Load Induced Blindness

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Abstract

This thesis has established the effects of perceptual load and working memory load on the conscious awareness of an expected task-unrelated stimulus. Participants performed a visual search task, in which perceptual load was manipulated, while attempting to detect the presence of a meaningless task-unrelated figure, referred to as the critical stimulus (CS). The results showed a consistent reduction in CS detection rate and detection sensitivity (with no accompanying change in response criterion), when the search task was of high perceptual load, compared to a low perceptual load condition. Alternative accounts of the results in terms of memory failure rather than the absence of conscious awareness, the differential search task reaction times in the low and high conditions of perceptual load, goal-neglect, and strategy were ruled out. The effects of perceptual load were generalised to a CS presented directly at fixation, while demonstrating that detection performance was superior for fixated stimuli than for stimuli in peripheral vision, despite size-scaling to account for cortical magnification. Furthermore, the experiments established a dissociation between the effect of perceptual load and the effect of working memory load on conscious awareness, and a second dissociation between the effect of working memory load on awareness and its effect on distractor interference: whereas detection sensitivity and distractor interference were both reduced alike under high perceptual load, working memory load led to increased distractor interference but had no effect on detection sensitivity. Overall, the results generalised perceptual load theory (e.g., Lavie, 1995) to measures of conscious perception, and established a contrast between the effect of working memory load on awareness and on distractibility.

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Chapter 1

General Introduction

1.1 Preface

Although our visual experience of the world appears rich and detailed, it is nevertheless a common occurrence that clearly visible events can be overlooked when attention is directed elsewhere: a motorcyclist might fail to notice a crucial road sign when concentrating intensely on navigating through traffic; a footballer waiting at the penalty spot is unlikely to be aware of action in the stands behind the goal when faced with a critical penalty shoot-out.

These kinds of examples clearly illustrate the consequence of not paying attention. Nevertheless, a debate has raged among psychologists for fifty years over whether perception is dependent on attention. With this thesis I aim to contribute to this debate by testing the hypothesis that the level of perceptual load in a task determines whether task-unrelated stimuli will be registered in conscious awareness: whereas tasks of high perceptual load can prevent awareness of task-unrelated information, tasks of low perceptual load allow awareness of task-unrelated information in addition to that of the task itself. This hypothesis stems from the perceptual load theory of attention; however, previous tests of the theory have typically relied on indirect measures of the perception of task-unrelated stimuli, such as neural activity or the effect of their presence on task reaction time. Direct measures, i.e., those involving conscious awareness, have been used in only one study.

I begin this introductory chapter with a review of evidence from the selective attention literature, illustrating the debate between early and late selection views regarding whether attention determines conscious perception. I continue by outlining a possible resolution to this debate in the form of the perceptual load model and reviewing the supporting evidence. Finally, I describe and justify the methodology I have employed, a short summary of which follows.

The experiments in this thesis were designed to alleviate the confounds that have long been associated with the inattentional blindness paradigm. In doing so, they provide a more thorough test of the effects of perceptual load on conscious perception. Furthermore, the experimental design allowed the use of detection sensitivity (d') as a measure of conscious perception. The experiments described in the following chapters demonstrate the phenomenon I have termed 'load induced blindness', and examine the effects of various factors, in addition to perceptual load, including task priority, probability of occurrence, location uncertainty, strategy, retinal location and working memory load.

1.2 Early versus Late Selection

Do we perceive events to which we are not paying attention? Although this question is fundamental to understanding the relationship between attention and perception, the answer has remained elusive during a half century of research, during which time two contrasting theories have emerged: proponents of 'early selection' suggest that selective attention occurs early on in the perceptive process and therefore perception is limited to what is attended (e.g., Broadbent, 1958; Treisman, 1960, 1969); on the other side of the debate, 'late selection' theorists propose that perception of everything in the field of vision proceeds automatically, independent of attention, and that selective attention occurs afterwards, only affecting higher level processes such as response selection and memory (e.g., Deutsch & Deutsch, 1963; Driver & Tipper, 1989; Norman, 1968; Tipper, 1985). A resolution to this debate has proved elusive, since both sides have been able to draw upon a considerable amount of empirical evidence.

1.2.1 Dichotic Listening Experiments

Participants are typically asked to attend to one of two auditory channels of information selected on the basis of physical properties, such as the ear to which it is presented or the gender of the voice. For example, a stream of words presented to one ear is spoken aloud (shadowed) while a second stream of words presented to the other ear is ignored (e.g., Cherry, 1953). Participants recall very little of the unattended stream except for particularly salient words such as the participant's name (Moray, 1959), and fail to notice that a certain word was repeated many times, or even that the language being spoken had changed (Broadbent, 1958). This occurs despite the unattended stream being just as loud, clear and easily comprehensible as the shadowed stream.

These experiments led to the formulation of Broadbent's (1958) filter theory of attention, in which it is proposed that perception is a two stage process: in the first stage, the physical properties of all stimuli are extracted in parallel; in the second, limited capacity stage, higher level features such as the meaning of words are processed. In the case of multiple inputs, a filter (i.e., attention) protects the second stage from overload, allowing through only those stimuli having a particular physical property. Unattended information, therefore, is processed no further than its purely physical features.

The dichotic listening experiments were criticised, however, for employing retrospective measures of perception of the unattended stream (e.g., Deutsch & Deutsch, 1963), since participants may have perceived the semantic content of the unattended stream but simply forgotten it by the time the questions were posed a short while later. Treisman and Geffen (1967; and Treisman & Riley, 1969) attempted to provide a solution to this problem by instructing participants to shadow one channel and to stop shadowing and tap with a ruler when certain target words were heard in either of the two channels. Many target words in the unattended stream went unnoticed whereas those in the shadowed stream were nearly all detected, despite the use of an online measure of perception rather than a retrospective one precluding an explanation in terms of memory failure.

1.2.2 Selective Reading and Looking Experiments

Neisser (1969) developed an analogue of the dichotic listening paradigm in the visual domain, in which participants read aloud every other line of a text and ignored the lines in between. The findings were comparable to those of the dichotic listening experiments - very little of the content of the unattended lines of text could be reported later. This research was extended to non-verbal stimuli (Becklen & Cervone, 1983; Littman & Becklan, 1976; Neisser & Becklen, 1975) by showing two superimposed motion picture scenes and asking participants to attend exclusively to the action in one scene while ignoring the other. Participants consistently failed to report unexpected, yet highly conspicuous events in the unattended scene in so-called 'selective looking' experiments (an example of which is shown in Figure 1).

In a further line of evidence, Rock, Schauer, and Halper (1976) reported chance level recognition of unattended outline figures presented while participants performed an unrelated task. The experiment involved making aesthetic judgments of a stream of objects crossing the display, whilst ignoring a second, overlapping stream that moved in the opposite direction. Participants were unable to recognise items from the unattended stream in surprise recognition memory tests later on. Similar results were obtained with static images (Rock & Gutman, 1981): participants' attention was directed at one of two superimposed line figures differentiated by colour, either by explicit instruction or by performance of a task involving only one figure. In a subsequent, unexpected recognition memory test, only the attended figures were recognised above chance level.

Figure 1. A frame from the selective looking study of Becklen and Cervone (1983). Participants monitored one team of ballplayers (black or white t-shirts), and a woman with an umbrella appeared unexpectedly during the clip (pictured here at the centre of the playing area).

These experiments, however, suffered from the same criticisms as the corresponding dichotic listening experiments: the retrospective measures employed prevented the exclusion of the possibility that participants had forgotten the unattended information by the time it was queried, rather than not perceived it at the time it was presented.

1.2.3 Inattentional Blindness

There has been a recent resurgence of studies employing techniques similar to the selective looking paradigm. The earlier studies were criticised at the time because of the unnatural, degraded appearance of the action in the films that were used - a consequence of the superimposition of two semi-transparent sets of images. Recently, however, Simons and Chabris (1999) obtained similar results without superimposing two sets of images, by having both attended and unattended activity in the same film (see Figure 2).

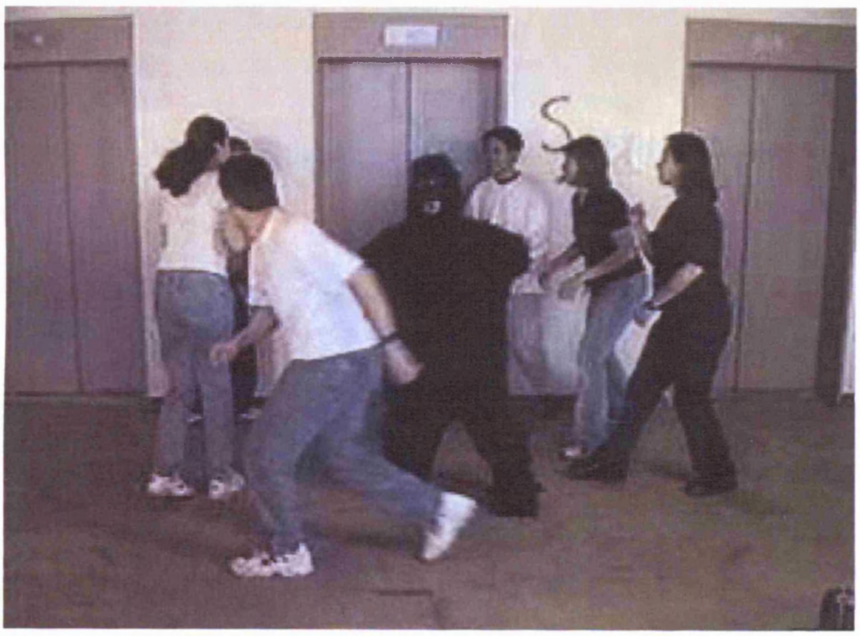

Figure 2. A frame from the film used by Simons and Chabris (1999). Participants were instructed to count passes of the ball by either the team in white or black t-shirts. Unexpectedly, a man in a gorilla suit walks across the shot, pausing momentarily to 'beat his chest'.

Interestingly, the complexity of the task participants performed correlated with awareness of the unattended event in this experiment, such that those performing a simpler task were significantly more likely to report it. This finding in particular strongly implicates the role of attention in determining conscious awareness of task-unrelated stimuli.

Computer-based experiments employing much simpler stimuli have yielded comparable findings. For example, Most and colleagues (Most, Scholl, Clifford, & Simons, 2005; Most, Simons, Scholl, & Chabris, 2000; Most et al., 2001) instructed participants to count the number of times that moving shapes of a certain colour ‘bounced’ off the sides of the screen, while ignoring moving shapes of another colour (see Figure 3).

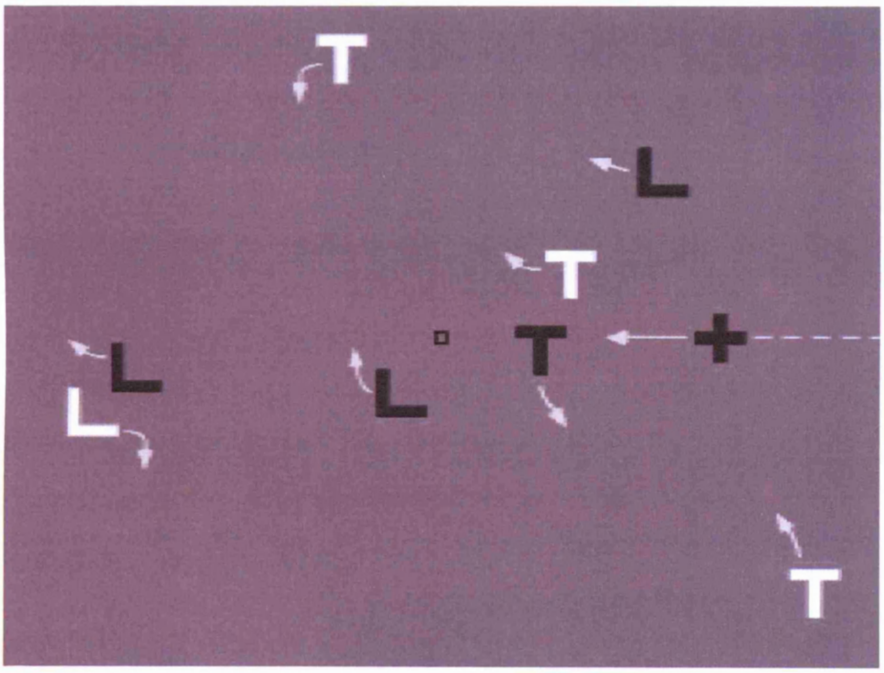

Figure 3. A frame from a typical sustained inattentional blindness paradigm (Most and colleagues). Participants kept count of the number of times either the black or white shapes 'bounced' off the edges of the display, while an additional, unexpected shape (here a black cross) crossed the display.

Reports of an unexpected but conspicuous cross-shape stimulus moving across the screen were infrequent, although its presence was almost always reported when there was no requirement to perform a task.

In a similar vein, Mack and Rock (1998) asked participants to judge whether the vertical or horizontal arm of a cross was longest, in a series of trials. On the final trial an additional stimulus was presented with the cross, and participants were subsequently asked if they had seen anything else in the display besides it (see Figure 4). A large proportion of participants failed to report having seen anything else in the display, despite being very likely to spot the additional stimulus when viewing the trial for a second time.

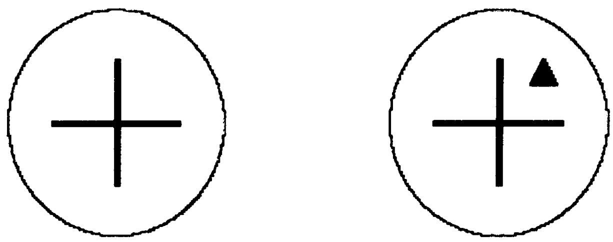

Figure 4. Examples of non-critical trial (left) and critical trial (right) displays in Mack and Rock's (1998) inattentional blindness paradigm. Participants judged whether the vertical or horizontal line of the cross was longer. Afterwards, they were asked if they noticed the presence of an unexpected, task-irrelevant stimulus (here a triangle).

1.2.4 Indirect Measures of Perception

Indirect measures of perception involve assessing the processing of unattended information through its effect on related attended information or on involuntary and unconscious responses to the unattended information itself. For example, Mackay (1973) demonstrated that words in the unattended stream could bias the interpretation of ambiguous shadowed sentences, and Lewis (1970), and also Underwood (1977) reported a delay in shadowing when words with a related meaning were presented simultaneously in the unattended stream. As another example, Corteen and Dunn (1974) detected a galvanic skin response when words previously conditioned with an electric shock were presented in the unattended stream. Since these studies demonstrate semantic processing of unattended stimuli, they can be taken as falsifications of Broadbent's (1958) filter theory and as evidence supporting the late selection view.

Further evidence for semantic processing of unattended information, and therefore late selection, comes from the classic Stroop (1935) experiments, in which participants were slower to report the colour of a word when the word itself was a contrasting colour, compared to when it was the same colour. The status of the Stroop effect as representing evidence of late selection, however, is thrown into doubt when it is considered that the unattended and attended information are different dimensions of the same stimulus. For that reason, it is unclear as to whether the unattended information can really be considered to be unattended. Indeed, when the two stimulus dimensions have been separated into two spatially distinct stimuli, i.e., a word and a patch of colour, studies have provided support for early selection (Kahneman & Henik, 1981), although others (Gatti & Egeth, 1978) have replicated the original Stroop task findings supporting late selection.

Many more studies in which the target and distractor stimuli are spatially separated have reinforced the late selection view of attention. Most notable of these is the response competition paradigm in which a task-irrelevant, but either response-congruent or -incongruent distractor is presented concurrently with a search display. Despite instruction to ignore such distractors, participants' reaction times are slower in the presence of incongruent distractors than congruent distractors, showing that the identity of the distractor had been processed and its association with the target response acknowledged (Eriksen & Eriksen, 1974; Flowers & Wilcox, 1982; Gathercole & Broadbent, 1987; Miller, 1987; Murphy & Eriksen, 1987).

Another noteworthy indirect measure of distractor processing providing evidence for the late selection view of attention is negative priming, which is the slowing of target reaction time when the target has previously appeared as a distractor. It has been proposed that negative priming supports late selection since it shows that the distractor must have been perceived and the subsequent response inhibited (Tipper, 1985). Negative priming persists even when the distractor is a picture and the targets are words (Tipper & Driver, 1988), indicating that the distractors are processed to a semantic level.

Not all studies employing indirect measures of unattended stimuli have yielded findings supporting late selection, however. Several experiments have demonstrated conditions under which a lack of interference from unattended distractors is observed. For example, when distractors are physically distinct from targets (Francolini & Egeth, 1980), or are located at a distance from targets (Eriksen & Hoffman, 1973), or when larger search set sizes are used (Miller, 1991; Navon, 1989), distractor perception has been shown to be reduced or eliminated.

There is considerable evidence, therefore, for both the early and the late selection view of attention, sometimes from the same paradigm and even the same experiment, leading some to suggest that the early and late selection debate may never be resolved (e.g., Allport, 1993). It must be pointed out, however, that no study employing direct measures of perception that I am aware of has ever supported the late selection view.

1.3 Perceptual Load Theory: A Possible Resolution

A possible resolution to the early or late selection debate has been suggested in the form of a hybrid 'perceptual load' model (Lavie, 1995; Lavie & Tsal, 1994). According to this model, focused attention on a task prevents perception of task-irrelevant stimuli (early selection), when the task processing requirements involve a high level of perceptual load that consumes all available attentional capacity. By contrast, when the task processing requirements involve low perceptual load, any spare attentional capacity spills over involuntarily, resulting in automatic perception of irrelevant stimuli (late selection).

Lavie and Tsal (1994) conducted an extensive examination of previous studies of selective attention and found that experiments supporting early selection typically involve high levels of perceptual load, such as large search set sizes (Miller, 1991; Navon, 1989). Conversely, experiments supporting late selection typically involve low levels of perceptual load, such as a search set size of one (Eriksen & Eriksen, 1974).

Similar attempts to resolve the early or late selection debate with the suggestion of a hybrid model were made by Kahneman and Chajczyk (1983) and Yantis and Johnston (1990) prior to Lavie's (1995; Lavie & Tsal, 1994) proposition. However, each of these models suffers from shortcomings that the perceptual load model overcomes: Kahneman and Chajczyk (1983) argue that the 'dilution' effect they report, supporting early selection, represents the serial allocation of attentional resources to a subset of the task-unrelated stimuli that were presented concurrently with the task stimulus. Later research, however, has shown that a parallel processing model fits the data better than a serial one (Yee & Hunt, 1991), and many investigators have concluded that a limited capacity model of attention may operate via a parallel process rather than serial (e.g., McLeod, 1977a; Townsend, 1971, 1974; Yantis & Johnson, 1990). Yantis and Johnston's (1990) hybrid model, on the other hand, fails to delineate the conditions that distinguish between situations in which attention can be focused, resulting in early selection, and those in which it is incompletely or ineffectively focused, resulting in late selection. Furthermore, Yantis and Johnston (1990) did not demonstrate both early and late selection within the same set of experiments as Lavie (1995, 2000; Lavie & Cox, 1997) has done. I describe these experiments next.

1.3.1 Behavioural Research Supporting Perceptual Load Theory

Response competition experiments have tested the effect of perceptual load on the influence of task-irrelevant distractors (Lavie, 1995; Lavie, 2000; Lavie & Cox, 1997). Typically, perceptual load is manipulated in a visual search task by varying the set size and a task-irrelevant but response-congruent, -neutral, or -incongruent flanker distractor is presented (example displays of high and low perceptual load are given in Figure 5). Under conditions of low perceptual load (e.g., set size one), search reaction times were slower in the presence of incongruent distractors than neutral or congruent distractors, suggesting that the identity of the distractor had been perceived. In the high perceptual load condition (e.g., set size six), such interference effects were eliminated: search reaction time was independent of distractor congruency. Further experiments made use of a go/no-go task in which task displays were identical, ruling out differences in the search displays as confounds of the effect of perceptual load.

