-identification (A-like vs. H-like) responses. Response latencies (RTs) were examined only for accurate responses, and only when they were longer than 200 ms and fell within three standard deviations of the overall mean for the participant, 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 Figures 6 and 7). Moreover, for each participant, no-distractor RTs and errors were randomly separated into five bins in each condition of perceptual load, and means 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 RTs were compared with *no*-distractor RTs as a function of (1) separation, (2) perceptual load and (3) working-memory span using a mixed-design ANOVA. This



allowed us to isolate *saliency-related interference* and to test whether the interference function of separation was affected by perceptual load and working-memory span.

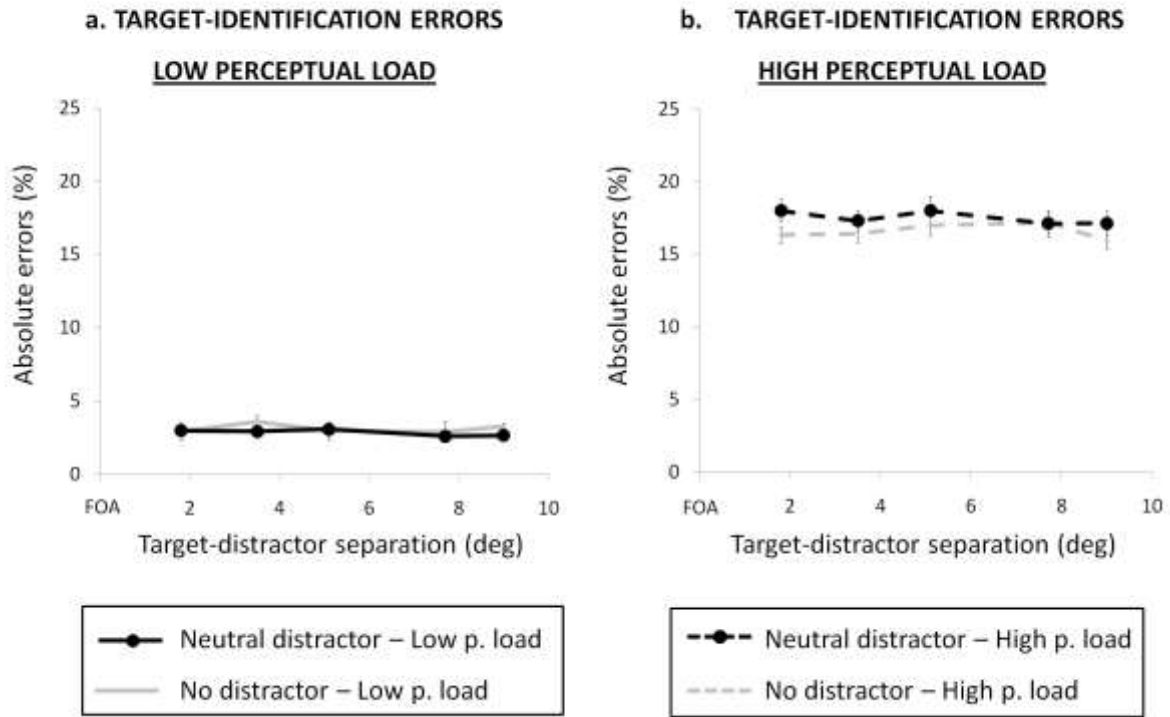


**Figure 6**

**Figure 6.** Experiment 3. Absolute neutral-distractor latencies in the low- and high-perceptual-load conditions (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor latencies in the low- and high-perceptual-load conditions. (FOA) = attended location. Error bars show +/- 0.5 SEM.

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.

**EXPERIMENT 3: EFFECT OF PERCEPTUAL LOAD**



**Figure 7**

**Figure 7.** Experiment 3. Absolute neutral-distractor errors in the low- and high-perceptual-load conditions (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor errors in the low- and high-perceptual-load conditions. (FOA) = attended location. Error bars show +/- 0.5 SEM.

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

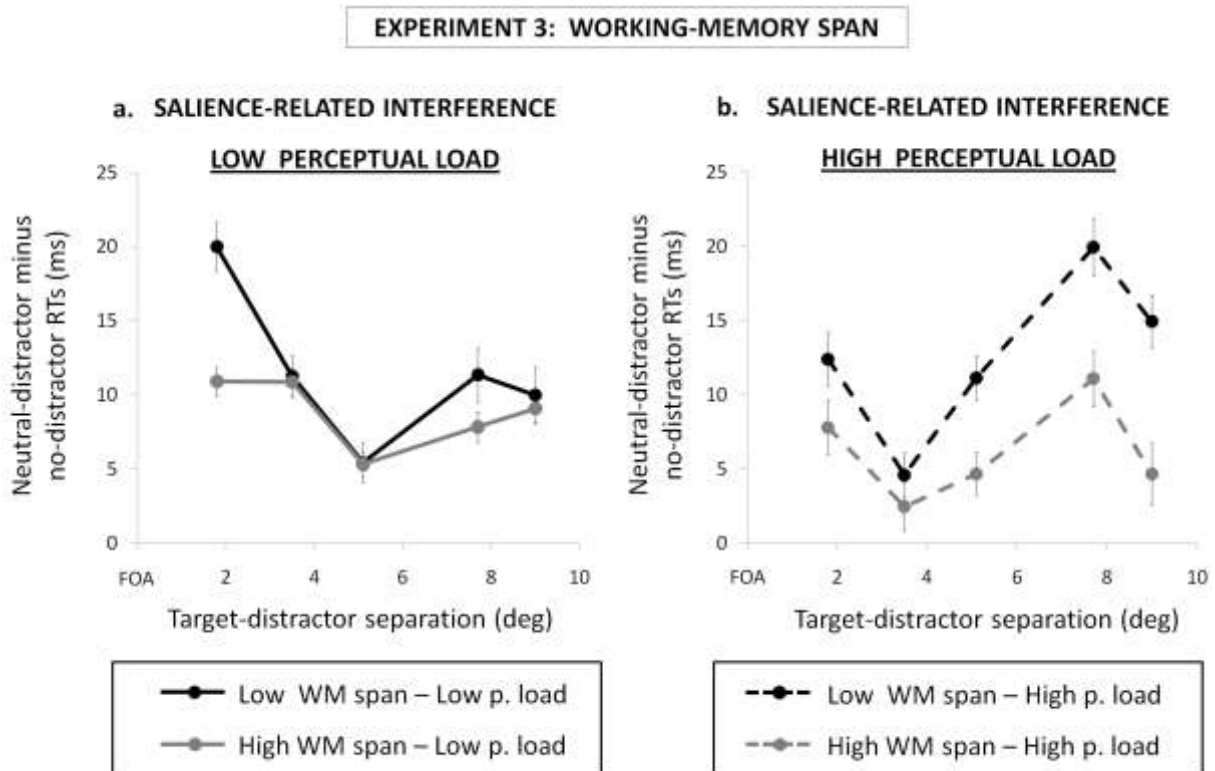
The analysis tested for the effects of four factors, namely, Presence of Neutral Distractor, Separation, Perceptual Load and Working-memory Span on target-identification RTs using a mixed-design ANOVA. Where there was a significant interaction, additional analyses, namely, ANOVAs and interpolation analyses, 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 *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 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 2).