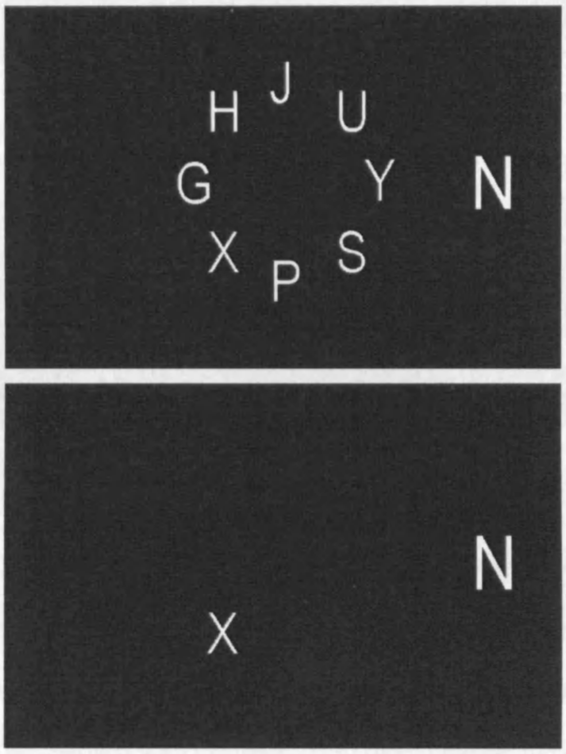

Figure 5. Examples of displays used by Lavie and colleagues. Participants made a forced-choice response to letter targets (X or N), which appeared either among seven non-target letters (high load, top picture) or with none (low load, bottom picture). An irrelevant distractor (congruent, neutral or incongruent [as here]) was presented concurrently in the periphery.

The effect of perceptual load has recently been replicated using pictures of real-world objects as distractors. Lavie, Ro, and Russell (2003) presented pictures of congruent or incongruent objects as flanker distractors in an object name categorisation task (fruit or musical instrument, see Figure 6), and found that interference effects from the distractor pictures were reduced when the perceptual load of the task was increased by adding non-word letter-strings to the displays.

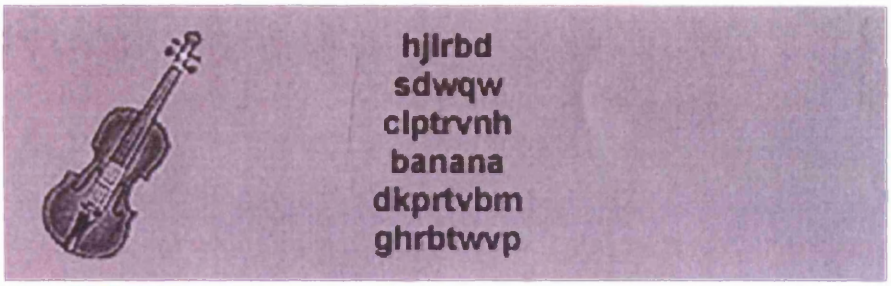

Figure 6. Example displays from Lavie et al. (2003). Participants classified a target word (politician or musician in the top picture; fruit or musical instrument in the bottom picture). In the low load condition the target word appeared alone; in the high load condition the target word appeared among five nonsense words (as in both examples here). The words were flanked by an object that was either congruent or incongruent with the target word (both here are the latter).

Perceptual load has also been found to modulate explicit recognition memory for faces. Jenkins, Lavie, and Driver (2005) reported that the level of perceptual load in a letter-string task (colour discrimination task for low load; letter search task for high load) determined participants' recognition memory performance for unfamiliar faces presented as irrelevant background distractors: under high perceptual load, recognition memory performance was poorer.

Beck and Lavie (2005), using the same manipulation of perceptual load as Lavie and Cox (1997), compared the response compatibility effects of distractors presented in the periphery with distractors presented directly at the point of fixation, and found that although fixation distractors exerted greater compatibility effects than peripheral distractors, increasing the perceptual load of a letter search task reduced the effects of distractors at fixation to the same extent as it reduced the effects of distractors in the periphery. Such a result suggests that the processing of information at fixation, despite being a higher priority, is subject to the same capacity limits as the processing of information elsewhere in the visual field.

Negative priming, the finding that responses to a target are slower when it has been previously presented as a distractor, has also been shown to be modulated by perceptual load (Lavie & Fox, 2000). When participants performed a search task of high perceptual load, the negative priming effect occurring under conditions of low perceptual load was eliminated. These results rule out active inhibition as an account of the effects of high perceptual load.

Such converging evidence showing the reduction of processing of task-irrelevant stimuli under high perceptual load supports the view that the availability of attentional capacity is the determinant of the perception of extraneous information.

1.3.2 Neuroimaging and Perceptual Load

In addition to the behavioural data, there is considerable support for the perceptual load model from neuroimaging research. Several studies have shown that perceptual load in a task modulates neural activity related to irrelevant distractors. For example, the perceptual load of a word task at fixation (monitor the word's case for low load; monitor the number of syllables for high load) determined the level of neural activity in V1, V2, and V5/MT associated with the presence of irrelevant motion distractors (Rees, Frith, & Lavie, 1997); activity in V4 in response to an unattended coloured stimulus was also reduced in the high perceptual load condition of a picture task in the contralateral hemi-field (Pinsk, Doniger, & Kastner, 2003); no neural activity related to ignored word distractors was observed while participants monitored a high load rapid stream of superimposed pictures for repetitions (Rees, Russell, Frith, & Driver, 1999), and similarly, reduced neural activity related to ignored pictures of places was found while monitoring a rapid stream of faces with added noise to render the task high load (Yi, Woodman, Widders, Marois, & Chun, 2004). Schwartz et al. (2005) reported that activity related to a task-irrelevant peripheral chequerboard stimulus was reduced while participants were performing a high perceptual load RSVP monitoring task compared to when the task was of low perceptual load with identical stimuli. This relative decrease was present in V1 and became larger for successive visual areas through to V4. Such attenuation of neural activity under high load conditions has even been found in the amygdala in response to emotional facial expressions, an area thought to be independent of attentional influence (Pessoa, McKenna, Gutierrez, & Ungerleider, 2002), and also in the lateral geniculate nucleus (O'Connor, Fukui, Pinsk, & Kastner, 2002), which is the earliest stage possible at which visual processing can be affected by higher order cognitive processes.

1.3.3 Perceptual Load and Conscious Awareness

Such converging evidence from behavioural and neuroimaging research strongly suggests that, as with indirect measures such as effects on reaction times, error rates and neural activity, subjective conscious awareness of extraneous information will be modulated by the level of perceptual load demanded by the task at hand. Whereas high perceptual load that engages full attention in the task should prevent awareness of irrelevant stimuli, low perceptual load will not exhaust capacity, resulting in a 'spilling-over' of awareness to include such stimuli. However, despite the focus of the theory on the extent to which task-irrelevant stimuli are perceived, in nearly all previous studies the conclusions about irrelevant stimulus processing are based upon indirect measures of perception, such as effects on target reaction times (RTs) or neural activity. Thus, although these studies demonstrate that the processing of task-irrelevant stimuli is determined by the level of perceptual load of task processing, in general support of load theory, they do not provide any evidence in support of the claim that perceptual load should determine conscious awareness. Specifically, the effects of perceptual load on neural activity related to task-irrelevant stimuli can not support any direct conclusions about conscious perceptual experience. Indeed Bahrami, Lavie, and Rees (2007) have recently shown that perceptual load can modulate V1 activity related to an invisible irrelevant stimulus that the participants did not consciously perceive. The effects of distractors on target reaction times in the behavioural experiments also can not support any direct conclusions about conscious perception since one can not deduce whether a participant was conscious of the distractors or not on the basis of their RT to the target. Indeed, the RT results can be construed either way. If the participants had never been conscious of the distractors in either of the load conditions then their effects on target RTs under conditions of low load can be explained by unconscious processing of stimulus-response associations. Conversely, if the participants had always been conscious of the distractors in both of the load conditions then the elimination of the distractor effects on target RTs under high load could be the result of post-perceptual response selection processes, although the argument that distractor RT effects may have simply dissipated during the longer RTs in high load tasks is ruled out by the fact that manipulations that increase task difficulty, and consequently RTs, without increasing perceptual load, e.g., working memory load (Lavie, 2000; Lavie et al., 2004) or stimulus degradation (Lavie & De Fockert, 2003), increase distractor effects rather than decrease them. While this body of research, therefore, provides convincing evidence that perceptual load determines neural activity related to task-irrelevant stimuli and the extent to which distractors interfere with task performance, it does not provide an answer to the question of whether the conscious awareness of task-irrelevant stimuli is affected by perceptual load.

1.3.4 Inattentional Blindness and Perceptual Load

Only one experiment so far has tested the effect of perceptual load on subjective conscious awareness. Cartwright-Finch and Lavie (2007) recently investigated the effects of perceptual load on awareness reports with the inattentional blindness paradigm. In a series of experiments, they found that the number of participants who reported being aware of a task-irrelevant stimulus presented unexpectedly was strongly dependent on the level of perceptual load of the task performed. Tasks of high perceptual load (the discrimination of cross arms of very similar length or visual search for a letter among similar non-target letters) yielded a considerably lower rate of awareness reports (typically around 40-50%), compared with tasks of low perceptual load (the discrimination of cross arms of very different length or colour, or visual search for a letter among very dissimilar non-target letters). This study conclusively demonstrates that high perceptual load is far more likely to produce inattentional blindness than low perceptual load. However, this study suffers from the limitations of the inattentional blindness paradigm that I describe next.

1.4 Criticisms of Inattentional Blindness

Two major criticisms have been levelled at the inattentional blindness paradigm. One concerns expectation and the other memory.

1.4.1 Expectation

With the inattentional blindness paradigm, the critical stimulus is not only unattended, but also unexpected. Inattention is therefore confounded with expectation and so the reduction in awareness may be caused by a lack of expectation rather than a lack of attention. Neisser and colleagues argued this point in their early work on selective looking (e.g., Neisser, 1979; Neisser & Becklen, 1975). A failure to expect or anticipate a stimulus might lead to 'blindness', since stimuli near threshold typically require a degree of familiarity to be consciously perceived (Braun, 2001). The same could theoretically be true for the supra-threshold stimuli used in the inattentional blindness paradigm.

Some studies avoid being confounded by expectation by comparing inattentional blindness under different conditions; for example, Cartwright-Finch and Lavie (2007) show that inattentional blindness is more likely under high perceptual load than low, instead of simply contrasting rates of inattentional blindness in the unattended trial with rates in a control trial in which the previously unattended extra stimulus is now anticipated (e.g., Mack & Rock, 1998). However, the conclusions of such studies are nevertheless limited to the case of surprise events.

1.4.2 Memory

Wolfe (1999) proposed the 'inattentional amnesia' hypothesis to explain the phenomenon of inattentional blindness. In the majority of inattentional blindness studies, participants are questioned a relatively long time after the offset of the stimulus and after the dissipation of the iconic representation. Rather than having not seen the irrelevant stimulus, therefore, participants may have simply forgotten it had been there.

A different account of inattentional blindness involving memory is that rather than the failure of awareness being the consequence of having forgotten something that was consciously seen, the failure is attributed to the object having never been encoded into memory in the first place (Moore, 2001; Moore & Egeth, 1997). Also, as both the presence of the extra stimulus and its physical appearance (e.g., colour, shape and location) are unexpected, it is possible that the extra stimulus is perceived, but only generates a weak signal (Barber & Folkard, 1972; Bashinski & Bacharach 1980; Davies, Kramer, & Graham, 1983; Teichner & Krebs, 1974) that is easily wiped out of memory with the delay incurred by the task response and the processing of the surprise question. The effects of perceptual load on awareness reports in the inattentional blindness paradigm may then, at least in part, reflect reduced encoding of the unexpected stimulus into memory instead of, or in addition to, reduced perception.

These two major confounds, expectation and memory failure, have persistently been proposed as alternative explanations of the findings of older selective looking and dichotic listening experiments, and more recent inattentional blindness studies alike, and have never been convincingly ruled out.

1.5 General Methodological Approach and Overview

The experiments in the following chapters examine the effects of perceptual load on conscious perception with a modified inattentional blindness paradigm in which the presence of a critical stimulus (CS) was expected in some of the trials. Furthermore, examples of the exact stimulus to be presented were shown, so that its visual appearance was known in advance, and participants completed a block of practice trials before starting the experiment. Thus, perception of this critical stimulus could be measured online, with responses occurring straight after the task response, or even immediately upon presentation (i.e., before the perceptual load task response, see Experiment 4). Since the irrelevant stimulus was fully anticipated and participants could respond to it immediately, this method rules out both the expectation and memory accounts of the inattentional blindness paradigm. Results showing a lower rate of detection of the critical stimulus with high perceptual load will therefore provide stronger evidence for the notion that attention is a prerequisite of conscious awareness. Furthermore, with the inattentional blindness paradigm there was no way to assess detection sensitivity as the CS was always presented just once. Since here the CS is presented multiple times, the effects of perceptual load on detection sensitivity (as distinct from response criterion) could be assessed. It follows directly from perceptual load theory that detection sensitivity for task-irrelevant stimuli will be reduced under conditions of high perceptual load, although this prediction has not, as yet, been tested.

It is important to note that although this prediction is directly derived from perceptual load theory, it contradicts the traditional view that early perceptual processes such as detection are capacity-free, and hence do not depend on the allocation of attention (Braun & Sagi, 1990; 1991; Posner & Boies, 1971; Shaw, 1984). This notion has typically been tested in experiments comparing detection and discrimination performance under single versus dual-task conditions. The comparison of single and dual-task conditions, however, is confounded by non-attentional processes such as making an additional response (only in the dual-task condition) and memory (due to the delay caused by making the first task response in the dual-task condition alone). In contrast, the test I have designed to determine whether detection sensitivity is governed specifically by the level of perceptual load (rather than general task difficulty, see Chapter 6) makes use of a task that remains the same in all respects (including the number of responses and the length of time that task decisions must be held in memory), apart from the perceptual load of the search task. This research, therefore, not only elucidates the role of perceptual load in conscious awareness, but also resolves the important issue of whether early perceptual processing, involving mere presence or absence detection, is subject to capacity limits.

Chapter 2 presents a demonstration of load induced blindness using the methodology I have introduced while ruling out accounts of the results in terms of the RT differences between the conditions of perceptual load. The experiments in Chapter 3 preclude accounts of the results in terms of goal-neglect, the priority of detection, memory failure and high CS location uncertainty. This was achieved by employing four different manipulations that each raise the priority of the detection task: making the detection response first, increasing the probability of CS presentation, introducing the requirement that a response is made even when the CS is absent so that a detection response is made on every trial, and reducing the number of locations in which the CS can appear. Chapter 4 addresses concerns regarding whether participants employ separate strategies in the different conditions of perceptual load by measuring load induced blindness when low and high perceptual load trials are intermixed within blocks. In Chapter 5, I investigate whether the retinal location at which the CS is presented affects detection, specifically comparing the fovea with peripheral locations. In addition, I examine whether perceptual load reduces detection sensitivity when the CS is presented at the fovea. The final issue I consider, in Chapter 6, is the effect of working memory load on detection. Recent studies of perceptual load theory have looked at how loading working memory can affect perception. Such studies have shown that working memory load has the opposite effect to perceptual load, but so far the assessment of the perception of task-unrelated stimuli has been limited to indirect measures such as RTs and neuroimaging. It is therefore important to test the effect of working memory load on conscious awareness.

Chapter 2

The Role of Perceptual Load

The experiments in Chapter 2 sought to establish the effect of perceptual load on the detection of a task-unrelated stimulus. Perceptual load theory proposes that perception of such a stimulus depends upon whether attentional capacity is exhausted by the perceptual demands of a concurrent task: the stimulus is perceived if task demands on attention are minimal; it will not be perceived, however, if attending to the task fully loads capacity. Hence, detection of the CS should suffer while participants are simultaneously performing a task of high perceptual load. By contrast, when the task is of low perceptual load, detection of the CS should be reliable since there is sufficient capacity available to perceive both the task stimuli and the CS.

2.1 Experiment 1

Participants were presented with a circle of letters on each trial and asked to search for either of the target letters X or N. They were also asked to detect a small, meaningless grey figure, referred to hereafter as the critical stimulus (or CS), that was presented outside of the letter circle. Example trials with the CS presented were shown at the start of the experiment. Perceptual load was manipulated by varying the target--non-target similarity in the circle of letters (e.g., Lavie & Cox, 1997). In the high perceptual load condition the non-target letters were H, K, M, W and Z, making this condition a set size 6 search task. In the low perceptual load condition the non-targets were all O's and were considerably smaller than the target letter: they can therefore be considered as place-holders rather than non-targets, rendering the low perceptual load condition effectively a set size 1 search task.. The experimental blocks were followed by a control block of trials in which the participants were asked to not perform the letter search task and just detect the presence of the CS. The search displays were the same as those in the experimental blocks. Any participant with a CS detection rate of lower than 75% in the control block was excluded.

2.1.1 Method

Participants. Sixteen participants were recruited at University College London (UCL) and were paid for their participation (the rate of pay was £6 per hour for all the experiments reported). One participant was excluded and replaced because her accuracy on the letter search task was under 65%, three because they detected less than 75% of the critical stimuli in the control block, and two because their false alarm rate in the control block was over 40%. The age range of those included was 19 to 35 years (M = 22.5 years, SD = 3.8 years) and there were four men. All of the participants had normal or corrected-to-normal vision and were naïve to the purposes of the experiment.

Apparatus and Stimuli. The experiments were created and run with E-Prime (Psychology Software Tools, Inc., 2003) on a Dell PC attached to a Sony 15" monitor. A viewing distance of 57 cm was maintained throughout the experiment with a chin rest. Six letters were presented equally spaced (nearest contours 0.95° apart), in a circle of 1.7° radius that was centred at fixation. The background of the display was mid-grey (RGB values: 204, 204, 204), the CS was a darker grey (RGB values: 153, 153, 153) and the letters were black. For a mask, a black mesh pattern covered the whole screen except for a square (9.5° by 9.5°) in the centre so as not to mask the circle of letters. The target letter, a capital letter X or N (0.6° by 0.6°), each equally likely, appeared at random but with equal probability at one of the six letter locations. The remaining five locations were occupied in the low perceptual load condition by smaller letter O's (0.2° by 0.2°) and in the high perceptual load condition by the letters H, K, M, W and Z (of the same size as the target letter). The CS, a grey meaningless shape (0.3° by 0.3°), was presented at one of six equally spaced locations arranged in a circle of radius 5.4°. Each CS location lay on an imaginary line that passed through the fixation point and bisected two adjacent letter locations.

The combinations of target letter location and CS location were counterbalanced, so that for each target letter location the CS was presented once in each of four locations, the two nearest locations to the target letter (one on either side) and the two farthest locations. The stimuli were presented in two blocks of 72 trials with the CS presented in 12 randomly selected trials per block (17%). It appeared twice in each of the six locations forming the imaginary circle, consisting of, for each target location, once in one of the two near-target letter locations (and in the other near location in the other block) and once in one of the two far locations (and in the other far location in the other block). A counterbalanced set of 144 different stimulus displays consisted of each of the target letters (two: X or N) in each of the letter circle locations (six), either without or with the CS in each location (six), and its location relative to the target (two: near or far). In the high perceptual load condition there were also 144 randomly selected non-target arrangements. The control block used half of the displays from the first experimental block and half from the second, such that the CS still appeared twice at each of the six locations.

Procedure. A schematic of the procedure of Experiment 1 is shown in Figure 7. A fixation dot was presented at the centre of the screen for 1 s at the start of each trial, followed by the search task display for 100 ms (which included the

CS in 17% of the trials). A mask was then presented for 500 ms and subsequently a blank screen that lasted for 2.1 s, during which participants made the search task response followed by the CS detection response. This 2.7 s interval elapsed whether any responses were made or not. The participants were instructed to make the search task response as quickly and as accurately as possible, and if they detected the CS, to make the detection response immediately following the search task response. Participants pressed the '0' key with their thumb for the target 'X', and the '2' key with their forefinger for the target 'N', using the numeric key pad with their right hands. Detection of the CS was indicated by pressing the 'S' key with the forefinger of the left hand. If no response or an incorrect response to the search task was made, a 'beep' was heard at the end of each trial. There was no feedback for detection.

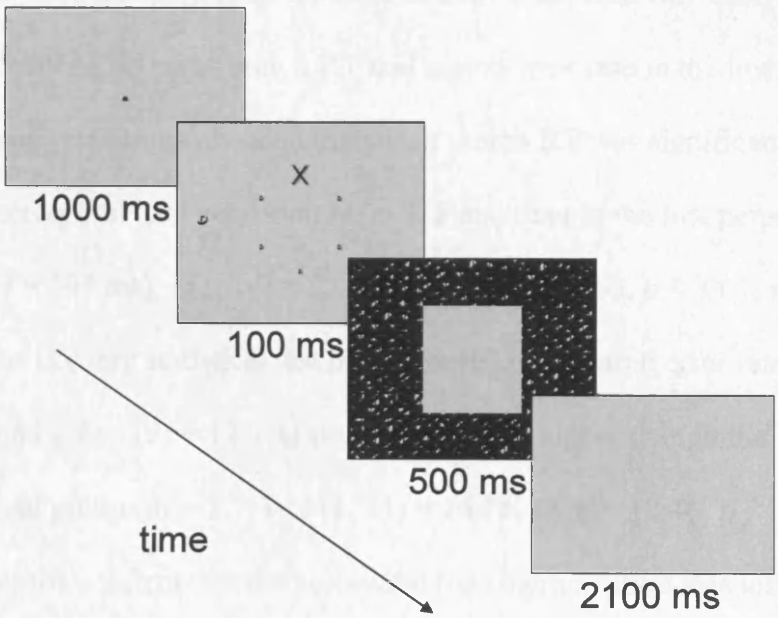

Figure 7. A schematic of the procedure of Experiment 1.

Before starting the experiment, the participants were shown nine example trials with no CS followed by six example trials with the CS. During each of these the participant confirmed verbally whether she had seen the CS or not, and they were repeated for participants who failed to see the CS at least three times. Each participant then completed two experimental blocks of 72 trials, both of the same level of perceptual load (low for half of the participants, high for the other half), followed by a control block of 72 trials (including 12 CS trials), in which participants were instructed to respond to the presence of the CS but to ignore the circle of letters.

2.1.2 Results and Discussion

Letter Search. Trials in which the search response was incorrect (see mean error rates) and those in which reaction time (RT) was greater than 1.5 s (M = 2.2% of correct trials per participant in Experiment 1) were excluded from the RT analyses in all of the experiments reported in this thesis. One way analyses of variance (ANOVA) on mean search RT and search error rate in the low and high perceptual load conditions revealed that mean search RT was significantly longer in the high perceptual load condition (M = 818 ms) than in the low perceptual load condition (M = 564 ms), $F(1, 14) = 23.99$, $MSE = 10{,}718.63$, $p < .001$, $\eta_p^2 = .63$ (two tailed, as is every statistical test in this thesis), and search error rate in the high perceptual load group (M = 12.9%) was significantly higher than in the low perceptual load group (M = 3.7%), $F(1, 14) = 26.74$, $MSE = 12.46$, $p < .001$, $\eta_p^2 = .66$. These results confirm that the perceptual load manipulation was effective.

CS Detection. Percentage detection rate and false alarm rate, *d'* (a measure of detection sensitivity that incorporates both detection rate and false alarm rate), and β (a measure of response criterion that represents the relative proportions of present and absent responses) were calculated for each participant, excluding any trials in which the search response was incorrect. The means of these are shown as a function of perceptual load in Table 1.

Table 1. Mean (and Standard Deviation) Percentage Detection and False Alarm Rates and Mean (and Standard Deviation) *d'* and β as a Function of Perceptual Load in Experiment 1.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	97.2 (3.4)	0.6 (1.0)	4.27 (0.34)	4.99 (3.76)
High	55.8 (36.4)	1.9 (4.7)	2.44 (1.31)	11.01 (8.34)

One way ANOVA indicated that detection rate was significantly lower in the high perceptual load condition than in the low perceptual load condition, $F(1, 14) = 10.38$, $MSE = 667.67$, $p = .006$, $\eta_p^2 = .43$, and that *d'* in the high perceptual load condition was also significantly lower than that in the low perceptual load condition, $F(1, 14) = 14.60$, $MSE = 0.92$, $p = .002$, $\eta_p^2 = .51$. β was not significantly different between the low and high load conditions, $F(1, 14) = 3.45$, $MSE = 41.87$, $p = .084$, $\eta_p^2 = .20$, despite a trend for a more stringent criterion in the high load.

Since the search task error rate was higher in the high perceptual load condition than in the low load condition, there were more critical trials excluded from the analysis in the high load condition ($M = 3.6$ out of 24 excluded [15.0%]) than in the low load condition ($M = 1$ out of 24 excluded [4.2%]). However, even when the incorrect search task trials were included in the analysis, detection rate and *d'* were still significantly lower in the high perceptual load condition (*M* detection rate = 54.2%, *M d'* = 2.45) than the low load condition (*M* detection rate = 96.4%, *M d'* = 4.21), $F(1, 14) = 11.03$, $MSE = 651.35$, $p = .005$, $\eta_p^2 = .44$ and $F(1, 14) = 13.71$, $MSE = 0.91$, $p = .002$, $\eta_p^2 = .50$ for detection rate and *d'*, respectively. Furthermore, β remained unaffected by perceptual load, $F(1, 14) = 3.83$, $MSE = 50.43$, $p = .071$, $\eta_p^2 = .22$.[1]

The distance between the search task target letter and the CS (coded as either 'near' or 'far') had a small but non-significant effect on detection rate (near $M = 78.7\%$; far $M = 74.4\%$), $F(1, 14) = 1.90$, $MSE = 78.34$, $p = .190$, $\eta_p^2 = .12$, and there was no interaction of distance and perceptual load, $F < 1$, in a two way ANOVA on detection rate with load and distance as factors (this analysis could not be performed for *d'* or β since it was not possible to assign false alarm responses to distance conditions).[2]

CS detection performance in the control block, during which participants did not perform the letter search task, was equivalent in the low (M detection rate = 96.9%, M false alarm rate = 0.4%, $M\ d' = 3.92$, $M\ \beta = 4.82$) and high (M detection rate = 99.0%, M false alarm rate = 3.3%, $M\ d' = 3.61$, $M\ \beta = 2.10$) perceptual load conditions, $F < 1$ for detection rate, $F(1, 14) = 2.68$, $MSE = 0.14$, $p = .124$, $\eta_p^2 = .16$ for *d'*, and $F(1, 14) = 6.04$, $MSE = 5.10$, $p = .028$, $\eta_p^2 = .30$ for β.[3] This significant difference in β indicates that participants in the high load condition had a more liberal criterion in the control block than those in the low load condition,

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[1] This extra analysis was performed for all the experiments in this thesis, and in every case the outcome was the same: whether the incorrect search task trials were included or not made no difference to the effect of perceptual load, whether on detection rate, *d'*, or β.

[2] The results of this analysis were the same for all the experiments in this thesis, therefore distance effects are not reported for any further experiments.

[3] These analyses on detection rate, *d'*, and β in the control block were repeated for each experiment in this thesis, and they did not reveal any significant differences other than here and in Experiment 6. They are therefore not reported for any further experiments except for Experiment 6.

which can be observed in their higher mean detection and false alarm rates. This may have been due to their experience of detecting the CS during the experimental blocks having been that much more difficult than for those in the low perceptual load condition. Nevertheless, clearly the lower detection rate and detection sensitivity in the high perceptual load experimental blocks was related to the actual performance of the search task, rather than just the appearance of the display, since detection rate and detection sensitivity were comparable in the low and high perceptual load conditions when participants did not have to perform the search task while attempting to detect the CS.

These findings represent preliminary evidence for the hypothesis that the level of perceptual load in a task dictates whether task-unrelated stimuli are detected or not. Whereas nearly all of the CS (M = 97.2%) were detected during a task of low perceptual load, this rate was reduced dramatically to approximately half (M = 55.8%), on average, for participants performing a task of high perceptual load. The results demonstrate that the availability of attention, here manipulated by the level of perceptual load in a letter search task, is critical for conscious perception of additional, task-unrelated stimuli.

2.2 Experiment 2

In Experiment 1, the mean search RT for the high perceptual load search task was about 250 ms longer than that for the low load search task. Since in Experiment 1 there was a single interval of 2.7 s in which to make the search task response followed by the CS detection response, the longer search RT in the high load condition left less time remaining to make the CS detection response compared to the low load condition. It is therefore possible that at least some of the misses in the high load condition were in fact very slow CS detection responses that were made after the 2.7 s interval had elapsed. In addition, the slower search task responses in the high load condition led to a longer delay between CS presentation and CS response in the high load than low load, and therefore the results could be explained in terms of a greater likelihood of memory failure in the high load condition.

In order to examine the effects of perceptual load on detection with an equal interval for detection responses in the low and high perceptual load conditions, and an equal delay between CS presentation and CS detection response, in Experiment 2 the presentation of the stimuli was followed by a fixed 2 s interval for the search response, and then another fixed 2 s interval for the CS detection response. Each interval elapsed regardless of whether a response was made or not.

Participants were told that they should make the search response as soon as possible following the display of stimuli, and then make the CS detection response upon the appearance of a question mark at the start of the second 2 s interval. With this procedure, the length of time available for making the CS detection response was longer than before and, most importantly, was identical in the two conditions of perceptual load. The interval between CS presentation and response was also now equal. A replication of the perceptual load effect on CS detection in Experiment 2 would therefore allow alternative explanations in terms of very slow detection responses or memory failure to be ruled out.

2.2.1 Method

Participants. Sixteen new participants were recruited from UCL and were paid for their participation. One was replaced because he detected less than 75% of the CS in the control block. The age range of those included was 18 to 34 years (M = 24.9 years, SD = 4.4 years) and there was one man.

Stimuli and Procedure. A schematic of the procedure of Experiment 2 is shown in Figure 8. The apparatus, stimuli, and procedure were the same as Experiment 1, except that the participants were instructed to withhold the detection response until the appearance of a question mark that was presented 2 s after the onset of the stimuli. This question mark was presented at the centre of the screen for 100 ms and was followed by a blank screen for a further 1.9 s. Both 2 s intervals elapsed regardless of whether a response was made or not.

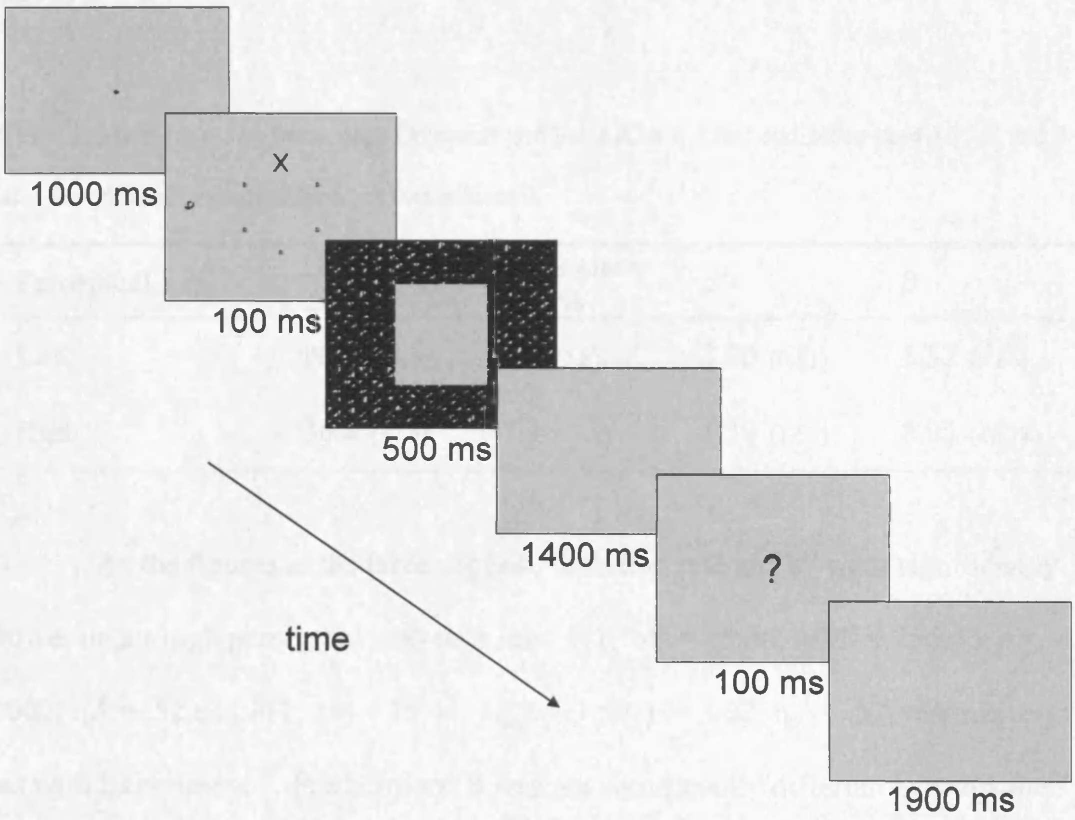


Figure 8. A schematic of the procedure of Experiment 2.

2.2.2 Results and Discussion

Letter Search. As with Experiment 1, mean search RT was significantly longer in the high perceptual load condition (M = 766 ms) than the low perceptual load condition (M = 593 ms), $F(1, 14) = 8.68$, $MSE = 13{,}742.09$, $p = .011$, $\eta_p^2 = .38$, and search error rate in the high perceptual load condition (M = 10.6%) was significantly higher than in the low perceptual load condition (M = 3.0%), $F(1, 14) = 58.27$, $MSE = 3.99$, $p < .001$, $\eta_p^2 = .81$. Hence perceptual load was successfully increased with the manipulation of search set size in Experiment 2.

CS Detection. Mean percentage detection and false alarm rates, and mean *d'* and β for correct search trials only as a function of perceptual load are presented in Table 2.

Table 2. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 2.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	90.0 (21.5)	2.5 (2.8)	3.70 (0.81)	5.52 (9.86)
High	36.8 (32.6)	7.9 (13.9)	1.30 (1.53)	8.95 (10.78)

As the figures in the table suggest, detection rate and *d'* were significantly lower under high perceptual load than low, $F(1, 14) = 15.06$, $MSE = 756.46$, $p = .002$, $\eta_p^2 = .52$ and $F(1, 14) = 15.44$, $MSE = 1.50$, $p = .002$, $\eta_p^2 = .52$, respectively, as with Experiment 1. Furthermore, β was not significantly different between the low and high load conditions, $F < 1$.

Experiment 2 therefore replicated the effect of perceptual load on CS detection found in Experiment 1, even though there was now more time available in both the low and high perceptual load conditions to make the detection response, and, most importantly, this longer interval was of equal duration in the two conditions and was independent of search RT. The effect of perceptual load on detection can therefore not be attributed to a larger number of very slow detection responses occurring after the interval had elapsed in the high load condition. Furthermore, the delay between CS presentation and when the CS response could be made was now fixed, and was therefore equal in the low and high perceptual load conditions, precluding an explanation of the results in terms of a greater likelihood of memory failure due to a longer delay in the high load condition.

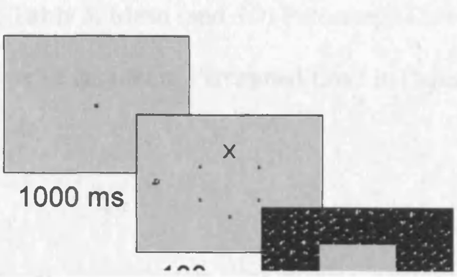
2.3 Experiment 3

In Experiments 1 and 2, the manipulation of perceptual load was validated by the fact that mean search RT in the high load condition was longer than that in the low load condition. However, since in Experiment 2 the interval for the search response always elapsed, there would have been less time remaining following the search response before the detection response was made in the high load condition. It is therefore possible that decision and response preparation processes related to CS detection were at a disadvantage in the high perceptual load condition, and this may have produced the reduction in detection rate and sensitivity. To rule out this possibility, it was necessary to assess the effect of perceptual load on CS detection in a design in which the RT for the letter search task was equal in the low and high perceptual load conditions, so that the interval between the search response and the detection response would also be equal. In Experiment 3, therefore, the participants were forced to wait until 2 s after the presentation of the stimuli before responding to the search task. I anticipated that this delay would equate search RT in the low and high load conditions. Unless the effect of perceptual load was due to the shorter time available in the high load to prepare for the detection response, the results of Experiment 3 should replicate those of Experiments 1 and 2.

2.3.1 Method

Participants. Sixteen new participants were recruited from UCL and were paid for their participation. One participant was replaced because her accuracy on the letter search task was lower than 65%, three because they detected less than 75% of the critical stimuli in the control block, and one because his mean search RT was over two standard deviations above the group mean. The age range of those included was 19 to 28 years (M = 23.5 years, SD = 3.3 years) and there were four men.

Stimuli and Procedure. A schematic of the procedure of Experiment 3 is shown in Figure 9. The apparatus, stimuli, and procedure were the same as Experiment 2 except that the participants were instructed to make their response to the search task 2 s after stimulus onset, at which point 'X/N?' was presented at the centre of the screen for 100 ms. This was followed by a 1.9 s blank screen, during which time the participants made the search response. Immediately following the search response, a question mark was presented at the centre of the screen for 100 ms, indicating that the detection response should now be made. Participants were allowed 2 s to make the CS detection response, and the next trial began either after their response or after the 2 s had elapsed.



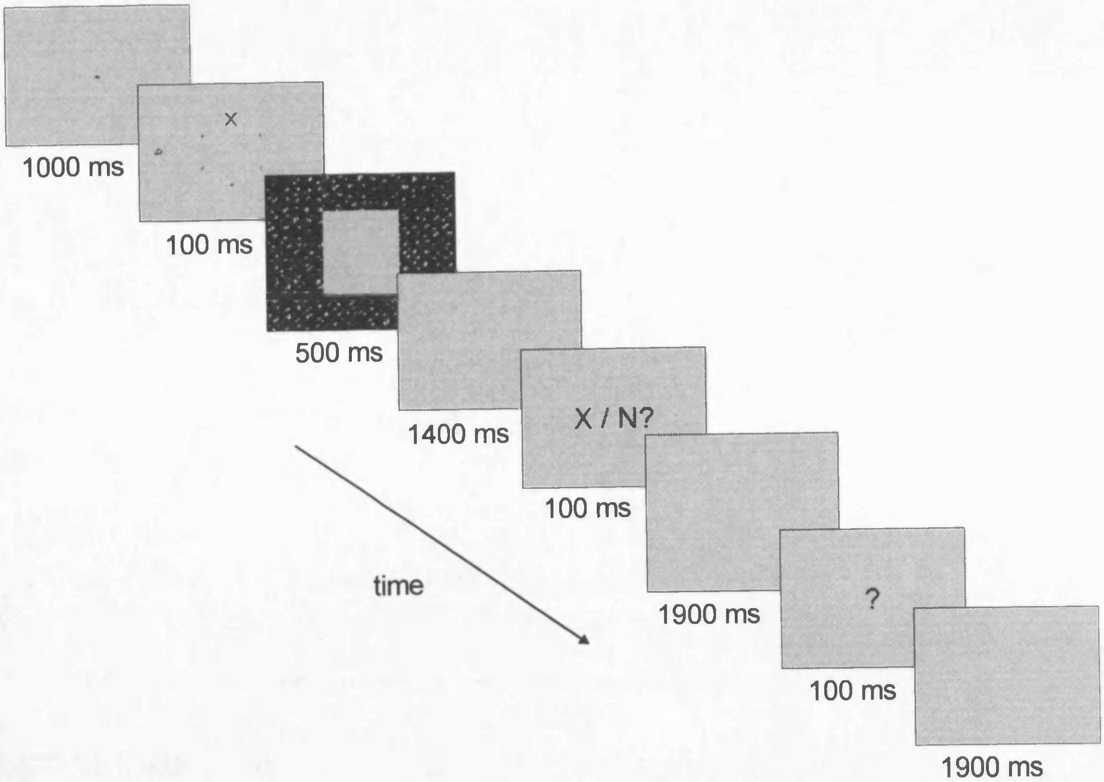


Figure 9. A schematic of the procedure of Experiment 3.

2.3.2 Results and Discussion

Letter Search. As predicted, with the 2 s delay of the search response there was no longer a difference in mean search RT between the high (M = 337 ms) and the low (M = 335 ms) perceptual load conditions, $F < 1$. The error rate in the high perceptual load condition (M = 20.7%) was, nevertheless, significantly higher than in the low perceptual load condition (M = 3.1%), $F(1, 14) = 31.38$, $MSE = 39.60$, $p < .001$, $\eta_p^2 = .69$, demonstrating that, despite the comparable RT, perceptual load was again successfully increased with the manipulation of search set size.