### 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 8).<sup>7</sup> No other effect of Working-memory Span was significant (all  $p$  values  $> 0.300$ ).



**Figure 8**

**Figure 8.** Experiment 3. Saliency-related interference of neutral distractors, derived by subtracting no-distractor latencies from neutral-distractor latencies, in the low- and high-perceptual-load conditions (left and right respectively), as a function of target-distractor separation (in deg) and working memory span (low or high). (●) = low working-memory span; (●) = high working-memory span; (FOA) = attended location. Error bars show  $\pm 0.5$  SEM.

### 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

<sup>7</sup> Additional analyses also showed that there was an inverted correlation between working-memory span and the amplitude of saliency-related interference across separations ( $r = -0.27, p = 0.052$ ).

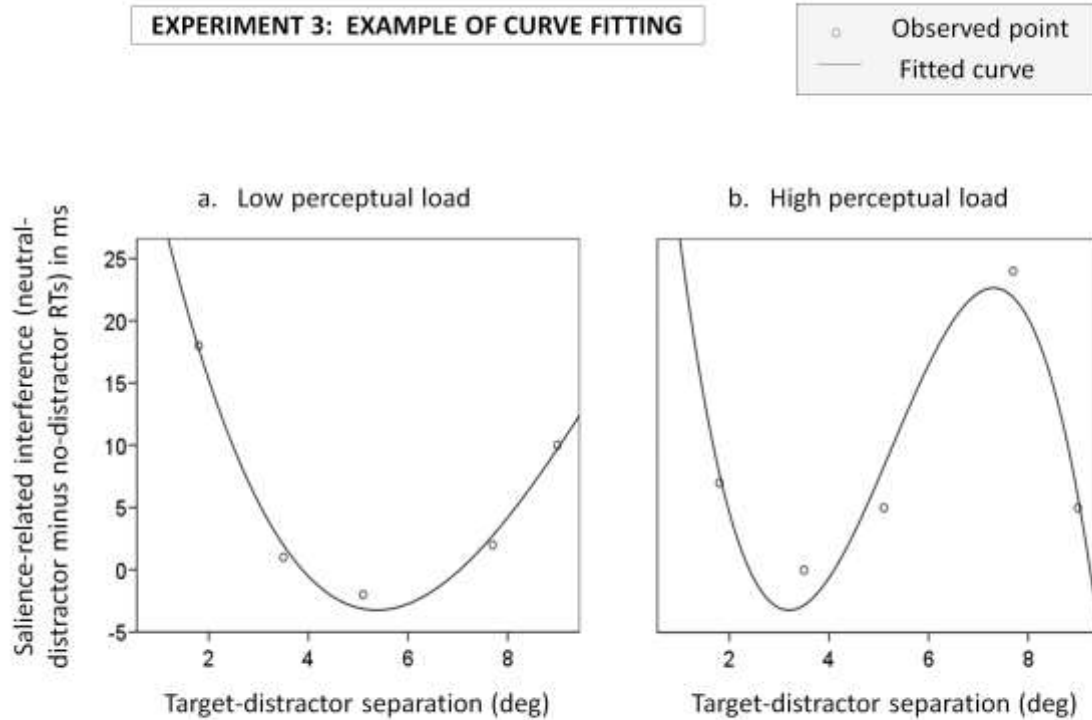
(see Figure 6). The two-way interaction between Perceptual Load and Separation was also significant ( $F(4,208) = 2.70$ ,  $p = 0.032$ ,  $\eta_p^2 = 0.149$ ). Moreover, the three-way interaction between Perceptual Load, Presence of Neutral Distractor, and Separation was significant ( $F(4,208) = 2.66$ ,  $p = 0.034$ ,  $\eta_p^2 = 0.149$ ), showing that *salience-related interference* as a function of separation was different in low- and high-perceptual-load conditions. No other interactions were significant (all  $p$  values  $> 0.100$ ).

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 2 (compare Figures 3 and 6). 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 Figure 6). 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 Figure 9 for an example of interpolation on *salience-related interference* in the two perceptual-load conditions). 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 (see high-perceptual-load condition of Experiment 3; Müller et al., 2005). It is important to note that, even when the data are best explained by a quadratic trend (see left of Figure 9), the function obtained by fitting a cubic model closely mirrors that obtained by fitting a quadratic model (because the cubic coefficient in the cubic model approaches zero, bringing the model close to a quadratic model).



**Figure 9**

**Figure 9.** Experiment 3. Example of curve fitting on one participant’s data. Salience-related interference of neutral distractors as a function of target-distractor separation (in deg) was fitted using a cubic model in both the low- and high-perceptual-load conditions (left and right respectively). The function of separation was best explained by a quadratic trend (left) or a cubic trend (right). (○) = observed data points; (□□) = curve fitted with a cubic model.

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. When the local minimum occurred outside the boundaries of the sampled interval (namely, at a smaller separation than 1.8 deg or a larger separation than 9.0 deg), the boundary closest to the local minimum was coded as the local minimum: for instance, if the local minimum occurred at 11.0 deg, the bottom was coded as 9.0 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 followed a linear trend, and the local minimum was therefore defined as the lowest point of the function within the sampled interval (i.e., either 1.8 or 9.0 deg, for linearly increasing and decreasing functions respectively).

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.

## Discussion

First of all, the low-perceptual-load condition of Experiment 3 produced a Mexican-hat interference function of separation similar to those observed in Experiments 1 and 2 (see left panel of Figure 6). Thus, neutral ('X') distractors were (as in Experiment 2) found to be effective in mapping the spatial profile of perceptual resources. Nevertheless, as neutral distractors can generate only salience-related interference, they are less sensitive probes of the profile of perceptual resources than incompatible distractors (which can generate *both* salience-related and response-related interference; see Figure 3). For this reason, incompatible distractors were used in all subsequent experiments (where the negative flanker effect was not a concern).

Experiment 3 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 one of our previous studies using central-target presentation (Caparos & Linnell, 2009) and with several findings of spatial cueing studies (Downing, 1988; Handy et al., 1996; Williams, 1988).