CS Detection. Mean percentage detection and false alarm rates, and mean d' and β for correct search trials only as a function of perceptual load are presented in Table 3.

Table 3. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) d' and β as a Function of Perceptual Load in Experiment 3.

Perceptual load	Detection rate %	False alarm rate %	d'	β
Low	86.0 (19.8)	1.8 (1.7)	3.53 (0.86)	6.90 (10.46)
High	47.9 (37.1)	4.5 (5.7)	1.84 (1.57)	7.34 (10.14)

Detection rate and d' were again significantly lower in the high load condition, $F(1, 14) = 6.53$, $MSE = 883.98$, $p = .023$, $\eta_p^2 = .32$ and $F(1, 14) = 7.16$, $MSE = 1.61$, $p = .018$, $\eta_p^2 = .34$ for detection rate and d', respectively, and β was not significantly different between the low and high load conditions, $F < 1$. These results rule out an alternative account of the poorer CS detection in the high load in terms of there being less time available for decision and response preparation processes for CS detection in that condition than in the low load condition.

2.4 Chapter Conclusions

The experiments in this chapter have demonstrated the effect of perceptual load on conscious awareness. Detection rate and sensitivity of an additional, task-irrelevant stimulus were reduced considerably when the perceptual load of the search task was increased from low to high, in all three experiments. Experiment 1 had an advantage over Experiments 2 and 3 in terms of the design being less susceptible to the claim that the CS was forgotten rather than not perceived, since the detection response was made immediately after the search response with no further delay (the detection response occurred in the region of 500 to 800 ms after CS presentation, rather than two seconds after CS presentation as in Experiments 2 and 3). However, this also meant that there was more time remaining to make the CS detection response in the low perceptual load condition than in the high load condition in Experiment 1, which could theoretically have resulted in fewer very slow CS detection responses being recorded in the high than low load, potentially confounding the results. Experiment 2 ruled out this potential confound since there was always 2 s available for detection responses in both load conditions. In Experiment 3, mean search RT was equal in the low and high perceptual load conditions. This was achieved by introducing a 2 s delay between the presentation of the stimuli and the search response. With this design, an alternative account of the results of Experiment 2, that detection sensitivity was reduced under high perceptual load due to less time being available for decision and response preparation processes after the longer high load search RT, was eliminated.

The findings presented in this chapter therefore support the hypothesis that perceptual load determines conscious awareness of task-irrelevant stimuli, and serve to further the resolution of the early and late selection debate by the perceptual load model.

Chapter 3

Detection Priority

The aim of this chapter was to address issues regarding the priority of CS detection, as well as alternative accounts of the results in terms of memory failure. In this chapter introduction I first consider task priority and goal-neglect, before discussing memory-based accounts of inattentional blindness.

A concern with using a dual-task paradigm such as that used here, is that participants may not give the two tasks equal priority – one task may be prioritised over the other. When performing both tasks together is relatively easy this is unlikely to be a problem; however, when performing both is more difficult, participants may have to prioritise one task at the expense of the other (Desimone & Duncan, 1995). In the case of the experiments reported here this is of particular concern, since performing both tasks is easier in the low load condition than in the high load condition, meaning that participants may prioritise the search task over the detection task to a greater extent in the high load than low load condition. If this were the case, it could result in poorer performance in the detection task in the high load, since the reduced priority of CS detection could, at least in some cases, lead participants to neglect the task requirements (i.e., monitor for the presence of the CS and make a response when it is detected), a phenomenon termed 'goal neglect' (Duncan, 1990, 1993, 1995; for related work, see De Jong, 2000, 2001; De Jong, Berendsen, & Cools, 1999; Kane & Engle, 2003; Roberts & Pennington, 1996; West, 2001).

Duncan proposed that organised behaviour can only occur in the absence of strong external cues for action if it can be guided by a hierarchy of goal abstractions. This guidance occurs via an attentional goal weighting process that relies on intact prefrontal cortex (PFC) function, and represents the essence of general fluid intelligence (Duncan, Emslie, Williams, Johnson, & Freer, 1996).

Support for this hypothesis has come from demonstrations that low-intelligence individuals, patients with PFC damage, and participants in dual-task conditions often fail to respond according to task goals when the environment lacks appropriate action prompts (e.g., Duncan, Burgess, & Emslie, 1995; Duncan et al., 1996). Strikingly, the failure to carry out planned goals is typically accompanied by an intact ability to articulate the goal when queried. This indicates that the goal was temporarily absent from working memory, i.e., it was 'neglected', and yet was retrievable from long-term memory.

Duncan et al. (1996) demonstrated goal-neglect using a paradigm in which participants were asked to read aloud the letters from one of two simultaneously presented RSVP streams of letters and numbers. Towards the end of each trial, a '+' or a '–' symbol was presented, interrupting the stream, the former indicating that attention should now be directed at the right-sided stream; the latter, the left-sided stream. In either case, a switch of attention from one side to the other may have been required, depending on which side was started with. Goal-neglect occurred when participants failed to switch streams when it was required. This phenomenon occurred with low Culture-Fair IQ participants, frontal lobe damaged patients (but not patients with damage in other areas) and elderly participants. It was demonstrated in higher IQ participants by combining the stream monitoring task with a dot location task (locating a dot presented either above or below the RSVP streams during some of the trials). In this dual-task condition, many participants neglected to switch between streams or to locate the dot.

Given the fact that the high perceptual load letter search task (set size six) was considerably more demanding than the low load letter search task (set size one), goal-neglect is certainly a potential confound of the perceptual load effect on

CS detection. When the search task was of high load, participants may have deprioritised CS detection by focusing on the search task (for which a response was required on every trial), thereby neglecting to look out for, and/or make a response to the CS. By contrast, the low load search task was not so difficult, and therefore doing both tasks simultaneously was less demanding, rendering goal-neglect less likely.

It should be noted, however, that one of the conditions engendering goal-neglect, according to Duncan et al. (1996), is a lack of strong external cues reinforcing task goals. In the paradigm I have employed, a question mark or the word 'spot?' was presented in every trial following the search task, potentially acting as a powerful and consistent reminder of the detection task. On the other hand, since it appeared in every trial, participants may have become habituated to its presence and have learned to ignore it to some extent.

Furthermore, De Jong et al. (1999) posit that in a situation in which trials occur rapidly, as they do here, goal-neglect is less likely to occur.[4] Indeed, one of the manipulations De Jong et al. (1999) used to induce goal-neglect was slowing the rate of trials (so that participants' minds might stray from task goals), and this was compared with a fast trial rate condition in which goal-neglect did not occur. With the experiments I report here, trials were always presented at a rapid rate, another feature of the experimental paradigm that discouraged goal-neglect.

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[4] Note that although the stimuli in each trial were presented rapidly in the experiments reported by Duncan et al. (1996) and yet goal-neglect still occurred, the task requirement that was neglected only had to be performed once in each 8 s trial, i.e., at a slow rate.

In addition to aspects of the methodology suggesting goal-neglect an unlikely incidence, the pattern of responses also does not support a goal-neglect interpretation. The phenomenon almost exclusively involves a complete disregard of the neglected task until it is entirely alleviated by an environmental prompt (e.g., verbal feedback) that it must be performed (Duncan et al., 1996). The data presented here, however, are such that CS detection responses in the high perceptual load condition occur uniformly across blocks of trials throughout the experiment, rather than spontaneously starting at some point after a complete lack of responses for a period of time. Furthermore, participants who exhibited goal-neglect in Duncan et al.'s (1996) study did not find the neglected task difficult and had no problems in performing it to a high degree of accuracy after being reminded of the task goals. The participants who undertook the experiments reported here, on the other hand, frequently remarked that they had found detecting the CS very difficult in the high perceptual load condition, despite actively looking for it. In spite of these arguments against a goal-neglect interpretation, however, it is important to rule it out as a confound empirically.

In order to prevent the occurrence of goal-neglect, four different measures were taken to raise the priority of the detection task. In Experiment 4 the order of responses was reversed so that the detection response was made immediately upon the appearance of the CS, before the search task response, whereas in all of the previous experiments it had been made after the search task response. In Experiment 5 the probability of CS presentation was increased. In Experiment 6 an absent response was introduced such that participants responded either present or absent on each trial, making a detection response on every trial rather than only when the CS had been detected. In Experiment 7 the increase in CS probability and absent response manipulations were combined. In Experiment 8 the location uncertainty of the CS was decreased by presenting it in two locations rather than six. This experiment additionally rules out an account of the results in terms of low expectancy (i.e., a high location uncertainty).

As well as increasing the priority of the detection task in order to counter alternative accounts in terms of goal-neglect, the manipulation of reversing the order of responses in Experiment 4 also serves as the strongest test of memory-based accounts of the results. Since the detection response came before the search response, it could be made immediately upon presentation of the CS, with no delay at all, thus minimising the possibility that the CS would be forgotten. As I reviewed in the General Introduction, an account of inattentional blindness in terms of forgetting the CS rather than not perceiving it has been proposed by a number of authors, most notably Wolfe (1999), who proposed the inattentional amnesia hypothesis to explain the phenomenon of inattentional blindness, pointing out that participants are questioned a relatively long time after the offset of the stimulus and so rather than having not seen it, may have simply forgotten it had been there. Alternatively, the CS may have never been encoded into memory at all (Moore, 2001; Moore & Egeth, 1997) or may have only generated a weak signal that could be easily wiped out of memory during the delay incurred by making the search response. According to such accounts, the effects of perceptual load on detection could reflect forgetting or diminished encoding of the CS into memory instead of, or in addition to, reduced awareness of the CS.

3.1 Experiment 4

If goal-neglect is the cause of the effect of perceptual load on CS detection, then increasing the priority of the CS detection task will reduce or eliminate the effect. One aspect of the CS detection task that may affect the priority that participants assign to it is the fact that the CS detection response is collected after the search response. In Experiment 4, therefore, the order of responses was reversed, so that the CS detection response was made first, before the search response, in order to raise its priority.

This manipulation also precludes an alternative account of the results in terms of memory, since the detection response was immediate. Equating the time available for preparation of the detection response in Experiment 3 ruled out most of the potentially confounding effects of differential search RTs in the low and high load conditions. However, since the detection response in Experiment 3 was made after the search response, an account of the results in terms of memory failure remains possible: although the same time interval elapsed between the presentation of the stimuli and the detection response in the low and high perceptual load conditions, the participants' attention was more engaged in processing the search task during that interval in the high load than in the low load condition. This may have reduced the depth of encoding of the CS into memory (where it had to be retained until the CS response could be made) in the high relative to the low load condition. It is therefore important to assess the effects of perceptual load on detection sensitivity in a design in which participants are asked to make the detection response immediately upon its presentation, i.e., before the search task response, rather than after it, as in the previous experiments.

3.1.1 Method

Participants. Twenty-two new participants were recruited from UCL and were paid for their participation. Two participants were replaced because their accuracy on the letter search task was below 65%, and two because they detected less than 75% of the CS in the control block. The age range of those included was 18 to 39 years ($M = 21.4$ years, $SD = 5.2$ years) and there were 10 men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were the same as Experiment 1, except that the participants were instructed to make the detection response first, as soon as they saw the CS, and to respond to the letter search task afterwards. If they did not see the CS, they were to respond to the letter search task as quickly and accurately as they could. A single 2.7 s interval was available to make both responses.

3.1.2 Results and Discussion

Letter Search. As the detection response was made before the search response, trials in which the CS was presented were excluded from the mean search RT analysis, since making a detection response before the search response would have greatly delayed search RT. The perceptual load manipulation was again effective: mean search RT was significantly longer in the high perceptual load condition ($M = 766$ ms) than the low perceptual load condition ($M = 640$ ms), $F(1, 20) = 5.57$, $MSE = 15{,}728.47$, $p = .029$, $\eta_p^2 = .22$, and error rate in the high perceptual load condition ($M = 21.2\%$) was significantly higher than in the low perceptual load condition ($M = 6.2\%$), $F(1, 20) = 39.46$, $MSE = 31.36$, $p < .001$, $\eta_p^2 = .66$.

CS Detection. Mean percentage detection and false alarm rates, and mean *d'* and β for correct search trials only as a function of perceptual load are presented in Table 4.

Table 4. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 4.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	71.7 (36.5)	1.8 (2.3)	3.10 (1.29)	7.74 (9.42)
High	40.6 (25.3)	1.3 (2.4)	1.98 (0.81)	14.14 (8.84)

As with the experiments in Chapter 2, detection rate and *d'* were significantly lower in the high load than low load condition, $F(1, 20) = 5.44$, $MSE = 982.61$, $p = .030$, $\eta_p^2 = .21$ and $F(1, 20) = 6.01$, $MSE = 1.16$, $p = .024$, $\eta_p^2 = .23$ for load effects on detection rate and *d'*, respectively. The figures for mean β revealed a numerical trend towards a more stringent criterion in the high load than the low load but the difference was not significant, $F(1, 20) = 2.69$, $MSE = 83.50$, $p = .117$, $\eta_p^2 = .12$. Experiment 4, therefore, replicated the perceptual load effect on CS detection found in Experiments 1-3, even though the order of responses was reversed so that the detection response came before the search response. The fact that in this experiment participants did not have to delay their detection response until after they had made the search response rules out alternative accounts of the results in terms of a perceptual load effect on memory rather than on detection sensitivity.

The Effect of Reversing the Order of Responses. The results of this experiment were compared with those of Experiment 2 in a series of two way ANOVA with perceptual load and order of responses as factors. As would be expected, there was a main effect of perceptual load on both detection rate, $F(1, 34) = 18.62$, $MSE = 889.49$, $p < .001$, $\eta_p^2 = .35$, and *d'*, $F(1, 34) = 28.81$, $MSE = 1.30$, $p < .001$, $\eta_p^2 = .40$; however, there was no main effect of order of responses on either, both $F < 1$. There was also no interaction: reversing the order of responses so that the detection response came first did not affect the modulation by perceptual load, since mean detection rate (71.7% and 40.6% for low and high perceptual load, respectively) and mean detection sensitivity (3.10 and 1.98 for low and high, respectively) were not significantly different to those of Experiment 2 (90.0% and 36.8%, and 3.70 and 1.30 for low and high, respectively), $F(1, 34) = 1.28$, $MSE = 889.49$, $p = .265$, $\eta_p^2 = .04$ for detection rate, $F(1, 34) = 2.92$, $MSE = 1.30$, $p = .097$, $\eta_p^2 = .08$ for *d'*. There were no significant effects on β, $F(1, 34) = 2.40$, $MSE = 93.06$, $p = .131$, $\eta_p^2 = .07$ for the main effect of perceptual load, $F(1, 34) = 1.37$, $MSE = 93.06$, $p = .249$, $\eta_p^2 = .04$ for the main effect of order of responses, and $F < 1$ for the interaction.

It is somewhat surprising that the overall mean detection rate in this experiment (56.1%) was lower than in Experiment 2 (63.4%, albeit not significantly so, and *M d'* was very similar: 2.54 and 2.50), considering that the detection response was now prioritised by being made first, before the search response. This may reflect a response switch-cost incurred when participants had to suppress the more frequent, and therefore dominant search response, to make way for the relatively infrequent detection response. Such a cost could have resulted in participants failing to make a detection response in some of the CS trials, and therefore may have reduced the rate of CS detection in this experiment.[5]

3.2 Experiment 5

In Experiment 4, alternative accounts of the results in terms of goal-neglect and memory failure were countered by having the detection response first, before the search response, thereby raising the priority of the detection task and eliminating the delay between CS presentation and response. The somewhat unexpected trend for a decrease in overall mean detection rate with the detection response made first indicates that there may have been a response switching cost, however. In Experiment 5, therefore, the order of responses was restored to that of Experiments 1-3, with the detection response following the search response.

In all the previous experiments the CS was presented in 17% of trials. Experiment 5 examined whether the perceptual load of the search task would determine detection performance when the CS was presented more frequently, in this case, in 50% of trials. More frequent presentations of the CS should raise the priority of the detection task, as participants' expectations that a CS would appear in any given trial would be greater. Furthermore, it might be expected that increasing the frequency of CS presentation would result in better detection

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[5] Importantly though, as such failures of response inhibition are likely to have had similar effects on detection in the low and high perceptual load conditions, such an effect can not serve as an alternative account of the effect of perceptual load on detection.

sensitivity, since it would increase participants' familiarity with the CS and give them much more practice at the task during the experiment.

3.2.1 Method

Participants. Eighteen new participants were recruited from the website, www.gumtree.com and were paid for their participation. Eight participants were replaced because they detected less than 75% of the CS in the control block, and two because their mean search RTs were greater than 2 *SD* above the group mean. The age range of those included was 18 to 36 years ($M = 24.5$ years, $SD = 4.7$ years) and there were 10 men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were the same as Experiment 2 except that the CS was presented in 36 of the 72 trials (50%) per block. In each block the CS was presented six times in each of its six possible positions. A fully counterbalanced set of 144 different stimulus displays, employed across two blocks of 72 trials, consisted of each of the target letters (two) in each of the letter circle positions (six), either without or with the CS in each position (six). In the high perceptual load condition there were also 144 randomly selected non-target arrangements. The control block used half of the displays from the first block and half from the second block.

3.2.2 Results and Discussion

Letter Search. As with the previous experiments, mean search RT was significantly longer in the high perceptual load condition ($M = 816$ ms) than in the low ($M = 664$ ms), $F(1, 16) = 7.13$, $MSE = 14{,}683.60$, $p = .017$, $\eta_p^2 = .31$, and error rate in the high perceptual load condition ($M = 27.3\%$) was significantly higher than in the low ($M = 9.0\%$), $F(1, 16) = 16.24$, $MSE = 93.13$, $p < .001$, $\eta_p^2 = .50$. Perceptual load was therefore again successfully increased with the manipulation of search set size in Experiment 5.

CS Detection. Mean percentage detection and false alarm rates, and mean d' and β for correct search trials only as a function of perceptual load are presented in Table 5.

Table 5. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 5.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	90.0 (9.1)	4.1 (5.2)	3.41 (1.00)	2.75 (2.36)
High	61.4 (26.3)	12.4 (19.0)	2.03 (1.19)	6.90 (7.25)

As the table suggests, detection rate in the high perceptual load condition was significantly lower than in the low perceptual load condition, $F(1, 16) = 9.46$, $MSE = 387.81$, $p = .007$, $\eta_p^2 = .37$. Detection sensitivity was also again significantly lower for the high than low perceptual load condition, $F(1, 16) = 7.02$, $MSE = 1.21$, $p = .017$, $\eta_p^2 = .31$. β was not significantly different between the low and high load conditions, $F(1, 16) = 2.67$, $MSE = 29.07$, $p = .122$, $\eta_p^2 = .14$.

The Effect of CS Frequency. The results of this experiment were compared with those of Experiment 2 (in which CS frequency was 17%) in a series of two way ANOVA with perceptual load and CS frequency as factors. As would be expected, there was a main effect of perceptual load on both detection rate, $F(1, 30) = 25.39$, $MSE = 559.84$, $p < .001$, $\eta_p^2 = .46$, and *d'*, $F(1, 30) = 22.48$, $MSE = 1.35$, $p < .001$, $\eta_p^2 = .43$. There was no main effect of CS frequency, $F(1, 30) = 2.24$, $MSE = 559.84$, $p = .145$, $\eta_p^2 = .07$ for detection rate, $F < 1$ for *d'*, and critically, there was no interaction between perceptual load and CS frequency, indicating that the effect of perceptual load was not significantly different between experiments, $F(1, 30) = 2.33$, $MSE = 559.84$, $p = .137$, $\eta_p^2 = .07$ for detection rate, $F(1, 30) = 1.66$, $MSE = 1.35$, $p = .208$, $\eta_p^2 = .05$ for *d'*. The higher frequency of CS presentation in this experiment did lead to numerical trends for an increase in both mean detection rate (61.4%) and mean *d'* (2.03) in the high load condition compared with the same condition in Experiment 2 (36.8% and 1.30), but in paired comparisons these trends did not reach significance, $t(15) = 1.72$, $SEM = 14.28$, $p = .106$ for detection rate, $t(15) = 1.10$, $SEM = 0.66$, $p = .287$ for *d'*. Detection performance in the low load remained the same (*M* detection rate = 90.0% and *M d'* = 3.41 in Experiment 5 compared to 90.0% and 3.70 in Experiment 2, $t < 1$ for both). There were no significant effects on β, $F(1, 30) = 1.87$, $MSE = 65.34$, $p = .182$, $\eta_p^2 = .06$ for the main effect of perceptual load, $F < 1$ for both the main effect of CS frequency and the interaction between CS frequency and perceptual load.