Experiment 3 also showed that although the effectiveness of cognitive-control mechanisms (as indexed by participants' working-memory span; Engle et al., 1992; Engle, 2002; Kane & Engle, 2002) affected the amplitude of salience-related interference across separations (i.e., the lower the memory span, the more distractors generated salience-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 8). 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 3 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 3, which arguably involved only a low cognitive load. Experiment 4 was designed to put cognitive-control mechanisms under more stress. This was achieved by adding a secondary calculation task to the target-identification task.

## EXPERIMENT 4

Experiment 4 used a perceptual task similar to that used in Experiment 2 and introduced a secondary cognitive-load task. The latter was intercalated between blocks of target-identification trials and involved performing easy or difficult mental calculations. In order to limit the number of trials in Experiment 4, only neutral and incompatible distractors were used and cognitive load was manipulated in different groups of participants. It was necessary to use a limited number of trials as (data from several of our experiments have shown that) the effect of cognitive load wears off with practice.

In this experiment, as in Experiments 1 and 2, both *incompatible-distractor response-related interference* (obtained by comparing incompatible-distractor with neutral-distractor performance) and *saliency-related interference* (obtained by comparing neutral-distractor with no-distractor performance) were measured. In addition, given that these two measures were shown in Experiment 2 to provide the same insight into the profile of perceptual resources, they were combined into a third composite measure (obtained by comparing incompatible-distractor with no-distractor performance) to maximize sensitivity.

## Method

### *Design*

A mixed design was used in which compatibility of the distractor (incompatible or neutral) and target-distractor separation (at controlled stimulus eccentricity) were manipulated within participants, and cognitive load was manipulated to be high or low in different groups of participants.

### *Participants*

40 participants from Goldsmiths College (25 females; 3 left-handed; mean age 25.6 yr; age range 19 to 50 yr) with normal or corrected-to-normal vision took part in the experiment in exchange for £10.

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

The method was as in Experiment 2. 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 3, there was no auditory feedback when target-identification responses were incorrect as this would have interfered with the cognitive task (see below).

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

A calculation task was interleaved between all target-identification trials in order to manipulate cognitive load (see Figure 10). Each block of 10 to 15 target-identification trials was preceded by the presentation of a two-digit ‘seed’ number (between 21 and 59) displayed at the centre of the screen for 2000 ms. 1000 ms after the disappearance of this seed 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 high-cognitive-load condition, the participants had mentally to add two to the seed 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. In the low-cognitive-load condition, the participants had mentally to add *one* to the seed number, irrespective of whether the computer had emitted two or three beeps, and 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-load 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 number they had arrived at (there was no time limit and no feedback was given).

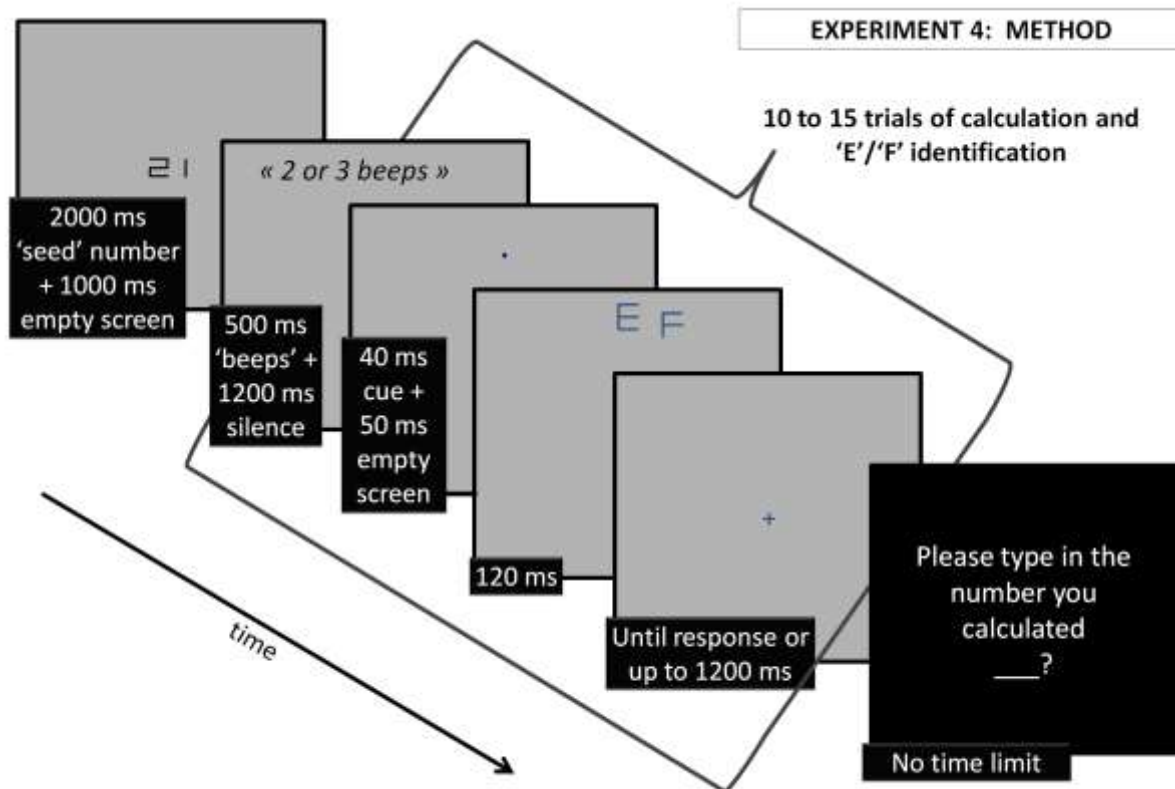


Figure 10

**Figure 10.** Experiment 4. A schematic representation of one block of ten to fifteen trials. Each block of trials started with the presentation of a two-digit ‘seed’ number. At the beginning of the trial, the computer emitted two or three beeps. In the high-cognitive-load condition, the participants had mentally to add two to the seed 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. In the low-cognitive-load condition, the participants had mentally to add one to the seed number, irrespective of whether the computer had emitted two or three beeps, and to keep the outcome in their mind. They had 1700 ms to perform this cognitive load task, after which they were presented with the ‘E’/‘F’ target-identification task. Immediately after they gave their response to the target, the next trial started, the computer again emitted two or three beeps and they had to add one (in the low-cognitive-load 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 number they had arrived at (there was no time limit and no feedback was given).

Experiment 4 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 39 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 working-memory task).

## 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 Figures 11 and 12). Moreover, for each participant, no-distractor RTs and errors were each randomly separated into four bins and means 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. These analyses extracted, respectively, *incompatible-distractor total interference*, *incompatible-distractor response-related interference*, and *saliency-related interference*, and tested whether each type of interference as a function of separation was modulated by cognitive load.

EXPERIMENT 4: EFFECT OF COGNITIVE LOAD

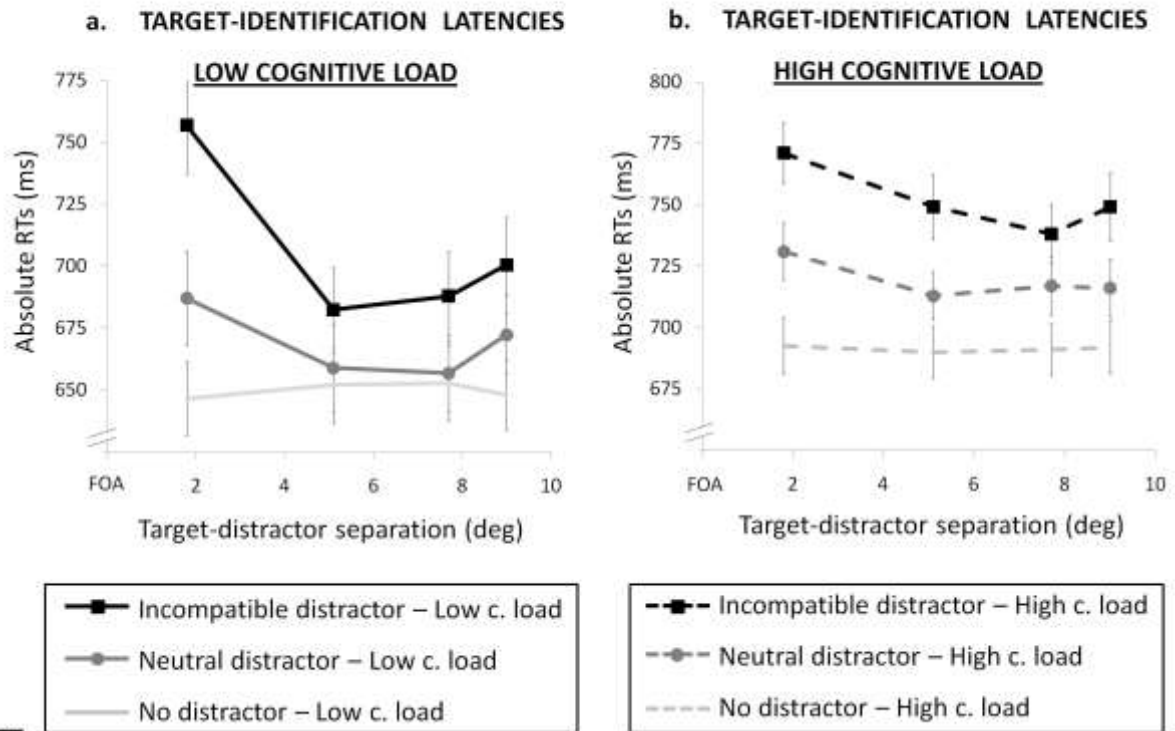


Fig 11

**Figure 11.** Experiment 4. Absolute incompatible- and neutral-distractor latencies in the low- and high-cognitive-load conditions (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor latencies in the low- and high-cognitive-load conditions. (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location. Error bars show +/- 0.5 SEM.

1. Comparison of incompatible- with no-distractor RTs as a function of separation and cognitive load

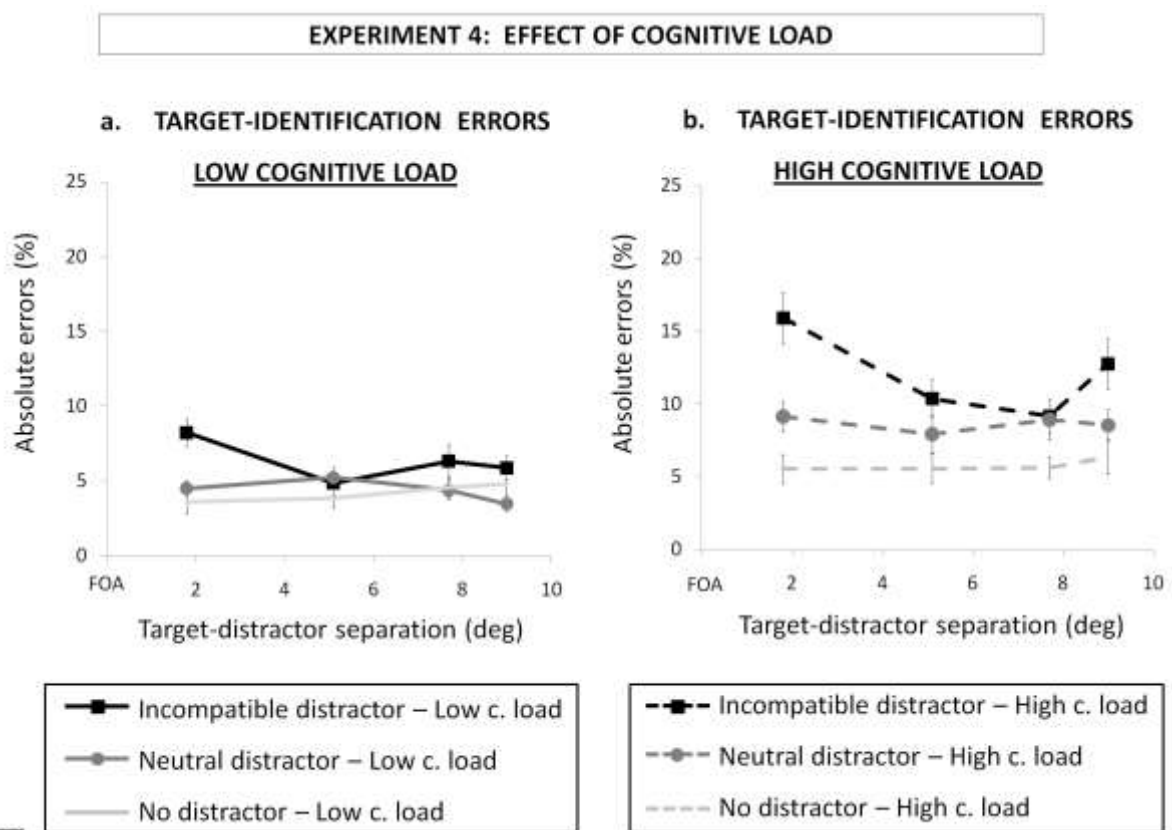
This analysis tested for the effects of three factors, namely, Presence of Incompatible Distractor, Separation and Cognitive Load on target-identification RTs using a mixed-design ANOVA. Where there was a significant interaction, additional analyses, namely, ANOVAs and interpolation analyses, were performed 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 the performance at target identification in RTs. 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 *incompatible-distractor total interference* as a function of separation was different in conditions of low and high cognitive load.