These results clearly demonstrate that perceptual load determines conscious perception even when the CS has a high frequency of occurrence, appearing in 50% of trials rather than 17%, as in the previous experiments.

3.3 Experiment 6

In Experiment 5, increasing the frequency of CS presentation raised the priority of the detection task but did not affect detection sensitivity. Another way of raising the priority of the detection task is to introduce an absent response, such that participants make a detection response on every trial. This was the design of Experiment 6. As with Experiment 5, this change should raise the priority of the detection task without influencing the effect of perceptual load.

3.3.1 Method

Participants. Eighteen new participants were recruited via the website, www.gumtree.com and were paid for their participation. Fifteen participants were replaced because they detected less than 75% of the CS in the control block, 10 because their accuracy at the search task was below 65%, and one because his false alarm rate in both the experimental blocks and the control blocks was 80%. The age range of those included was 20 to 44 years (M = 25.1 years, SD = 5.9 years) and there were eight men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were the same as Experiment 2, except that participants were instructed to press the 'A' key when the CS was absent and press the 'S' key when it was present. In addition, a minor procedural change was made – the question mark signifying that the detection response could be made was now presented for the full 2 s response interval with no blank following it.

3.3.2 Results and Discussion

Letter Search. As with the previous experiments, mean search RT was significantly longer in the high perceptual load condition (M = 879 ms) than the low perceptual load condition (M = 644 ms), $F(1, 16) = 10.69$, $MSE = 23{,}208.80$, $p = .005$, $\eta_p^2 = .40$, and error rate in the high perceptual load condition (M = 20.4%) was significantly higher than in the low perceptual load condition (M = 8.6%), $F(1, 16) = 12.75$, $MSE = 49.90$, $p = .003$, $\eta_p^2 = .44$, indicating that the perceptual load of the search task was again successfully increased with the manipulation of search set size in Experiment 6.

CS Detection. Mean percentage detection and false alarm rates, and mean *d'* and β for correct search trials only as a function of perceptual load are presented in Table 6.

Table 6. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 6.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	84.5 (11.5)	3.1 (2.7)	3.08 (0.76)	4.71 (4.73)
High	55.6 (30.0)	28.6 (21.3)	0.99 (0.68)	3.10 (4.61)

Participants in the high perceptual load condition were significantly less likely to detect the CS than those in the low perceptual load condition, $F(1, 16) = 7.34$, $MSE = 511.76$, $p = .015$, $\eta_p^2 = .31$, and *d'* in the high perceptual load condition was also significantly lower than that in the low perceptual load condition, $F(1, 16) = 37.77$, $MSE = 0.52$, $p < .001$, $\eta_p^2 = .70$. β was not significantly different between the low and high load conditions, $F < 1$. These results replicate the previous pattern of results found in Experiments 1-5.

CS detection in the control block, in which participants did not perform the letter search task was again equivalent in the low and high perceptual load conditions in terms of detection rate ($M = 91.7\%$ for low load and 90.7% for high load, $F < 1$) and β ($M = 4.96$ for low load and 2.85 for high load, $F(1, 16) = 1.84$, $MSE = 10.84$, $p = 0.193$, $\eta_p^2 = .10$); however, *d'* was significantly reduced, $F(1, 16) = 7.54$, $MSE = 0.35$, $p = 0.014$, $\eta_p^2 = .32$, in the high load ($M = 2.83$) compared to the low load ($M = 3.59$). This was due to a greater number of false alarms ($M = 1.1\%$ for low load and 8.9% for high load). However, *d'* for the high load control block remained significantly higher than *d'* for the high load experimental blocks,

$F(1, 8) = 64.93$, $MSE = 0.23$, $p < .001$, $\eta_p^2 = .89$, showing that the effect of perceptual load depends on actual performance of the search task.

The Effect of Requiring a Detection Response on Every Trial (Either Present or Absent). The results of this experiment were compared with those of Experiment 2 (in which detection responses were only made when the CS was present) in a series of two way ANOVA with perceptual load and CS response requirement as factors. As would be expected, there was a main effect of perceptual load on both detection rate, $F(1, 30) = 22.89$, $MSE = 625.95$, $p < .001$, $\eta_p^2 = .43$, and *d'*, $F(1, 30) = 43.82$, $MSE = 0.98$, $p < .001$, $\eta_p^2 = .59$. Raising the priority of the detection task by introducing an absent response produced a small but non-significant increase in overall mean detection rate (from 63.4% in Experiment 2 to 70.1% in Experiment 6, $F < 1$), but overall mean detection sensitivity showed a trend towards a decrease (from a *d'* of 2.50 in Experiment 2 to a *d'* of 2.04, also not significant, $F(1, 30) = 1.86$, $MSE = 0.98$, $p = .183$, $\eta_p^2 = .06$). This was due to an increase in the overall mean false alarm rate from 5.2% in Experiment 2 to 15.9% in Experiment 6, $F(1, 30) = 5.72$, $MSE = 169.63$, $p = .023$, $\eta_p^2 = .16$. Adding a requirement to make a detection response in every trial therefore tended to increase the rate of present responses; however, since both detection rate and false alarm rate increased, detection sensitivity did not also increase. There was a numerical trend for a decrease in the effect of perceptual load (*M* detection rate reduced by 28.9% under high perceptual load in Experiment 6 compared to 53.2% in Experiment 2, *M d'* reduced by 2.09 in Experiment 6 compared to 2.40 in Experiment 2), but there was no significant interaction of perceptual load by CS response requirement for either detection rate, $F(1, 30) = 2.03$, $MSE = 625.95$, $p = .165$, $\eta_p^2 = .06$, or *d'*, $F < 1$, although there was for false alarm rate, $F(1, 30) =$

5.03, $MSE = 169.63$, $p = .032$, $\eta_p^2 = .14$. Further analyses revealed that false alarm rate in the high load condition of Experiment 6 was higher ($M = 28.6\%$) than in Experiment 2 ($M = 7.9\%$), $t(15) = 2.34$, $SEM = 8.85$, $p = .033$, although this did not produce a significant decrease in detection sensitivity ($M = 0.99$ in Experiment 6 compared to 1.30 in Experiment 2, $t < 1$), due to a trend for a countering increase in detection rate (from $M = 36.8\%$ in Experiment 2 to 55.6% in Experiment 6, $t(15) = 1.25$, $SEM = 15.13$, $p = .230$). Performance in the low load condition in the two experiments, however, was comparable: M detection rate = 84.5% compared to 90.0% in Experiment 2, $t < 1$; M false alarm rate = 3.1% compared to 2.5%, $t < 1$; and M $d' = 3.08$ compared to 3.70, $t(15) = 1.62$, $SEM = 0.38$, $p = .125$. There were no significant effects on β, $F(1, 30) = 1.52$, $MSE = 61.44$, $p = .227$, $\eta_p^2 = .05$ for the main effect of CS response requirement, $F < 1$ for both the main effect of perceptual load and the interaction between perceptual load and CS response requirement.

The trend towards an increase in detection rate and the significant increase in false alarm rate in the high load condition of Experiment 6 indicate that participants made more present responses than in Experiment 2 (and this carried over into the control block, hence the lower d' due to an increase in false alarms). Thus, introducing an absent response, thereby raising the priority of the detection task, led to a trend for a reduction in response criterion (i.e., a greater likelihood of making a present response) in the high load condition, from M $\beta = 8.95$ in Experiment 2 to M $\beta = 3.10$ (although this was not significant, $t(15) = 1.48$, $SEM = 3.94$, $p = .159$). However, as reported above, there was no change in detection sensitivity. Such an increase in the proportion of present responses, producing a trend for a rise in detection rate and a significant rise in false alarm rate, and hence not improving detection sensitivity, indicates that the manipulation of adding an absent response did indeed have the desired effect of raising the priority of the detection task, but clearly the effect of perceptual load on detection did not depend on task priority, since it was unaffected.

3.4 Experiment 7

In Experiment 7, the manipulations used to increase the priority of the detection task in the previous two experiments were combined. The CS was therefore presented in 50% of trials, as in Experiment 5, and the participants made a detection response on every trial, either 'present' or 'absent', as in Experiment 6.

3.4.1 Method

Participants. Sixteen new participants were recruited from UCL and were paid for their participation. Five participants were replaced because their accuracy on the letter search task was below 65%, four because they detected less than 75% of the CS in the control block, and two because their mean search RT was either two standard deviations above or below the group mean. The age range of those included was 18 to 26 years (M = 20.0 years, SD = 2.3 years) and there were five men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were the same as those used in Experiment 6, except that the CS was presented in 36 of the 72 trials (50%) per block.

3.4.2 Results and Discussion

Letter Search. As with the previous experiments, a longer mean search RT and a greater proportion of errors were found in the high perceptual load condition (M = 870 ms and M = 23.7%) than the low perceptual load condition (M = 533 ms and M = 10.9%), $F(1, 14) = 64.69$, $MSE = 7026.05$, $p < .001$, $\eta_p^2 = .82$ for RT, $F(1, 14) = 12.24$, $MSE = 54.17$, $p = .004$, $\eta_p^2 = .47$ for error rate.

CS Detection. The mean percentage detection and false alarm rates and mean *d'* and β for correct search task trials only as a function of perceptual load are presented in Table 7.

Table 7. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 7.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	92.3 (6.0)	4.7 (4.9)	3.38 (0.72)	2.17 (1.43)
High	64.1 (19.5)	14.9 (10.0)	1.61 (0.88)	3.52 (6.01)

As an inspection of the table reveals, the effect of perceptual load on detection rate and *d'* was replicated in Experiment 7, $F(1, 14) = 15.32$, $MSE = 208.34$, $p = .002$, $\eta_p^2 = .52$ for detection rate, $F(1, 14) = 19.58$, $MSE = 0.64$, $p = .001$, $\eta_p^2 = .58$ for *d'*. β did not differ between the low and high load conditions, $F < 1$. Experiment 7 therefore demonstrates that perceptual load reduces detection rate and sensitivity even when two manipulations designed to increase the priority of the detection task were combined: increasing the frequency of CS presentation from 17% to 50% of trials, and collecting present and absent responses rather than just present responses.

The Effect of CS Frequency When Requiring a Detection Response on Every Trial (Either Present or Absent). The results of this experiment were compared with those of Experiment 6 (in which CS frequency was 17% but detection responses were required on every trial) in a series of two way ANOVA with perceptual load and CS frequency as factors. As would be expected, there was a main effect of perceptual load on both detection rate, $F(1, 30) = 18.68$, $MSE = 370.17$, $p < .001$, $\eta_p^2 = .38$, and *d'*, $F(1, 30) = 54.75$, $MSE = 0.58$, $p < .001$, $\eta_p^2 = .65$. But there was no main effect of CS frequency for either, $F(1, 30) = 1.52$, $MSE = 370.17$, $p = .228$, $\eta_p^2 = .05$ for detection rate, $F(1, 30) = 3.06$, $MSE = 0.58$, $p = .091$, $\eta_p^2 = .09$ for *d'*. The increase in CS frequency from 17% to 50% with the present or absent detection response design led to non-significant trends in the high load condition for a higher detection rate ($M = 64.1\%$ in Experiment 7 vs. 55.6% in Experiment 6, $t < 1$), and a higher *d'* ($M = 1.61$ in Experiment 7 vs. 0.99 in Experiment 6, $t(15) = 1.63$, $SEM = 0.38$, $p = .124$), as it did in Experiment 5, although this time the low load condition data followed the same trend for an increase: *M* detection rate = 92.3% in Experiment 7 vs. 84.5% in Experiment 6, $t(15) = 1.73$, $SEM = 4.53$, $p = .105$, and *M d'* = 3.38 in Experiment 7 vs. 3.08 in Experiment 6, $t < 1$. Again, however, as with Experiment 5, there was no interaction of perceptual load and CS frequency, $F < 1$ for both detection rate and *d'*, so the effect of perceptual load was not reduced in this experiment. There were no significant effects on β, all $F < 1$.

These results demonstrate that perceptual load determines detection rate and sensitivity even when the detection task has a higher priority due to an increase in the probability of the CS being presented and the fact that participants were required to make a detection response on every trial (either present or absent).

3.5 Experiment 8

In all the experiments so far, the CS was presented in one of six possible locations. Experiment 8 examined whether the perceptual load of the search task would determine detection sensitivity even when the CS was presented in one of only two locations, either on the left or the right side of the circle of letters. In a similar way to increasing the frequency of presentation of the CS (as in Experiments 5 and 7), reducing the possible number of CS locations ought to raise the priority of detection since the expectancy that the CS will appear in each location will necessarily increase (i.e., the probability that the CS would appear in each of the six locations on any given trial in Experiments 5 and 7 was 0.08, whereas with two locations it would be 0.25).

It is known that reducing location uncertainty can significantly increase the probability of stimulus detection (e.g., Bashinski & Bacharach, 1980; Posner, Nissen, & Ogden; 1978; Posner, Snyder, & Davidson, 1980). This enhancement of detection may, at least in part, be due simply to the reduced probability of false alarms (Davies, Kramer, & Graham, 1983). However, attention may also play a role, as many studies have demonstrated a better ability to focus spatial attention with reduced location uncertainty (e.g., Posner et al., 1978, 1980).

It is therefore possible that with reduced uncertainty of CS location, participants would be able to pay focused attention to it, even in conditions of high perceptual load. Previous tests of perceptual load theory, however, have often demonstrated that high perceptual load eliminates the processing of an irrelevant stimulus presented in one of two possible locations (e.g., Lavie, 1995; Lavie & Cox, 1997; Lavie & Fox, 2000), although these studies inferred perception from the congruency and negative priming effects of an irrelevant distractor stimulus on search RTs. Nevertheless, Experiment 8 should replicate the effect of perceptual load on the detection of the CS found in the previous experiments, when the CS is presented in just one of two possible locations.

3.5.1 Method

Participants. Forty new participants were recruited from UCL and were paid for their participation. Two participants were replaced because they detected less than 75% of the CS in the control block, one because his accuracy at the letter search task was below 65%, and one because his false alarm rate in the control blocks was 61%. The age range of those included was 18 to 40 years ($M = 22.9$ years, $SD = 5.0$ years) and there were 11 men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were identical to Experiment 7 except that the CS was presented at one of two locations, one on the left and one on the right of the circle of letters on the horizontal midline, both 5.4° of visual angle from the fixation point. In each block the CS was presented 18 times in each of its two possible positions, three times in each position for each of the six possible target positions. A counterbalanced set of 144 different stimulus displays consisted of each of the target letters (two) in each of the letter circle positions (six), as well as the CS in each position (two). In the high perceptual load condition there were also 144 randomly selected non-target arrangements.

3.5.2 Results and Discussion

Letter Search. As with the previous experiments, perceptual load was effectively manipulated with the increased search set size: mean search RT was significantly longer in the high perceptual load condition ($M = 932$ ms) than the low perceptual load condition ($M = 699$ ms), $F(1, 38) = 20.84$, $MSE = 25{,}834.57$, $p < .001$, $\eta_p^2 = .35$, and error rate in the high perceptual load condition ($M = 23.3\%$) was significantly higher than in the low perceptual load condition ($M = 8.4\%$), $F(1, 38) = 47.57$, $MSE = 46.98$, $p < .001$, $\eta_p^2 = .56$.

CS Detection. Table 8 shows mean percentage detection and false alarm rates and mean *d'* and β for correct search trials only as a function of perceptual load.

Table 8. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 8.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	87.3 (12.0)	7.5 (8.8)	3.02 (1.06)	2.31 (2.88)
High	75.5 (23.2)	22.2 (15.4)	1.70 (0.78)	1.48 (2.04)

Detection rate and *d'* were again significantly lower in the high load than low load condition, $F(1, 38) = 4.11$, $MSE = 342.19$, $p = .050$, $\eta_p^2 = .10$ and $F(1, 38) = 20.29$, $MSE = 0.87$, $p < .001$, $\eta_p^2 = .35$, respectively, even though the CS was now presented in one of two locations rather than in one of six as had been the case in all previous experiments. β was no different between conditions, $F(1, 38) = 1.15$, $MSE = 6.23$, $p = .291$, $\eta_p^2 = .03$.

The Effect of Location Uncertainty. Since Experiments 7 and 8 employed the same stimuli and procedure, the only difference being the location uncertainty of the CS, between-experiment comparisons were conducted in a series of two way ANOVA with perceptual load and location uncertainty as factors. As would be expected, there was a main effect of perceptual load on both detection rate, $F(1, 52)$

$= 15.01$, $MSE = 306.15$, $p < .001$, $\eta_p^2 = .22$, and *d'*, $F(1, 52) = 33.97$, $MSE = 0.81$, $p < .001$, $\eta_p^2 = .40$. The main effect of reducing location uncertainty from six locations in Experiment 7 (*M* detection rate = 78.2%, *M d'* = 2.50) to two locations in Experiment 8 (*M* detection rate = 81.4%, *M d'* = 2.36) was not significant for either detection rate or *d'*, $F < 1$ for both. Moreover, the effect of perceptual load on detection did not differ significantly between Experiment 7 (in which *M* detection rate was reduced by 28.2%, *M d'* by 1.77) and Experiment 8 (in which *M* detection rate was reduced by 11.8%, *M d'* by 1.32), $F(1, 52) = 2.51$, $MSE = 306.15$, $p = .119$, $\eta_p^2 = .05$ for detection rate, $F < 1$ for *d'*, despite a numerical trend towards a reduction in the perceptual load effect. There were no significant effects on β, $F < 1$ for the main effect of perceptual load, $F(1, 52) = 1.11$, $MSE = 9.65$, $p = .297$, $\eta_p^2 = .02$ for the main effect of location uncertainty, and $F(1, 52) = 1.44$, $MSE = 9.65$, $p = .235$, $\eta_p^2 = .03$ for the interaction.

These results clearly demonstrate that perceptual load determines conscious awareness even when the CS has a high location certainty, appearing in just one of two possible locations, as in previous perceptual load studies using indirect measures of distractor processing.

3.6 Chapter Conclusions

The experiments in this chapter have demonstrated that goal-neglect is not responsible for the effect of perceptual load on CS detection. With four different manipulations designed to increase the priority of the detection task, both detection rate and detection sensitivity were still significantly reduced under high perceptual load. The effect was found when the detection response was made immediately upon stimulus presentation, before the search task response (Experiment 4), when the frequency of CS presentation was increased (Experiments 5 and 7), when participants made a detection response (present or absent) on every trial (Experiments 6 and 7), and when location uncertainty was reduced by decreasing the number of locations in which the CS could be presented from six to two (Experiment 8).

Experiment 4 also convincingly ruled out memory based accounts of the results as the effect of perceptual load was demonstrated in a design in which the detection response was made immediately upon CS presentation rather than after the search task response, as it was in the other experiments.

The effect of perceptual load persisted when location uncertainty was decreased by presenting the CS in only two possible locations (Experiment 8), as in previous response competition experiments assessing the extent to which distractors were perceived (e.g., Eriksen & Eriksen, 1974; Lavie, 1995). Experiment 8 therefore ruled out an account of the results in terms of low expectancy, i.e., a high location uncertainty.

The findings therefore do not reflect an effect of perceptual load on goal-neglect or the priority of the detection task: the slight increases in detection rate in Experiments 5 to 8 did not translate into improvements in detection sensitivity, since they were accompanied by corresponding increases in false alarm rate. Instead, the results demonstrate that the availability of limited capacity attention is critical for conscious perception, in direct support of the central tenet of perceptual load theory, namely, that the level of perceptual load in a task determines the extent to which task-irrelevant information is perceived.