**Fig 12**

**Figure 12.** Experiment 4. Absolute incompatible- and neutral-distractor errors in the low- and high-cognitive-load conditions (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor errors in the low- and high-cognitive-load conditions. (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location. Error bars show  $\pm 0.5$  SEM.

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 11). 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. 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 3 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.

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

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 ( $F(1,38) = 1.24, p = 0.272, \eta_p^2 = 0.032$ ). Neither was the interaction between Cognitive Load and Compatibility ( $F(1,38) =$

0.07,  $p = 0.800$ ,  $\eta_p^2 = 0.002$ ) nor that between Cognitive Load and Separation ( $F(3,114) = 1.30$ ,  $p = 0.278$ ,  $\eta_p^2 = 0.033$ ). On the other hand, 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 *incompatible-distractor response-related interference* was large, the function of separation was almost *flat* in the high-load condition (see Figure 11). 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. 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 3 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.

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

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.

### Discussion

In Experiment 4, the increase in cognitive load did not show the main effect on distractor interference expressed in Experiment 3 (namely, it did not show an increase in the *amplitude* of distractor interference across separations with a decrease in the effectiveness of cognitive control). Consequently, it did not support the suggestion of Experiment 3 that the effectiveness of cognitive-control mechanisms affects post-perceptual levels of selection. On the other hand, unlike in Experiment 3, it was found that decreasing the effectiveness of cognitive control causes the profile of perceptual resources to spatially *defocus* (as indexed by the shifting *out* of the bottom of the Mexican-hat function). This defocusing of perceptual resources 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.

It was possible that the effect of cognitive load on the profile of perceptual resources 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, Finioia, 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 Experiment 4 were not only due to an effect on the orienting of perceptual resources.

### EXPERIMENT 5

The cognitive-load manipulation that was used in Experiment 5 was different from that used in Experiment 4. This time, the participants had to memorize either one (low-cognitive-load condition) or six (high-cognitive-load condition) digits before the beginning of each block of twenty trials. Another difference with Experiment 4 was that the target was presented *centrally*. As a result, the manipulation of target-distractor separation was confounded with a manipulation of distractor eccentricity. With such a design, decreasing cortical magnification with increasing separation will make it more difficult to index an increase in distractor interference which is the hallmark of a Mexican-hat profile of perceptual resources (Caparos & Linnell, 2009). Additionally, perceptual load is inherently lower (since the target occurs in the fovea), meaning that the Mexican-hat profile must be less focused (see Experiment 3) and therefore easier to confuse with a gradient profile (see Caparos & Linnell, 2009). In order to increase the chances of revealing a Mexican-hat profile of perceptual resources *and* of observing an outward shift of the bottom of the Mexican hat with increasing cognitive load, the flanker task was performed in combination with a secondary perceptual task designed to increase perceptual load (and thus focus the profile of perceptual resources; see Caparos & Linnell, 2009).

On each trial, 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 discriminate the position of a gap in the target letter which varied independently of the target identity (i.e., perform a difficult secondary perceptual task). In addition, across blocks of trials, a cognitive-load task was added to the dual task 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. As in Experiment 4, distractor interference was measured in three ways, using (1) *incompatible-distractor response-related interference*, (2) *saliency-related interference* and (3) *incompatible-distractor total interference* (i.e., the sum of 1 and 2),

## Method

### *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 cognitive load was manipulated to be high or low in different groups of participants.

### *Participants*

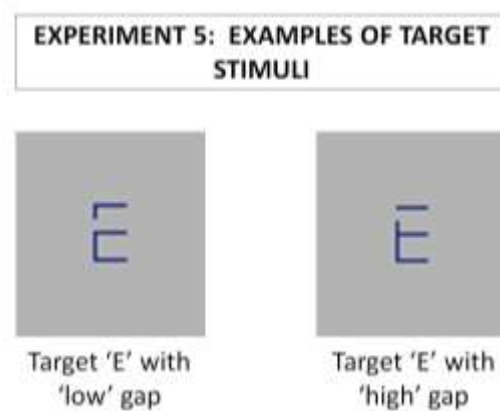
70 participants (56 females; 7 left-handed; mean age 19.9 yr; age range 16 to 36 yr), with reported normal or corrected-to-normal vision, participated in the experiment.

### *Stimuli and procedure for the target-identification and the gap-discrimination 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 required participants to discriminate the

position of a gap in the target letter ('high' vs. 'low' 2-AFC). This secondary task was used to increase perceptual load and focus perceptual resources over the attended (target) location.

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 13). 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 13.** Experiment 5. 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 position. Auditory feedback was given about incorrect responses for both tasks.

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

Experiment 5 also required participants to perform a tertiary working-memory task. This task was intercalated between blocks of target-identification/gasp-discrimination trials and was used to generate cognitive load.

Before each block of twenty trials, a vertical array of six digits was presented to the participants during 2500 ms (for the cognitive-load task). They had to memorize either (1) the the lowest number of the sequence (low-cognitive-load condition) or (2) the whole sequence of six numbers in the correct 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 two conditions of the cognitive-load task were performed by different groups of participants.

## 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 flanker task, we analysed results from the secondary perceptual task to ascertain that it was adequately well performed. It was found that the gap was incorrectly reported as ‘high’ in 13.2% of ‘low-gap’ trials and as ‘low’ in 13.1% of ‘high-gap’ trials. Cognitive load had no effect on gap-detection accuracy ( $F(1,68) = 0.42, p = 0.517, \eta_p^2 = 0.006$ ).

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 location of the gap was correctly discriminated. 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 79.8% 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 14 and 15). Moreover, for each participant, no-distractor RTs and errors were randomly separated into five bins, and means were calculated for each bin. The bins were used as baselines to match the five target-distractor separations. The same three analyses were performed on mean RTs as in Experiment 4.

EXPERIMENT 5: EFFECT OF COGNITIVE LOAD

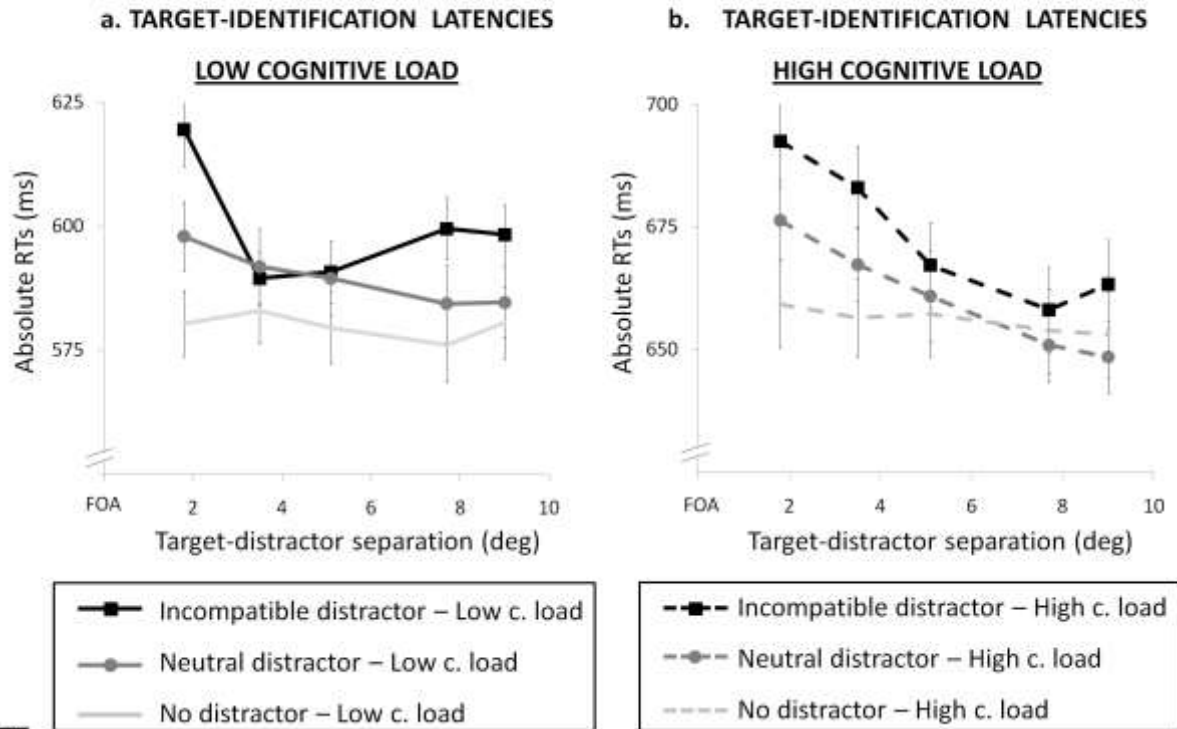


Fig 14

**Figure 14.** Experiment 5. Absolute incompatible- and neutral-distractor latencies in the low- and high-cognitive-load conditions (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor latencies in the low- and high-cognitive-load conditions. (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location. Error bars show +/- 0.5 SEM.

1. Comparison of incompatible- with no-distractor RTs as a function of separation and cognitive load

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,  $F(1,68) = 16.95, p < 0.001, \eta_p^2 = 0.200$  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 14). 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 14). 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 (see Results of Experiment 3 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 5.01 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, *incompatible-distractor total interference* produced significant 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.

EXPERIMENT 5: EFFECT OF COGNITIVE LOAD

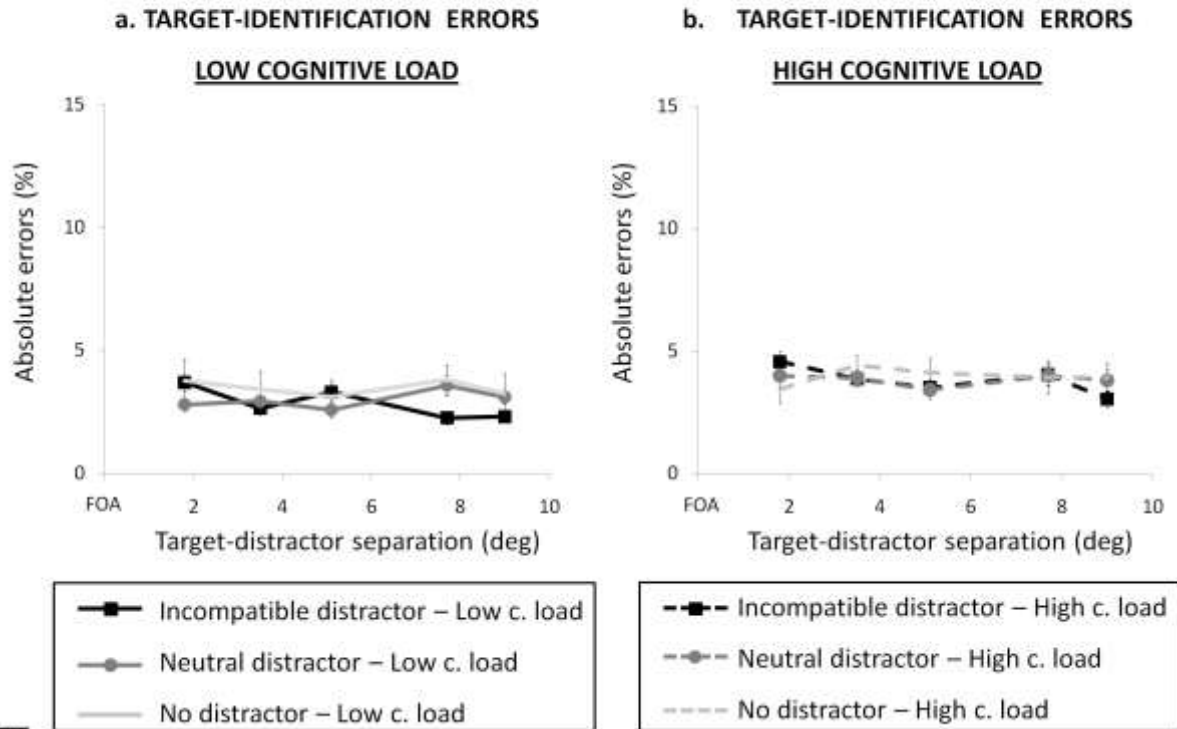


Fig 15

**Figure 15.** Experiment 5. Absolute incompatible- and neutral-distractor errors in the low- and high-cognitive-load conditions (left and right respectively) as a function of target-distractor separation (in deg), and no-distractor errors in the low- and high-cognitive-load conditions. (■) = incompatible distractor; (●) = neutral distractor; (FOA) = attended location. Error bars show +/- 0.5 SEM.

2. Comparison of incompatible- with neutral-distractor RTs as a function of separation and cognitive load

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 present but did not significantly vary with separation.

*Effect of Cognitive load*

While the interaction between Cognitive Load and Separation was significant ( $F(4,272) = 2.74, p = 0.029, \eta_p^2 = 0.086$ ), no other interaction was significant (all  $p$  values  $> 0.100$ ). No further analyses were thus performed on these data.