Chapter 4

Strategy

Since in all the experiments so far each participant undertook either the low or high perceptual load condition alone, an alternative account of the effect of perceptual load on detection sensitivity is that participants may have employed different strategies in the different perceptual load conditions. This is possible despite the task instructions being the same, i.e., search for a letter X or N and monitor for the presence of the CS, since the high perceptual load search task was considerably more difficult than the low load search task and therefore a different strategy may have had to have been adopted in order to be able to accomplish it. It is therefore possible that the use of a different strategy in the high perceptual load condition may have produced the poorer CS detection performance, rather than the demands on perceptual capacity placed by high perceptual load in the search task. One way to rule out an alternative account in terms of strategy, therefore, is to present each participant with trials of both levels of perceptual load in a randomly intermixed order, rather than exclusively either low or high perceptual load trials. With this design, participants can not prepare for one level of perceptual load or the other, and therefore can not employ a particular strategy. A design with randomly intermixed perceptual load trials has been adopted in several studies (Cartwright-Finch & Lavie, 2007; Lavie & Cox, 1997; Theewes, Kramer, & Belopolsky, 2004), each successfully ruling out differential strategies as an alternative explanation of the perceptual load effect, as I describe next.

Lavie and Cox (1997) presented participants with search tasks of four different levels of perceptual load by varying the number of non-targets in the search display: either zero, one, three or five different non-targets were added. The different perceptual load trials were presented in a randomly intermixed order and interference effects on RTs from a congruent or incongruent flanker distractor were significantly reduced when search set size was six compared to the other, smaller set sizes, implying that capacity may only be consumed when more than four items require focused attention.

Theeuwes et al. (2004) replicated the results of Lavie and Cox (1997) with just two levels of perceptual load, low (set size one) and high (set size six), rather than four. As with Lavie and Cox (1997), load trials were presented in a randomly intermixed order. An additional analysis looking at the level of load in the preceding trial as well as that in the current trial revealed that whereas the level of load on the preceding trial made no difference in a low load trial, only high load trials that followed high load trials showed a significantly reduced distractor effect on search RT.

Cartwright-Finch and Lavie (2007) presented participants with trials of low and high perceptual load in a randomly intermixed order and included a CS on the final trial, i.e., an inattentional blindness trial. Participants performing a high perceptual load search task on the final trial were more likely to fail to notice the CS than those performing a low perceptual load search task, thus ruling out differential strategies as an alterative account of the effect of perceptual load on conscious awareness, since the participants could not prepare for a low or high load trial since they could not anticipate which would occur from trial to trial.

In this chapter, before reporting an experiment with low and high perceptual load trials presented in a randomly intermixed order (Experiment 10), I first describe an experiment in which the conditions were blocked in a within-subjects design (Experiment 9), as opposed to the experiments in the previous chapters in which the conditions were manipulated between-subjects. This was done in order to first ascertain that the effect of perceptual load could be replicated when the participants experienced both levels of load. In both Experiments 9 and 10, the probability that the CS was presented on any given trial was 50%, as it had been in Experiments 5 and 7 in the previous chapter, and the total number of CS trials also remained the same in order to maintain the amount of experience participants would have in detecting the CS. In Experiment 11, the probability of CS presentation was reduced to 17% in order to see if there was any change in the effect of perceptual load on detection when there were fewer CS presented in each block of randomly intermixed load trials.

4.1 Experiment 9

So far, the conditions of low and high perceptual load had always been manipulated between-subjects such that each participant had either low or high perceptual load search task trials throughout the experiment. This design was used for the purpose of eliminating order and practice effects. It was important, however, to establish that the effects of load on detection can be found when it is manipulated within-subjects, as it has been previously with other paradigms (e.g., Lavie, 1995, with response competition, and Lavie and Fox, 2000, with negative priming). In Experiment 9, therefore, each participant carried out both conditions of low and high perceptual load.

4.1.1 Method

Participants. Sixteen new participants were recruited from UCL and were paid for their participation. Five participants were replaced because they detected less than 75% of the CS in the control block, and seven because their accuracy at the letter search task was below 65%. The age range of those included was 18 to 32 years (*M* = 23.0 years, *SD* = 4.4 years) and there were seven men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were the same as Experiment 7 except that participants were presented with two blocks of low perceptual load trials and two blocks of high perceptual load trials (order of blocks was counterbalanced: either ABBA or BAAB). A counterbalanced set of 144 different stimulus displays, employed across four blocks of 36 trials each, consisted of each load condition (two), each of the target letters (two) in each of the letter circle positions (six), either without or with the CS in each position (six). In the high perceptual load condition there were also 72 randomly selected non-target arrangements. The control block used half of the displays from the first block and half from the second block. Note that the total number of trials in which the CS was presented (72) remained the same as in Experiment 7 to avoid confounding a comparison with that experiment with the effects of participants having more experience and practice at detecting the CS.

4.1.2 Results and Discussion

Letter Search. Perceptual load was again successfully increased with the manipulation of search set size in Experiment 9: mean search RT was significantly longer in the high perceptual load condition (*M* = 916 ms) than the low perceptual load condition (*M* = 678 ms), $F(1, 15) = 143.16$, $MSE = 3156.38$, $p < .001$, $\eta_p^2 = .91$, and error rate in the high perceptual load condition (*M* = 21.2%) was significantly higher than in the low perceptual load condition (*M* = 7.5%), $F(1, 15) = 106.19$, $MSE = 14.12$, $p < .001$, $\eta_p^2 = .88$.

CS Detection. Mean percentage detection and false alarm rates, and mean *d'* and β for correct search trials only as a function of perceptual load are presented in Table 9.

Table 9. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 9.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	85.8 (19.8)	13.0 (12.0)	2.58 (0.98)	1.63 (1.91)
High	72.8 (27.0)	19.0 (14.6)	1.79 (1.08)	1.73 (2.53)

In the high perceptual load condition, participants were less likely to detect the CS than in the low perceptual load condition, $F(1, 15) = 8.28$, $MSE = 169.57$, $p = .011$, $\eta_p^2 = .36$. Detection sensitivity (*d'*) was again significantly lower in the high perceptual load condition than in the low perceptual load condition, $F(1, 15) = 18.19$, $MSE = 0.28$, $p = .001$, $\eta_p^2 = .55$. Response criterion (β) was not significantly different between the low and high load conditions, $F < 1$. As each participant completed both conditions of low and high perceptual load in Experiment 9, two way ANOVA on detection rate and *d'* with perceptual load and order of blocks (ABBA or BAAB) as factors were carried out. Mean detection rate and *d'* for the order ABBA (where A is low perceptual load and B is high perceptual load) were higher than those for the order BAAB: 92.0% and 2.79 for low perceptual load, 75.8% and 1.91 for high perceptual load for ABBA; 79.9% and 2.38 for low perceptual load, 69.6% and 1.68 for high perceptual load for BAAB. However, neither the main effect of order, nor the interaction between order and perceptual load was significant for either detection rate or *d'* (all $F < 1$).

Thus, Experiment 9 provides a successful replication of the effect of perceptual load on conscious detection using a design in which the level of load is manipulated within-subjects rather than between-subjects as it was in the previous experiments.

Load Manipulated Within-Subjects versus Between-Subjects. The effect of perceptual load on CS detection was somewhat smaller in this experiment than in Experiment 7 (*M d'* reduced by 0.79 in Experiment 9, and by 1.77 in Experiment 7). Whether this reduction was significant or not can not be ascertained statistically since within and between-subjects manipulations of the same independent variable can not be entered into a single analysis of variance. The reduced effect appears to be the result of poorer detection sensitivity in the low perceptual load condition in Experiment 9 (*M d'* = 2.58), compared to Experiment 7 (*M d'* = 3.38), mainly due to an increase in false alarm rate (*M* = 13.0% in Experiment 9; 4.7% in Experiment 7), but there was also a slight decrease in detection rate (*M* = 85.8% in Experiment 9, and 92.3% in Experiment 7). Performances in the high load conditions of the two experiments were more similar to each other: *M d'* was 1.79 in Experiment 9, and 1.61 in Experiment 7 (*M* detection rate 72.8% in Experiment 9; 64.1% in Experiment 7, *M* false alarm rate 19.0% in Experiment 9 and 14.9% in Experiment 7), but there was, nevertheless, a small increase in sensitivity under high load conditions, which, coupled with the more sizeable decrease in the low load condition, led to the overall reduction in the perceptual load effect. The poorer low perceptual load performance was to some degree expected, however, since half the number of low perceptual load CS trials (36) were undertaken in this experiment compared to Experiment 7 (72, so that the total number of CS trials over the whole experiment remained the same). For this reason, despite the same 50% probability of CS presentation in this experiment and in Experiment 7, a more appropriate comparison when considering individual load conditions may be with Experiment 6, in which the CS was presented with 17% probability (i.e., in 24 trials). Indeed, mean detection rate and mean *d'* in the low load condition in this experiment (85.8% and 2.58) were closer to those of Experiment 6 (84.5% and 3.08) than those of Experiment 7 (92.3% and 3.38).

4.2 Experiment 10

The purpose of Experiment 10 was to determine whether the effect of perceptual load on CS detection can be replicated in a design in which low and high perceptual load trials are presented in a randomly intermixed order. A replication with such a design would preclude alternative accounts of the results in terms of any potential differences in strategy employed by the participants in the two conditions of perceptual load. As with Experiment 9, the frequency of CS presentation was 50% for each condition of perceptual load and the participants made a CS detection response on every trial (either 'present' or 'absent').

4.2.1 Method

Participants. Twenty-two new participants were recruited from UCL and were paid for their participation. Three participants were excluded and replaced because their accuracy on the letter search task was lower than 65%, and two because they detected less than 75% of the critical stimuli in the control block. The age range of those included was 18 to 25 years (M = 20.4 years, SD = 1.7 years) and there were 13 men.

Stimuli and Procedure. The apparatus, stimuli and procedure were the same as Experiment 9 except that low and high perceptual load trials were presented in a randomly intermixed order within each block. A counterbalanced set of 144 different stimulus displays, employed across two blocks of 72 trials, consisted of each load condition (two), each of the target letters (two) in each of the letter circle positions (six), either without or with the CS in each position (six). In the high perceptual load condition there were also 72 randomly selected non-target arrangements.

4.2.2 Results and Discussion

Letter Search. As with the previous experiments, mean search RT was significantly longer (high load $M = 857$ ms; low load $M = 674$ ms) and error rate significantly higher (high load $M = 21.3\%$; low load $M = 6.0\%$) in the high perceptual load condition than the low perceptual load condition, $F(1, 21) = 199.96$, $MSE = 1844.82$, $p < .001$, $\eta_p^2 = .91$ and $F(1, 21) = 90.68$, $MSE = 28.29$, $p < .001$, $\eta_p^2 = .81$, for RT and error rate, respectively. Thus perceptual load was successfully increased with the manipulation of search set size randomly intermixed within blocks.

CS Detection. Mean percentage detection and false alarm rates and mean *d'* and β for correct search trials only as a function of perceptual load are presented in Table 10. Detection rate and *d'* were again significantly lower in the high load than low load condition, $F(1, 21) = 4.61$, $MSE = 145.89$, $p = .044$, $\eta_p^2 = .18$ and $F(1, 21) = 4.65$, $MSE = 0.17$, $p = .043$, $\eta_p^2 = .18$, for the load effect on detection rate and *d'*, respectively. β was not significantly different between the low and high load conditions, $F < 1$.

Table 10. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 10.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	87.1 (12.4)	13.0 (19.3)	2.70 (1.06)	1.78 (1.67)
High	79.4 (16.8)	9.9 (10.4)	2.43 (1.01)	2.21 (1.78)

Thus, Experiment 10 provides a successful replication of the effect of perceptual load on conscious detection using a design in which the level of load is randomly intermixed within each block of trials and hence precludes any strategy-based accounts of the results.

The Effect of Load From the Previous Trial. As mentioned in the Chapter Introduction, in a response competition study in which low and high perceptual load trials were presented in a randomly intermixed order, Theeuwes et al. (2004) found that whereas the level of load in the preceding trial made no difference in a low load trial, only high load trials that followed high load trials showed a significantly reduced distractor effect on search RTs. A similar analysis was conducted with the data from Experiment 10. Theeuwes et al.'s (2004) finding with indirect distractor effects was not replicated: two way ANOVA with load and load of previous trial as factors revealed a significant main effect of load on both detection rate and *d'*, $F(1, 21) = 5.01$, $MSE = 281.96$, $p = .036$, $\eta_p^2 = .19$ for detection rate, $F(1, 21) = 6.18$, $MSE = 0.27$, $p = .021$, $\eta_p^2 = .23$ for *d'*, as would be expected, but no main effect of load of previous trial, $F < 1$ for both detection rate and *d'*, and no interaction, $F < 1$ for detection rate, $F(1, 21) = 1.26$, $MSE = 0.30$, $p = .274$, $\eta_p^2 = .06$ for *d'*. In addition, in a third analysis on β there were no significant effects, $F(1, 21) = 1.95$, $MSE = 1.42$, $p = .177$, $\eta_p^2 = .09$ for the main effect of load, and $F < 1$ for both the main effect of load of the previous trial and the interaction.

Intermixed Load Versus Blocked Load. The results of this experiment were compared with those of Experiment 9, in which the perceptual load conditions were blocked, in a series of two way ANOVA with perceptual load and condition arrangement as factors. As would be expected, there was a main effect of perceptual load on both detection rate, $F(1, 36) = 13.10$, $MSE = 155.91$, $p = .001$, $\eta_p^2 = .27$, and *d'*, $F(1, 36) = 24.22$, $MSE = 0.22$, $p < .001$, $\eta_p^2 = .40$. But there was no main effect of condition arrangement for either, $F < 1$ for detection rate, $F(1, 36) = 1.37$, $MSE = 1.92$, $p = .250$, $\eta_p^2 = .04$ for *d'*. The size of the perceptual load effect on detection rate in this experiment ($M = 7.7\%$ decrease from low to high perceptual load) was smaller than that of Experiment 9 ($M = 13.0\%$ decrease from low to high load); however, this change was not significant, $F < 1$. The perceptual load effect on detection sensitivity, however, was significantly smaller in this experiment (*M* difference in $d' = 0.27$), compared with Experiment 9 (*M* difference in $d' = 0.79$), $F(1, 36) = 5.85$, $MSE = 0.22$, $p = .021$, $\eta_p^2 = .14$. Further inspection of the data reveals that performance in the low load condition was nearly identical in the two experiments: *M* detection rate was 87.1% and 85.8%, *M* false alarm rate for both was 13.0%, and *M d'* was 2.70 and 2.58 (for Experiments 10 and 9 respectively), whereas performance in the high load condition was better in this experiment than in Experiment 9: *M* detection rate = 79.4% and 72.8%, *M* false alarm rate 9.9% and 19.0%, and $M\ d' = 2.43$ and 1.79 (for Experiments 10 and 9 respectively). The reduction in the perceptual load effect on detection sensitivity in Experiment 10 was therefore due to an improvement in detection performance in the high load condition rather than poorer performance in the low load condition compared to Experiment 9. There were no significant effects on β, all $F < 1$.

4.3 Experiment 11

In Experiment 10, the effect of load was significantly reduced when load trials were presented in a randomly intermixed order and when the CS was presented in 50% of trials. It is possible that with intermixed perceptual load trials the effect of load might be stronger when the CS is presented less frequently. Experiment 11, therefore, was the same as Experiment 10 in all respects except that the CS was presented in 17% of trials rather than 50%.

4.3.1 Method

Participants. Twenty-two new participants were recruited from UCL and were paid for their participation. Ten participants were replaced because they detected less than 75% of the CS in the control block, four because their accuracy at the letter search task was lower than 65%, three because their mean letter search RT was either two *SD* above or below the group mean, and one because her false alarm rate in the control blocks was 72%. The age range of those included was 19 to 29 years ($M = 22.0$ years, $SD = 2.9$ years) and there were seven men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were the same as Experiment 10 except that the CS was presented in 17% of trials, and there were four blocks of 72 trials rather than two so that the number of trials in which the CS was presented per condition was not too low (i.e., 24 rather than 12).

4.3.2 Results and Discussion

Letter Search. Perceptual load was again successfully increased with the manipulation of search set size randomly intermixed within blocks: mean search RT was significantly longer (high load $M = 833$ ms; low load $M = 655$ ms) and error rate significantly higher (high load $M = 19.6\%$; low load $M = 5.6\%$) in the high perceptual load condition than the low perceptual load condition, $F(1, 21) = 141.56$, $MSE = 2458.49$, $p < .001$, $\eta_p^2 = .87$ and $F(1, 21) = 109.63$, $MSE = 19.67$, $p < .001$, $\eta_p^2 = .84$ for RT and error rate, respectively.

CS Detection. Table 11 shows mean percentage detection and false alarm rates and mean *d'* and β for correct search trials only as a function of perceptual load.

Table 11. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 11.

Perceptual load	Detection rate %	False alarm rate %	*d'*	β
Low	84.0 (15.7)	17.3 (20.5)	2.45 (1.05)	3.87 (7.55)
High	71.5 (26.3)	14.4 (19.8)	2.17 (1.20)	4.29 (5.73)

Detection rate and *d'* were again significantly lower in the high load than low load condition, $F(1, 21) = 15.15$, $MSE = 114.43$, $p = .001$, $\eta_p^2 = .42$ and $F(1, 21) = 4.68$, $MSE = 0.18$, $p = .042$, $\eta_p^2 = .18$ for the load effect on detection rate and *d'*, respectively. β was not significantly different between the low and high load conditions, $F < 1$. Thus, Experiment 11 provides a successful replication of the effect of perceptual load on conscious detection using a design in which the level of load is randomly intermixed within each block and CS frequency is 17% of trials rather than 50% (as in Experiment 10).

The Effect of CS Frequency. The results of this experiment were compared with those of Experiment 10 (in which CS frequency was 50%) in a series of two way ANOVA with perceptual load and CS frequency as factors. As would be expected, there was a main effect of perceptual load on both detection rate, $F(1, 42) = 17.41$, $MSE = 130.29$, $p < .001$, $\eta_p^2 = .29$, and *d'*, $F(1, 42) = 7.91$, $MSE = 0.19$, $p = .007$, $\eta_p^2 = .16$. But there was no main effect of CS frequency for either, $F(1, 42) = 1.20$, $MSE = 556.37$, $p = .279$, $\eta_p^2 = .03$ for detection rate, $F < 1$ for *d'*. Reducing the frequency of CS presentation produced a numerical trend in mean detection rate for a stronger effect of perceptual load (12.5% reduction rather than 7.7% reduction in Experiment 10); however, this was not significant, and neither was it for *d'*, $F < 1$ for both. There were no significant effects on β, $F < 1$ for the main effect of perceptual load, $F(1, 42) = 2.23$, $MSE = 42.64$, $p = .143$, $\eta_p^2 = .05$ for the main effect of CS frequency, and $F < 1$ for the interaction.

4.4 Chapter Conclusions

Three experiments with a within-subjects design showed reduced conscious awareness when attention is focused on a task of high perceptual load compared to when it is focused on a task of low perceptual load. Irrespective of whether perceptual load conditions were blocked (Experiment 9), or were randomly intermixed within each block (Experiments 10 and 11), detection rate and detection sensitivity were both significantly lower in high load trials than low load trials. Furthermore, this effect was demonstrated with relatively high and low frequencies of CS presentation: 50% in Experiment 10, and 17% in Experiment 11.

The effect of perceptual load on detection, however, became weaker with the change from a between-subjects design to a within-subjects design, predominantly as a result of an increase in the rate of false alarms in the low perceptual load condition. The perceptual load effect became weaker still with the change from having the conditions of perceptual load in separate blocks to having load conditions randomly intermixed within each block. This may reflect the fact that there was a strategy component of the perceptual load effect in the experiments in Chapters 2 and 3.

Chapter 5

Load Induced Blindness at Fixation

We have seen in the preceding chapters that loading perception can prevent task-irrelevant stimuli from entering into conscious awareness. Such stimuli have, thus far, been presented exclusively in the peripheral field of view. An important question to ask is, could an object appearing directly at the point of fixation fail to enter awareness, or is conscious perception at fixation independent of perceptual load? Furthermore, is awareness of objects at fixation more likely than when they appear in peripheral vision, or equally likely?