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

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*

Cognitive Load did not interact with any factor (all  $p$  values  $> 0.100$ ).

### Discussion

First, as already reported in Caparos and Linnell (2009), in the low-cognitive-load condition, 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 (Experiments 1 to 4 here; Müller et al., 2005). 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, once again, as in Experiment 4, the amplitude of distractor interference (both saliency-related and response-related interference) was not overall higher in the high- than the low-cognitive-load condition (see Discussion of Experiment 4). On the other hand, the findings of Experiment 5, like those of Experiment 4, 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). This finding was significant only in the analyses of *incompatible-distractor total interference* (i.e., the combination of saliency-related and response-related interference). It appeared that the sensitivity of the method was increased by using a combination of *saliency-related* and *response-related* interference rather than either alone.

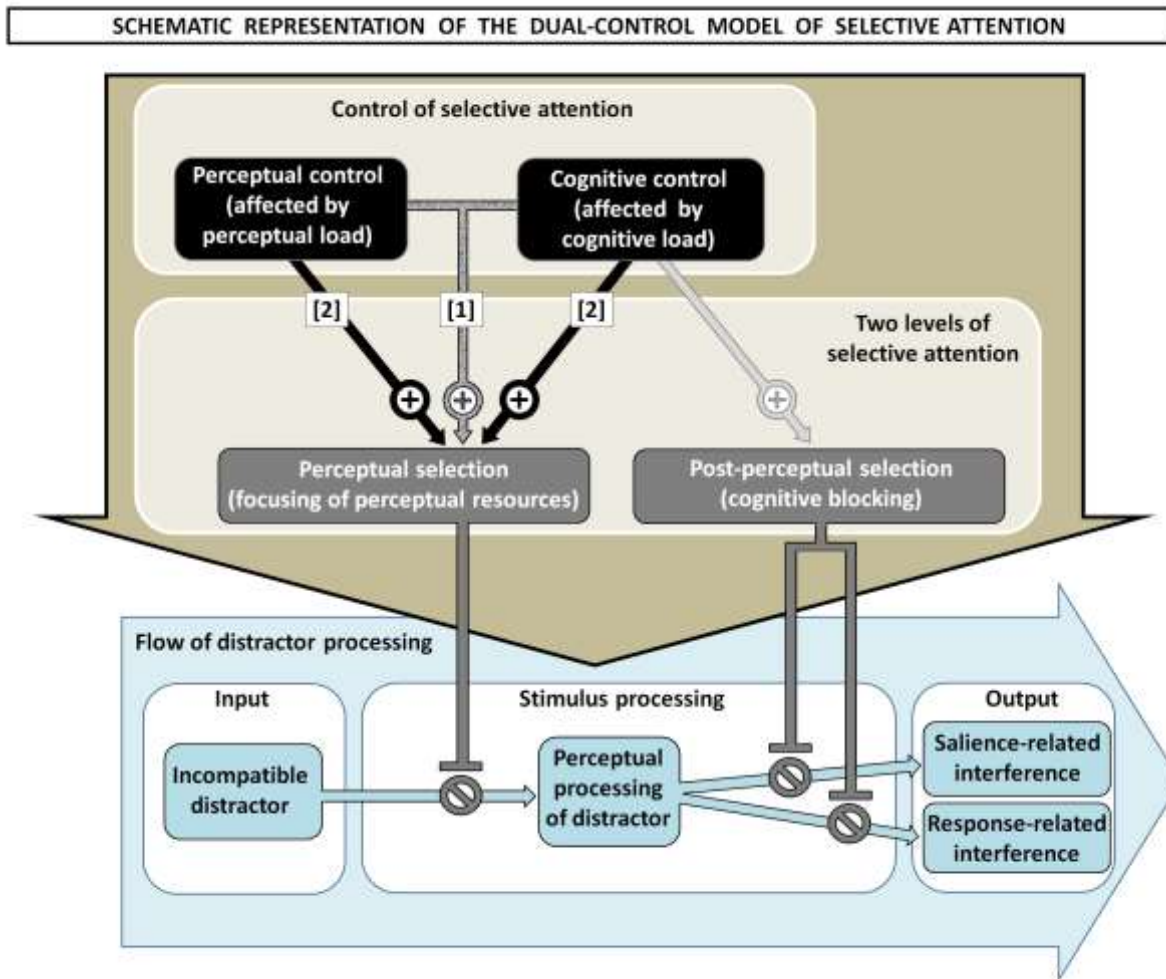
In conclusion, the results of Experiments 4 and 5 confirm that cognitive-control mechanisms are involved in the spatial focusing (and not only the orienting; see Discussion of Experiment 4) of perceptual resources.

## GENERAL DISCUSSION

The five experiments presented in this study produced the following main results:

- (a) distractor interference as a function of separation was found to describe a Mexican-hat pattern with (what we refer to here as) salience-related interference (Experiments 2 and 3; see Figures 3 and 6), response-related interference (Experiments 1, 2, 4 and 5; see Figures 2, 3, 11, 12 and 14), and a combination of salience-related and response-related interference (Experiments 4 and 5; see Figures 11, 12 and 14);
- (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; Experiment 3; see Figure 6);
- (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 4 and 5; see Figures 11, 12 and 14).
- (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 3; see Figure 8);

Our results have the following four implications. First, both distractor response-related interference (generated by a competition for response preparation) and distractor salience-related interference (generated by a competition for perceptual representation) reveal a Mexican-hat profile of perceptual resources when only the former has previously been found to do so (Müller et al., 2005). Second, increasing perceptual load does focus perceptual resources in space as shown with spatial-cueing 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 this study appear consistent with the view that selective attention operates at two different levels (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, 2005; Lavie & Fox, 2000; Lavie et al., 2004; MacDonald & Lavie, 2008; Maylor & Lavie, 1998; Paquet, 2001; Yi et al., 2004). These four implications are summarized in Figure 16 and are elaborated below.



**Figure 16**

**Figure 16.** A schematic representation of the dual-control model of selective attention. [1] = perceptual- and cognitive-control mechanisms affect the profile of perceptual resources through interactive effects; [2] = perceptual- and cognitive-control mechanisms affect the profile of perceptual resources through independent effects.