In terms of resources, the visual system is hugely biased towards processing information that falls on the fovea (the point of fixation). It has been established that visual perception is superior at the fovea than in the periphery: acuity and contrast sensitivity are heightened due to the triplication of cone density (Devalois & Devalois, 1988; Fiorentini & Berardi, 1991), and although the area of the fovea covers only 1% of the retina, over 50% of the visual cortex is devoted to foveal vision and cells' receptive fields are much smaller making resolution higher (Connolly & Van Essen, 1984; Daniel & Whitteridge, 1961; Hubel & Wiesel, 1974). In addition to this perceptual superiority, there is a multitude of evidence that attention is closely tied to the point of fixation. In spite of demonstrations that attention can be shifted away from fixation when the eye is stationary (Posner, 1980; Posner, Nissen, & Ogden, 1978), research strongly suggests that attention and fixation are intimately linked, since the eyes tend to follow shifts of attention (Bryden, 1961; Crovitz & Davies, 1962) and, conversely, attention is typically reallocated in the direction of gaze (Chelazzi et al., 1996; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Shephard, Findlay, & Hockey, 1986). In addition, similar regions of frontoparietal cortex are activated by saccades and shifts of spatial attention when the eye is stationary (Corbetta et al., 1998).

Several lines of research have addressed the effect of eccentricity on visual search, although only some of these have involved stimuli presented at the fovea. Carrasco, Evert, Chang, and Katz (1995) asked participants to perform a visual search task for a conjunction of features in a square grid containing up to 36 items. Target eccentricity varied between 0.7° and 3.5°. RTs and error rates increased monotonically with increasing eccentricity, even with very short exposure durations (104 and 62 ms), thus ruling out eye movements and multiple covert attentional shifts as confounds. A follow-up study (Carrasco & Frieder, 1997) suggested that this eccentricity effect was entirely due to the poorer visibility of peripheral targets, since the effect was eliminated when the sizes of the stimuli were scaled in accordance with the cortical magnification formula of Rovamo and Virsu (1979). Wolfe, O'Neil, and Bennett (1998), however, have contested this conclusion: they found that visibility differences made only a minor contribution to the eccentricity effect, since it persisted when items' sizes were scaled. The discrepancy between these results may be explained by the fact that Carasco and Frieder's (1997) search items in the non-scaled condition were much smaller than Wolfe et al.'s (1998) and so were less visible. The size-scaling in Carasco and Frieder's (1997) experiment would therefore have aided visibility to a much greater extent than in Wolfe et al.'s (1998). Furthermore, Wolfe et al. (1998) demonstrated that the eccentricity effect was eliminated when the search set size was one (i.e., when targets were presented alone so no search was required) and when search items were presented in a ring centred at fixation and of variable radius (1.8° to 7°) so that all items were of equal eccentricity. These results strongly suggest that there is more than visibility at work in the eccentricity effect, and indeed Wolfe et al. (1998) propose that attention is the culprit – i.e., objects closer to fixation are prioritised in processing terms over those in the periphery.

Studies comparing the processing of stimuli at fixation and in the periphery involving the response competition paradigm have also produced conflicting data. Goolkasian (1981) used a Stroop paradigm to investigate the effects of distractors presented at fixation. The word of a colour, i.e., either 'RED' or 'GREEN', was presented at fixation as a distractor, as well as a target colour patch in the periphery, at varied eccentricities. As with the visual search studies, display durations were brief to prevent eye movements (this was the case with all the response competition experiments I review next). The incongruent fixation distractor interfered with colour classification at all target locations except the most distant and the effect weakened as target eccentricity increased. A peripheral distractor condition was not included in this experiment, however, and therefore it was not possible to directly compare the effects of fixation distractors with peripheral distractors. Later, Goolkasian (1999) presented either a target at fixation with a peripheral distractor at varied eccentricity, or a distractor at fixation with the target in the periphery at varied eccentricity. Targets and distractors were either a capital letter 'A' or a capital 'B' and the presentation time was 50 ms, a short enough duration to ensure that no eye movements were possible. Distractor compatibility effects varied not only in association with the distractor's distance from the target, but also with respect to the retinal location of the target and distractor stimuli. The processing of targets presented at fixation was slowed by the presence of an incompatible distractor at any location in the periphery, whereas targets in the periphery were only affected by a distractor at fixation if they were close together. Thus distance effects were obtained across a wider area of visual space when distractors were located in the periphery rather than at fixation. Furthermore, the compatibility effects of fixation distractors were smaller than those of peripheral distractors. Goolkasian suggested that this indicates that the processing of stimuli at fixation may be more effectively controlled and therefore, that stimuli at fixation can be more easily ignored than those presented in the periphery. However, Goolkasian's methodology was confounded, since the peripheral targets in the fixation distractor condition would have been more difficult to identify than the targets at fixation in the peripheral distractor condition due to poorer visibility, and furthermore, peripheral targets could be presented in multiple locations whereas fixation targets were always presented at the same location, resulting in lesser location certainty for peripheral targets, a quality known to impair performance (Bashinski & Bacharach, 1980). Thus, the demand on attentional resources required by the task was not equivalent between fixation and peripheral distractor conditions, and therefore fixation distractors may have been rendered less effective than peripheral distractors by the greater load on attention in the fixation distractor condition.

Beck and Lavie (2005) succeeded in comparing the response compatibility effects of distractors at fixation with distractors in the periphery, while avoiding the confounds that Goolkasian's experiments were subject to. They presented the task stimuli in a parafoveal circle so that the task was identical across fixation and peripheral distractor conditions in which only the location of the distractor was varied and the target-to-distractor distance always remained constant. Beck and Lavie obtained results in contrast to Goolkasian's, such that the decrement to reaction time elicited by incongruent over congruent distractors was greater from those presented at fixation than those presented peripherally. These effects could not be attributed to the perceptual superiority of the fovea, as they persisted even when the sizes of the stimuli were scaled by the cortical magnification factor (Rovamo & Virsu, 1979). Neither could they be attributed to cueing by the fixation point, or the fact that fixation distractors were presented in the centre of the target letter-circle, while peripheral distractors were presented outside it, as these potential confounds were also cast aside by additional experiments. The authors contend that fixation distractors exerted greater compatibility effects than peripheral distractors due to a prioritisation of attention at fixation that affects the strength of competition for response selection between distractor and target stimuli. An additional important finding from this study was that increasing the perceptual load of the task reduced the effects of distractors at fixation to the same extent as it reduced the effects of distractors in the periphery. Such a result suggests that the processing of information at fixation, despite being a higher priority, is subject to the same capacity limits as the processing of information elsewhere in the visual field.

However, in all these studies the conclusions regarding irrelevant stimulus processing are based upon indirect measures of perception, such as the effects of distractors on target RTs. They can not support any direct conclusions about conscious perception since it can not be deduced whether a participant was conscious of the distractors or not on the basis of their RT to the target. While much of this research, therefore, provides convincing evidence that the processing of information at fixation is prioritised over the processing of information elsewhere in the visual field, it can tell us nothing about the participants' conscious awareness of such information.

Only one previous study has employed a direct measure of conscious perception. Mack and Rock (1998) compared levels of inattentional blindness for an unexpected object presented at fixation with the same object presented in the periphery. Twenty-five percent of participants viewing the peripheral unexpected object did not notice it, whereas as many as 85% of those viewing the same object at fixation failed to notice its presence. However, as with Goolkasian's experiments, the attentional resources demanded by the task were not equivalent between conditions, as the target stimulus in the fixation unexpected object condition was presented peripherally, and in one of four locations, whereas the target stimulus in the peripheral unexpected object condition was always presented at fixation. The perceptual inferiority of peripheral vision, the additional strain on attention engendered by having to focus attention way from fixation, and the greater location uncertainty when the target stimulus was presented in the periphery would have resulted in a greater demand on attention than when the target stimulus was presented at fixation. These counter-intuitive results can therefore be explained in terms of fewer attentional resources being available to perceive the unexpected object when it was presented at fixation, since such resources would have been drawn by the higher load on attention required to perform the task when the target stimulus was presented in the periphery.

The experiments in this chapter compare awareness of a CS presented at fixation with awareness of a CS presented in one peripheral location under different levels of perceptual load (except Experiment 14 that had only a high perceptual load condition). Perceptual load was manipulated by increasing the search set size from one to six as with the previous chapters, and the CS was presented either at fixation, in which case it was smaller, or in the periphery. It was predicted that conscious awareness of the CS would be greater at fixation, but should still be reduced by high perceptual load.

5.1 Experiment 12

Experiment 12 examined whether the perceptual load of the search task would determine detection even when the CS was presented directly where participants were looking, i.e., at the point of fixation. As a comparison, the CS was also presented in one location outside of the circle of letters, either on the left or the right side. The peripheral CS was the same size as in previous experiments, but the fixation CS was made smaller than the peripheral CS in accordance with the cortical magnification formula of Rovamo and Virsu (1979) to compensate for the poorer contrast sensitivity of peripheral vision and the smaller area of cortex activated by peripheral stimuli.

5.1.1 Method

Participants. Twenty new participants were recruited from UCL and were paid for their participation. One participant was replaced because she detected less than 75% of the CS in the control block, and two because their accuracy at the letter search task was below 65%. The age range of those included was 19 to 32 years (M = 21.3 years, SD = 2.8 years) and there were eight men.

Stimuli and Procedure. The apparatus, stimuli, and procedure were identical to Experiment 2 except that the CS was presented in only one of two locations, one at fixation (the centre of the screen) and the other on one side, either on the left or on the right of the circle of letters on the horizontal midline, 5.4° of visual angle from the fixation point. The CS was presented in 50% of trials and half of them were at fixation, with the other half in the periphery. Note that due to the change from six possible CS locations (as in all previous experiments except Experiment 8) to two possible CS locations (as in Experiment 8), the location certainty of the CS increased from 17% in each location to 50% in each location. The fixation CS (at 0° eccentricity) subtended 0.11° by 0.11° and the peripheral CS, presented at 5.4° eccentricity, subtended 0.3° by 0.3° was thus 2.76 times larger than the fixation CS in accordance with the cortical magnification formula of Rovamo and Virsu (1979). The letter circle was made slightly larger (1.8° radius) to make the distance between the nearest target letters and the CS the same whether the CS was presented at fixation or in the periphery. As with Experiments 6-11, the question mark signifying that the detection response could be made was presented for 2 s with no blank following it. A counterbalanced set of 144 different stimulus displays consisted of each of the target letters (two) in each of the letter circle positions (six), as well as the CS in each position (two).

5.1.2 Results and Discussion

Letter Search Task. Perceptual load was successfully increased with the manipulation of search set size in Experiment 12: mean search RT was significantly longer in the high perceptual load condition (M = 847 ms) than the low perceptual load condition (M = 702 ms), $F(1, 18) = 5.19$, $MSE = 20{,}182.47$, $p = .035$, $\eta_p^2 = .22$, and error rate in the high perceptual load condition (M = 20.0%) was significantly higher than in the low perceptual load condition (M = 8.7%), $F(1, 18) = 12.85$, $MSE = 49.67$, $p = .002$, $\eta_p^2 = .42$.

CS Detection. Mean percentage detection rate as a function of perceptual load and CS location, and mean percentage false alarm rate and mean d' and β as a function of perceptual load are presented in Table 12 (correct search trials only). Since false alarm responses could not be assigned to CS location conditions, in all the experiments in this chapter false alarm rate, *d'*, and β are not given by CS location.

Table 12. Mean (and *SD*) Percentage Detection Rate as a Function of Perceptual Load and CS Location and Mean (and *SD*) Percentage False Alarm Rate and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 12.

	CS location				
	Fixation	Periphery			
Perceptual load	Detection rate %		FA rate %	*d'*	β
Low	80.2 (29.2)	98.0 (4.3)	5.0 (8.0)	3.37 (1.07)	3.42 (2.69)
High	46.0 (34.7)	74.1 (38.1)	3.4 (3.2)	2.27 (1.24)	7.28 (9.07)

In a three way ANOVA on detection rate with load, CS location, and side as factors and a two way ANOVA on *d'* with load and side as factors, there were main effects of perceptual load, as expected: detection rate and *d'* were significantly lower under high perceptual load than low, $F(1, 16) = 7.61$, $MSE = 1094.01$, $p = .014$, $\eta_p^2 = .32$ and $F(1, 16) = 4.71$, $MSE = 1.29$, $p = .045$, $\eta_p^2 = .23$ for detection rate and *d'*, respectively. In a further two way ANOVA on β with load and side as factors, there was no main effect of perceptual load, as with previous experiments, $F(1, 16) = 1.76$, $MSE = 42.39$, $p = .204$, $\eta_p^2 = .10$. The main effect of CS location on detection rate was also significant, but contrary to expectations mean detection rate was lower at fixation than in the periphery, $F(1, 16) = 6.55$, $MSE = 644.49$, $p = .021$, $\eta_p^2 = .29$. There was no interaction of load and location, $F < 1$. A paired comparison revealed that the detection rate for CS presented at fixation was significantly reduced by high perceptual load, $t(18) = 2.39$, $SEM = 14.37$, $p = .028$, and that the detection rate for CS presented in the periphery followed the same trend, but fell short of achieving significance, $t(18) = 1.97$, $SEM = 12.11$, $p = .064$. These results support the previous finding that load modulates the interference effect of distractors at fixation as well as those in the periphery (Beck & Lavie, 2005).

Whether the peripheral CS was presented on the left or the right had no effect on detection rate, *d'*, or β: $F(1, 16) = 1.94$, $MSE = 1094.01$, $p = .183$, $\eta_p^2 = .11$; $F(1, 16) = 2.29$, $MSE = 1.29$, $p = .150$, $\eta_p^2 = .13$; $F < 1$; there was no interaction of side with load: $F(1, 16) = 1.53$, $MSE = 1094.01$, $p = .234$, $\eta_p^2 = .09$ for detection rate; $F < 1$ for *d'*; $F(1, 16) = 2.83$, $MSE = 42.39$, $p = .112$, $\eta_p^2 = .15$ for β; in the three way ANOVA on detection rate there was no interaction of side with CS location or side with load and CS location, both $F < 1$.

Fixation CS were harder to detect for two reasons – they were very small (Goolkasian [1994, 1999] has shown previously that size scaling can only correct for cortical magnification when fixation stimuli subtend at least 0.7° - here they subtended 0.1°) and they may have been masked by the after-image of the question mark presented at fixation to indicate when the CS detection response should be made. These issues were addressed in the next experiment.

5.2 Experiment 13

In order to provide a better test of whether stimuli at fixation are more likely to enter conscious awareness than stimuli in the periphery, in Experiment 13 the fixation CS was increased in size to 0.7° in accordance with the findings of Goolkasian (1994, 1999). The size of the peripheral CS therefore became 1.9°.

Furthermore, the question mark used to indicate the time to make the CS detection response was replaced with a low-pitched tone in order to prevent the afterimage of the centrally located question mark masking the fixation CS on the following trial.

5.2.1 Method

Participants. Fifteen new participants were recruited from UCL and were paid for their participation. Three participants were replaced because their accuracy at the letter search task was below 65%. The age range was 18 to 30 years (M = 22.5 years, SD = 3.5 years) and there were five men. All of the participants had normal or corrected-to-normal vision and were naïve to the purposes of the experiment.

Stimuli and Procedure. The apparatus, stimuli and procedure were the same as Experiment 12 except that the participants were now instructed to press the 'A' key when the CS was absent rather than make no response. The fixation CS (at 0° eccentricity) was increased in size to 0.7° by 0.7° (from Goolkasian, 1994, 1999), which meant that the peripheral CS (remaining at 5.4° eccentricity as in Experiment 12) was now 1.9° by 1.9° (2.76 times larger in accordance with the cortical magnification formula of Rovamo & Virsu, 1979). Due to the large increase in size of the peripheral CS, the letter circle had to be made slightly smaller (1.7° radius) to equate the distance between both CS locations and the nearest target letters. Finally, the question mark presented for 2 s to indicate when participants should make their detection response was replaced with a 2 s low-pitched tone.

5.2.2 Results and Discussion

Letter Search. Perceptual load was again successfully increased with the manipulation of search set size in Experiment 13: mean search RT was significantly longer and error rate significantly higher in the high perceptual load condition (M RT = 1039 ms and M error rate = 21.3%) than the low (M RT = 682 ms and M error rate = 6.0%), $F(1, 13) = 44.54$, $MSE = 10{,}309.71$, $p < .001$, $\eta_p^2 = .77$ for RT, and $F(1, 13) = 18.97$, $MSE = 44.62$, $p = .001$, $\eta_p^2 = .59$ for error rate.

CS Detection. Mean percentage detection rate as a function of perceptual load and CS location, and mean percentage false alarm rate and mean *d'* and β as a function of perceptual load are presented in Table 13 (correct search trials only).

Table 13. Mean (and *SD*) Percentage Detection Rate as a Function of Perceptual Load and CS Location and Mean (and *SD*) Percentage False Alarm Rate and Mean (and *SD*) *d'* and β as a Function of Perceptual Load in Experiment 13.

	CS location				
	Fixation	Periphery			
Perceptual load	Detection rate %		FA rate %	*d'*	β
Low	98.6 (3.4)	90.3 (13.4)	3.7 (2.4)	3.55 (0.34)	4.41 (8.53)
High	88.6 (17.4)	90.8 (17.0)	3.9 (4.6)	3.38 (0.99)	2.21 (0.85)

As the table suggests, detection rate was not significantly lower under high perceptual load than low, $F < 1$. *d'* across locations was also not significantly lower in the high load condition, and neither was β, both $F < 1$. There was also no effect of CS location on detection rate, $F(1, 11) = 1.01$, $MSE = 65.82$, $p = .337$, $\eta_p^2 = .08$. Clearly the larger sized CS were much easier to detect, unfortunately resulting in a ceiling effect in this experiment, but nevertheless there was a numerical trend towards an interaction between load and CS location, $F(1, 11) = 3.05$, MSE = 65.82, $p = .109$, $\eta_p^2 = .22$, such that under low perceptual load, there was a trend for more fixation CS being detected (M = 98.6%) than peripheral CS (M = 90.3%), $t(5) = 1.94$, SEM = 4.30, $p = .111$, but there was very little difference (M = 2.2%) between fixation and peripheral CS under high perceptual load, $t < 1$. In addition, there was a non-significant numerical trend for fewer fixation CS being detected under high (M = 88.6%) than low (M = 98.6%) perceptual load, $t(13) = 1.37$, SEM = 7.30, $p = .195$, but there was no difference for peripheral CS (M = 90.8% vs. 90.3%), $t < 1$. Whether the peripheral CS was presented on the left or the right had no effect on detection rate, and did not interact with load or location or both, all $F < 1$.

5.3 Experiment 14

In Experiment 13, CS detection performance was near to ceiling, so in Experiment 14 the CS was made fainter in order to reduce the contrast between the CS and the background so that detection would be more difficult, thus preventing a ceiling effect. Only the high perceptual load condition was run to ensure that detection performance was off the ceiling. Detection rate was predicted to be higher for fixation CS than peripheral CS.

5.3.1 Method

Participants. Eight new participants were recruited from UCL and were paid for their participation. Eight participants were replaced because they detected less than 75% of the CS in the control block, and six because their accuracy at the letter search task was below 65%. The age range of those included was 21 to 29 years (M = 25.3 years, SD = 3.0 years) and there were two men.

Stimuli and Procedure. The apparatus, stimuli and procedure were the same as Experiment 13 except that the letter search task was always of high perceptual load, the CS was presented in 50% of trials rather than 17% (as per Experiment 7), and the CS was a lighter shade of grey (RGB values: 197, 197, 197).

5.3.2 Results and Discussion

Letter Search. Mean search RT was 767 ms and mean error rate was 15.0%, both of which are comparable to high perceptual load search task performance in previous experiments.

CS Detection. Mean percentage detection rate as a function of CS location, and mean percentage false alarm rate and mean d' and β are presented in Table 14 (correct search trials only).

Table 14. Mean (and SD) Percentage Detection Rate as a Function of CS Location and Mean (and SD) Percentage False Alarm Rate and Mean (and SD) d' and β in Experiment 14.

	CS location				
	Fixation	Periphery			
Perceptual load	Detection rate %		FA rate %	d'	β
High	90.5 (9.4)	53.4 (26.5)	10.5 (6.3)	1.93 (0.70)	1.90 (0.40)

As can be seen in the table, detection rate was significantly higher when the CS was presented at fixation compared to when it was presented in the periphery, $F(1, 6) = 15.76$, $MSE = 349.59$, $p = .007$, $\eta_p^2 = .72$, and whether the peripheral CS was presented on the left or the right had no effect on detection rate, $F(1, 6) = 2.24$,

$MSE = 345.87$, $p = .185$, $\eta_p^2 = .27$, and there was no interaction between these two factors, $F(1, 6) = 1.63$, $MSE = 349.59$, $p = .249$, $\eta_p^2 = .21$. These data provide support for the notion that a greater attentional weight at fixation leads to stimuli being more likely to enter into awareness than stimuli appearing elsewhere in the visual field.