### Sampling the spatial profile of perceptual resources: paradigms and baselines

Numerous studies have addressed selective attention using paradigms based on Eriksen's flanker task. They have typically used the response-related interference from distractors to index the allocation of perceptual resources at the location of the distractor. This type of interference has been measured either by comparing the effect of incompatible distractors with that of compatible distractors (e.g., Anderson & Kramer, 1993; LaBerge et al., 1991; Lavie et al., 2004; Pan & Eriksen, 1993) or by comparing the effect of incompatible distractors with that of neutral distractors (Eriksen & St. James, 1986; Kramer et al., 1994; Lavie, 1995; Lavie & de Fockert, 2003; Yantis & Johnston, 1990). Both types of response-related interference have been measured as a function of separation to index the spatial profile of perceptual resources (Eriksen & St. James, 1986; McCarley & Mounts, 2008; Müller et al., 2005; Pan & Eriksen, 1993; Yantis & Johnston, 1990).

The present study confirmed that the profile of perceptual resources can be measured using response-related interference as a function of separation. In addition, it showed that another type of distractor interference typically disregarded in flanker studies, namely, salience-related interference, can be used to index this profile (consistent with previous findings; McCarley & Mounts, 2008). It was found that the Mexican-hat profile derived from salience-related interference as a function of separation was indistinguishable from that derived from response-related interference as a function of separation. It follows that response-related and salience-related interference (see Figure 16) can be used interchangeably to measure the profile of perceptual resources (see Experiment 2).

Nevertheless, it appears that, of the two types of interference, response-related interference is a more sensitive index of the profile of perceptual resources than salience-related interference. Indeed, while we have been able to show an effect of perceptual load on the profile of perceptual resources using just salience-related interference (see Experiment 3) and just response-related interference (Caparos & Linnell, 2009), we have been able to show an effect of cognitive load on this profile using just response-related interference but *not* just salience-related interference (see Experiment 4).

Even if response-related interference is a more sensitive index than salience-related interference, studies that measure the profile of perceptual resources by looking only at response-related interference arguably use a more blunt measure. Indeed, in Experiment 5, the effect of cognitive load on the focus of the profile of perceptual resources did not reach significance when using only response-related interference, but did when using the combination of both response-related and salience-related interference. Thus, by combining both types of interference into one measure (i.e., by using *incompatible-distractor total interference*, namely, by comparing incompatible-distractor performance with no-distractor performance), one obtains a more sensitive index of perceptual resources and, therefore, a more powerful tool for studying selective attention.

Note that using salience-related rather than only response-related interference of the distractors brings the flanker paradigm closer to the dot-probe, Posner spatial-cueing (Posner, 1980) and inattentional-blindness paradigms sometimes used to index the allocation of perceptual resources in space (e.g., Bahcall & Kowler, 1999; Cutzu & Tsotos, 2003; Downing, 1988; Handy et al., 1996; Hopf et al., 2006; Macdonald & Lavie, 2008). In these paradigms, a (task relevant or irrelevant) probe occurs at an unpredictable location and the probe detectability and access to awareness is used to index the allocation of perceptual resources.

### Effects of perceptual load on the extent of spatial focus of perceptual resources

This study confirmed using the flanker task that, under conditions of high perceptual load, perceptual resources become more spatially focused (see Figure 6; Downing, 1988; Handy et al., 1996; Williams, 1988). The focusing effect of perceptual load has been demonstrated using the spatial-cueing 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, 2005; Lavie & Fox, 2000; Lavie et al.,



2004; LaBerge, 1991). In fact, this study showed that drawing conclusions about the focus of perceptual resources using data from a single separation can be misleading. 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 Figure 6; Caparos & Linnell, 2009). This finding is currently not predicted by the widely cited perceptual-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 direction of 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) probably arose because the latter study used stimuli with higher perceptual load. Equally, 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. As a result, a Mexican-hat function would present as a gradient function. In fact, in another study (Caparos & Linnell, 2009), 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 describes a gradient. This adds load to the list of factors that have been proposed (Hopf et al., 2006; Mounts, 2000; Müller et al., 2005) 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, this study shows that perceptual load focuses perceptual resources in space. It also 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, this study 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 load conditions, it may be mistaken for a gradient.

#### Effects of cognitive-control mechanisms on the spatial focusing 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 stimulus (MacDonald & Lavie, 2008). The results of

Experiment 3 appear consistent with this suggestion: while individual differences in working-memory span (i.e., in the effectiveness of cognitive-control mechanisms; Engle et al., 1992; Engle, 2002; Kane & Engle, 2002) 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 8).

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 3 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 3, all participants had to do was to keep in mind the target template and task instructions).

Experiments 4 and 5 sought to overcome the above limitations by exerting strong demands on cognitive control with a calculation task (Experiment 4), or a difficult working-memory task (Experiment 5; as in MacDonald & Lavie, 2008, and Yi et al., 2004), 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 11, 12 and 14), thus providing evidence that cognitive-control mechanisms are after all involved in the focusing of perceptual resources and lending support to the study of Scerif et al. (2006; see Figure 16).

This effect of cognitive load on the focus of perceptual resources suggests that cognitive load may affect what we see. It has been proposed that when perceptual resources are spatially focused, individuated objects are likely to be perceived, whereas when they are defocused, the global properties of the scene will be more readily seen (Chong & Treisman, 2003; Treisman, 2006). Moreover, in conditions of defocused 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 then 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 Müller-Lyer that we have evidence depend on global 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).

## Visual selective attention operates at two different levels

Experiments 3 to 5 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 3 (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 16; Lavie et al., 2004; de Fockert et al., 2001; 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 3 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 8; 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 4 and 5 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.

## Do perceptual-load and cognitive-control effects 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, 2005; Lavie et al., 2004; MacDonald & Lavie, 2008) with resources being focused independently of any top-down regulation.

Yet, Experiments 4 and 5 showed that the focusing of perceptual resources is modulated by cognitive-control mechanisms (as indexed by the effect of cognitive load; see Figure 16), making it possible 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 (see [1] in Figure 16).

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 (see [2] in Figure 16). The function of such a cognitive mechanism might be to allow one to exclude irrelevant distractors even when perceptual load is *low*.

There exists a final possibility that, while perceptual and cognitive-control mechanisms are partially independent, they also exert interacting effects. These possibilities are currently being investigated in our laboratory. Our results will lead to a better understanding of the dual-control model of selective attention.

### Conclusions

In summary, this study used a modified version of Eriksen's flanker paradigm (Eriksen & Hoffman, 1972, 1973) to test the effect of perceptual and cognitive load on distractor interference. It used two dependent variables, namely, the distractor-interference function of separation and the amplitude of distractor interference across separations, 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). It produced the following four important results: (1) the spatial profile of perceptual resources is shaped like a Mexican hat (Müller et al., 2005; Caparos & Linnell, 2009); (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 16). According to this model, the focus of perceptual resources and what we see is modulated not only by perceptual but also by cognitive-control mechanisms. The neuroanatomical locus and timing of this cognitive control on perceptual selection is currently being investigated in our laboratory using manipulations modelled on those introduced in this study.

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