5.4 Chapter Conclusions

The results of Experiment 12 demonstrated that the effect of perceptual load on conscious awareness can be generalised to stimuli located at fixation. Furthermore, Experiment 14 showed that stimuli at fixation are more likely to enter awareness than stimuli appearing in peripheral vision, despite being size-scaled to equate visibility. These results compliment previous research that employed indirect measures of perception, showing that distractor interference effects are modulated by perceptual load but that interference from fixation distractors is greater than from peripheral distractors (Beck & Lavie, 2005). Taken together, these findings support the notion that stimuli falling upon the fovea are prioritised for processing. In other words, there is a greater weight of attention at the fovea that renders any information located there more capable of causing interference and more likely to enter conscious awareness.

Chapter 6

The Role of Working Memory Load

An important dissociation in load theory is between the effects of perceptual load and working memory load on selective attention (Lavie, 2000; Lavie, Hirst, De Fockert, & Viding, 2004). Whereas high perceptual load reduces distractor processing, high working memory load increases distractor processing. This dissociation is important as it highlights two different means of attentional control. The effects of perceptual load indicate a rather passive means of attentional selection, whereby the irrelevant distractors are simply not perceived when perceptual capacity is exhausted by task-relevant processing under high perceptual load. The effects of working memory load indicate a more active executive control role: working memory actively maintains stimulus processing priorities in a task, so when working memory is loaded with task-unrelated material, processing of distractors in the selective attention task is increased. Evidence for this dissociation has come from studies demonstrating that in contrast with the reduction in distractor effects found with tasks of high perceptual load, high working memory load increases distractor effects, on both RTs (in the response competition and attentional capture paradigms, e.g., Lavie, 2000; Lavie & De Fockert, 2005; Lavie et al., 2004) and neural activity (related to irrelevant distractor faces in a Stroop-like paradigm, De Fockert, Rees, Frith, & Lavie, 2001). I review these studies below.

Lavie et al. (2004) asked participants to perform a low perceptual load search task with a congruent or incongruent distractor presented on each trial (low perceptual load so that the distractors would be processed), while manipulating the availability of cognitive control processes by varying the load on working memory. This was achieved by requiring that participants remember either a single digit (low working memory load) or a set of six digits (high working memory load), while performing the search task. Participants' memory for the set of digits was tested by asking whether a probe digit (presented after the search task had been completed on each trial) had been a member of the memory set or not. Lavie et al. (2004) intended that by loading working memory, the availability of cognitive control processes required to differentiate between competing relevant and irrelevant stimuli would be reduced, resulting in an increase in the frequency of intrusions from irrelevant stimuli. This is exactly what was found: in the high working memory load condition, incongruent distractors produced a larger RT decrement and a larger increase in error rates compared to congruent distractors, than in the low working memory load condition. This finding supports the theory that the availability of cognitive control processes, and specifically, working memory, determines the efficiency of selective attention.

The effect of working memory load is precisely the opposite to that of perceptual load (Lavie, 1995), i.e., under high perceptual load distractor effects are decreased, whereas under high working memory load, distractor effects increase. These two effects were demonstrated in the same experiment by Lavie et al. (2004), in which both perceptual load and working memory load were manipulated: under low perceptual load, there were large distractor effects on RTs in both conditions of working memory load, but they were larger under high working memory load than low (111 ms vs. 72 ms). Under high perceptual load, these distractor effects all but disappeared, but were still larger under high working memory load (35 ms vs. -8 ms under low working memory load). Thus, the increase in interference caused by loading working memory can be seen to occur even under conditions of high perceptual load, and likewise, high perceptual load still drastically diminishes the processing of task-irrelevant information even when the ability of cognitive control to maintain the focus of selective attention on task priorities is impaired. The stark contrast between the opposing outcomes of loading the perceptual and working memory systems gives weight to Lavie and colleagues' hypothesis that there exist two dissociable mechanisms by which selective attention can resist distraction: a passive form of control in which interference is eliminated when there is insufficient capacity remaining to process any information other than that specific to the task at hand, and an active form that engages working memory in maintaining current task processing priorities, thereby suppressing the processing of information not related to the task.

Loading working memory is not the only way to diminish the availability of cognitive control processes that would otherwise strive to prevent distraction. Indeed, a greater demand on such processes also occurs during multi-tasking (e.g., Della Sala, Baddeley, Papagano, & Spinnler, 1995; D'Esposito et al., 1995; Miller & Cohen, 2001; Shallice & Burgess, 1996). Lavie et al. (2004) demonstrated that exactly the same effect as that produced by loading working memory is achieved when executive control is required to coordinate two tasks simultaneously. Distractor interference effects exerted during the performance of a single, low perceptual load search task were compared with those produced while participants undertook the same search task immediately following the completion of a working memory task (the same stimuli and individual task procedures as those used in the aforementioned experiments by Lavie et al. (2004) were employed – the only difference being that the working memory task probe was presented and responded to before the search task display was presented). Two such experiments were run, one in which the working memory task was of low load, and another in which it was of high load. The results were the same regardless of the level of working memory load: distractor effects on RTs were increased by approximately 30 ms in both cases, a comparable increase to those produced by the change from low working memory load to high in Lavie et al.'s (2004) other experiments. Overall distractor effects were somewhat smaller in these single vs. dual-task experiments (approx. 60 ms) than in the low vs. high working memory load experiments (between 100 and 200 ms), as would be expected, since the low vs. high working memory load experiments were all also dual-task situations, so the demand on cognitive control was compounded by the combination of working memory load and dual-task coordination.

The support for Lavie and colleagues' cognitive control hypothesis has been broadened recently by the finding that the effects of attentional capture by singletons are increased under conditions of high working memory load, just as are the effects of response competitive distractors. Lavie and De Fockert (2005) reported that two different manipulations of working memory load each produced an approximately 40 ms increase in RT decrement in the presence of a singular green circle among a set of red circles compared with when there were only red circles, while a line orientation task was performed in which each line was contained within one coloured circle. The increased distraction that occurs when cognitive control processes are rendered less effective in preventing intrusions is therefore not limited to response-related distractors, but also occurs in the presence of perceptually salient singletons.

Lastly, the effects of working memory load on the processing of irrelevant information have been replicated in a neuroimaging study involving the response competitive distractor effects of pictures of faces (De Fockert et al., 2001). A working memory task involving the maintenance of the order of a sequence of digits (the numbers one to four in a random order in the high working memory load condition; in numerical order in the low working memory load condition) was interleaved with a name categorisation task, in which famous politicians' and pop stars' names had to be identified as such while congruent or incongruent pictures of the faces of the same celebrities were presented. Not only were face distractor interference effects greater in high working memory load than low, for both RTs (78 ms vs. 46 ms; note an increase of approximately 30 ms as per the aforementioned experiments) and error rates, but neural activity in the fusiform gyrus and other areas of extrastriate cortex known to be associated with the processing of faces (e.g., Kanwisher, McDermott, & Chun, 1997) occurring when the distractor faces were presented, was greater under conditions of high working memory load than low. Taken together, the behavioural and neuroimaging findings reported by De Fockert et al. (2001) provide highly convincing evidence in support of the hypothesis that extraneous information is not so easily dismissed when processes of cognitive control are less readily available to maintain current task priorities due to the loading of working memory.

As with the vast majority of the research on perceptual load, however, the evidence that working memory load increases distractor processing is thus far limited to indirect measures that can not lead to any definitive conclusions regarding conscious perception. The next experiments therefore sought to examine the effects of working memory load on detection. Experiment 15 compared detection sensitivity of the CS while performing a low perceptual load search task under conditions of high and low working memory load. Experiment 16 manipulated perceptual load, in addition to working memory load, while assessing the effects of those manipulations and their interaction, on CS detection sensitivity in some blocks of trials, and on response competitive distractors in others.

6.1 Experiment 15

In Experiment 15, the visual search and CS detection task were interleaved with a working memory task. A memory set of either one digit (in the low working memory load condition) or six digits (in the high working memory load condition) was presented at the start of each trial followed by the search and detection tasks. Participants had to retain the digit(s) in working memory while performing the search and detection tasks in order to judge whether a probe digit presented at the end of the trial had been a member of the memory set. The search task was always of low perceptual load and was identical to that used in the previous experiments.

6.1.1 Method

Participants. Twelve new participants were recruited from UCL and were paid for their participation. One participant was replaced because he detected less than 75% of the CS in the control block, and another because his false alarm rate was 100% in the experimental blocks. The age range of those included was 20 to 32 years (M = 25.5 years, SD = 4.1 years) and there were four men.

Stimuli and Procedure. A schematic of the procedure of Experiment 15 is shown in Figure 10. The stimuli and procedure for the visual search and CS detection task were the same as those used in the low perceptual load condition of Experiment 7. The stimuli for the working memory task (as per Lavie, 2000; Lavie et al., 2004) consisted of a memory set of either a single digit (low working memory load) or six digits (high working memory load). The digits for each memory set were selected at random from 0 to 9, and each digit was equally likely to be present in the memory set of each load condition. The order of the six digits in the memory set of the high working memory load condition was random, with the constraint that no more than two digits were presented in sequential order. The digits were black, subtended 0.7° by 0.5°, and were centred on the screen, in a row when there were six digits (high load condition). The memory probe digit had the same colour and dimensions as the memory set digits and was also centred on the screen. Whether a probe was or was not a member of the memory set was equally likely, and was counterbalanced with respect to CS presence and CS position. In the high working memory load condition the probe digit was equally likely to have been in any of the six digit positions in the memory set. At the beginning of each trial, a fixation dot was presented for 1 s followed by a 1 s presentation of the memory set display. A mask consisting of a 4° by 1.4° patch of random noise (black and grey) occupying the same position as the six digits was then presented for 500 ms followed by a blank screen (500 ms). The letter circle was then displayed (100 ms) followed by a mask (500 ms) and then the words 'which letter?' at the centre of the screen (1400 ms), during which time participants made their response to the search task. Next, the word 'spot?' (black letters subtending 0.9° by 0.7°) was presented at the centre of the screen until the detection response was made (either present or absent, 'S' or 'A' key). The detection response was followed by the presentation of the memory probe at the centre of the screen, which remained on screen until participants made their memory task response. Participants used their left hand to press the 'S' key if the probe was present in the memory set, or the 'A' key if it was absent. Incorrect memory task responses were followed by a beep (lower in pitch than the beep given as feedback for the search task). In the control block the participants were instructed to ignore the memory set and simply press ‘A’ in response to all memory probes. Each of the working memory load conditions was presented in a 72-trial block consisting of a counterbalanced set of stimulus displays, with equal likelihood of each of the target letters (two), in each of the letter circle positions (six), either without or with the CS in each position (six). Half of the participants performed the low load block first and the other half performed the high load block first. The control block used half of the trials from the low load block and half from the high load block.

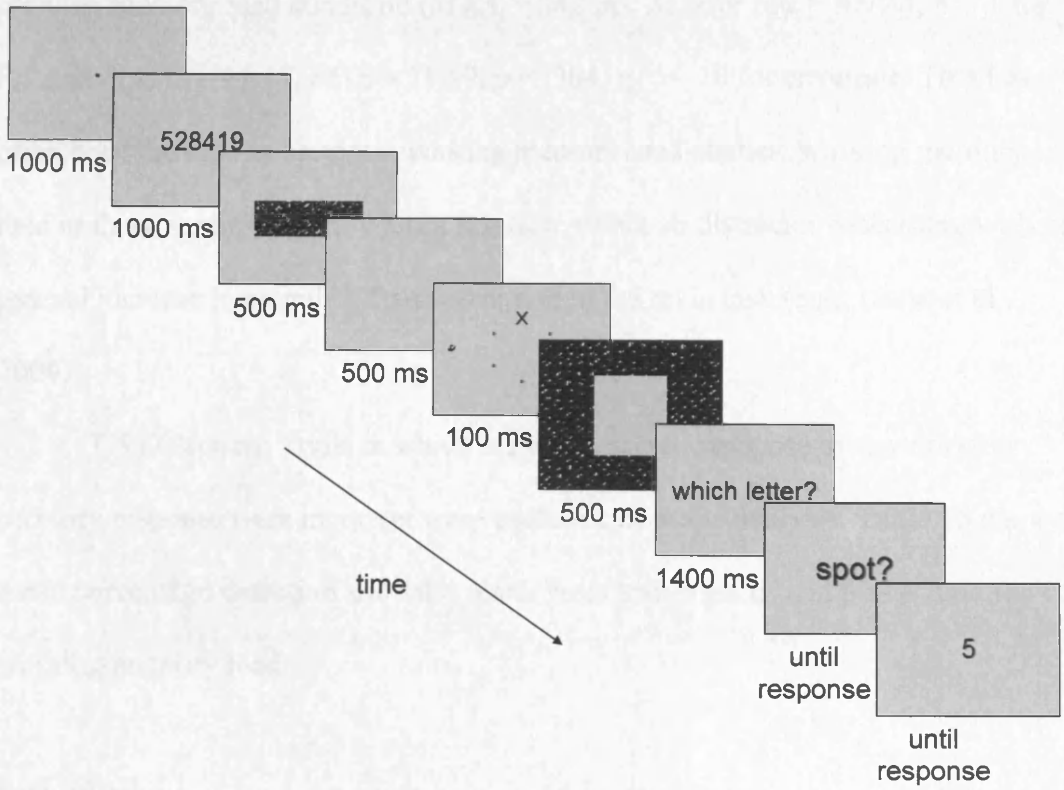

Figure 10. A schematic of the procedure of Experiment 15.

6.1.2 Results and Discussion

Working Memory Task. Longer mean RT and a greater number of errors in the high working memory load condition (*M* RT = 1296 ms; *M* error rate = 14.6%) than in the low working memory load condition (*M* RT = 1028 ms; *M* error rate = 7.7%) confirmed that the manipulation of working memory load by memory set size was effective, $F(1, 11) = 17.93$, $MSE = 24{,}116.41$, $p = .001$, $\eta_p^2 = .62$ for RT; $F(1, 11) = 8.24$, $MSE = 33.99$, $p = .015$, $\eta_p^2 = .43$ for error rate.

Letter Search. Mean search RT and error rate were no different in the high working memory load condition (*M* RT = 848 ms; *M* error rate = 3.4%) and the low working memory load condition (*M* RT = 842 ms; *M* error rate = 4.9%), $F < 1$ for RT and $F(1, 11) = 1.17$, $MSE = 11.59$, $p = .304$, $\eta_p^2 = .10$ for error rate. This has often been the case in previous working memory load studies: working memory load in these studies typically has a selective effect on distractor processing with no general increase in overall RT and error rate in the main task (e.g., Lavie et al., 2004).

CS Detection. Trials in which either the search response or the working memory response were incorrect were excluded from the analysis. Table 15 shows mean percentage detection and false alarm rates and mean *d'* and β as a function of working memory load.

Table 15. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Working Memory Load in Experiment 15.

Working memory load	Detection rate %	False alarm rate %	*d'*	β
Low	91.1 (20.8)	10.9 (12.4)	3.13 (1.25)	0.94 (0.82)
High	89.5 (25.3)	10.1 (16.2)	3.11 (1.43)	0.86 (0.40)

As can be seen in the table, detection rate and *d'* were no different in the high and low working memory load conditions, $F < 1$ for load effects on both detection rate and *d'*. β was also not significantly different between memory load conditions, $F < 1$.

Thus, in contrast with the consistent reduction in the detection rate and sensitivity of CS detection with high, compared to low, perceptual load in Experiments 1-11, Experiment 15 demonstrates that detection is unaffected by working memory load.

6.2 Experiment 16

In Experiment 16, the effect of working memory load on detection was compared with its effect on distractor interference effects. As I reviewed in the introduction to the chapter, previous research has shown that distractor effects (e.g., the difference in mean RT between congruent distractor trials and incongruent distractor trials) increase under high working memory load (e.g., Lavie et al., 2004). To enable this comparison, a distractor letter that was either congruent or incongruent with the search task response was presented with the search task in half of the blocks (response competition blocks) with high or low working memory load, and the other half were detection blocks with high or low working memory load (as in Experiment 15).

In Experiment 15, detection performance had been near ceiling (90.3% mean detection rate and mean *d'* of 3.12), so there had not been a great deal of scope for working memory load to increase detection rate or detection sensitivity. To resolve this, a high perceptual load search task condition was included in Experiment 16 in order to produce a lower baseline level of detection sensitivity and hence provide more conducive conditions for an increase with high working memory load to occur. Experiment 16, therefore, involved manipulations of both perceptual load and working memory load, while separately measuring the effects on both distractor interference effects and detection sensitivity.

6.2.1 Method

Participants. Seventeen new participants were recruited from UCL and were paid for their participation. Four participants were replaced because they detected less than 75% of the CS in the control block, and 4 because their accuracy at the letter search task was below 65%. The age range of those included was 19 to 31 years (M = 23.6 years, SD = 3.5 years) and there were seven men.

Stimuli. The letter search task was changed for this experiment to match that used previously in experiments which demonstrated an increase in distractor effects under high working memory load (De Fockert et al., 2001; Lavie, 2000; Lavie & De Fockert, 2005; Lavie et al., 2004). The target letter, a capital letter X or N (0.65° by 0.5°), each equally likely, appeared at random but with equal probability at one of six letter locations in a horizontal line that was centred at fixation. In the low perceptual load condition the remaining five locations were unoccupied whereas in the high perceptual load condition they were occupied by five non-target capital letters (H, K, M, W and Z) of the same size as the target letter and presented equally spaced (nearest contours 0.4° apart). In the response competition blocks, a slightly larger (0.7° by 0.55°), congruent or incongruent distractor letter (i.e., also a capital letter X or N), was presented either above or below the middle of the line of possible target letter locations, centred at 1.5° above the centre of the screen, on the vertical midline. In the detection blocks, the CS, the same meaningless grey shape (0.3° by 0.3°) used in all the previous experiments was also presented either above or below the middle of the line of letters, centred at 3.5° above the centre of the screen, on the vertical midline. This distance was used in order to preserve the distance between the search task letters and the CS that was used in all of the previous experiments. The frequency of CS presentation was 50%, with half above the line of letters and half below. Note that due to the change from six possible CS locations (as in Experiments 1-7, 9-11, and 15) to two possible CS locations (as in Experiments 8, and 12-14), the location certainty of the CS increased from 17% in each location to 50% in each location. The background of the display was black (RGB values: 0, 0, 0), the CS was a dark grey (RGB values: 25, 25, 25), and the letters (including the distractors) were grey (RGB values: 125, 125, 125). For a mask, a black mesh pattern covered the whole screen except for a square (6° by 6°) in the centre so as not to mask the target letters.

The successor naming memory task (De Fockert et al., 2001; Lavie & De Fockert, 2005; Sternberg, 1967) was employed in this experiment since this task is known to be particularly demanding on working memory and therefore may be more likely to have an effect on CS detection. The stimuli consisted of a set of 5 digits (always containing 0, 1, 2, 3 and 4) of which the order was varied between low and high working memory load conditions: they were presented in numerical order in the low working memory load condition and in a random order, but always beginning with 0, in the high working memory load condition. They were grey (RGB values: 125, 125, 125), subtended 0.7° by 0.55° each, and were centred on the screen, in a row. The memory probe was selected at random from the set of 5 digits (0, 1, 2, 3 or 4), although it was never 4 in the low working memory load condition because no digit ever followed 4 in that condition (4 is the last digit in the sequence when they are arranged in numerical order). The memory probe was equally likely to have been in any position in the sequence given at the start of the trial except last (since no digit followed the last one), and it had the same colour and dimensions as the memory set digits, and was centred on the screen with a question mark after it.

Procedure. Schematics of the procedures in the detection and response competition blocks of Experiment 16 are shown in Figures 11 and 12, respectively. At the beginning of each trial, a fixation dot was presented for 500 ms followed by a 1500 ms presentation of the memory set for the high working memory load condition or a 750 ms presentation for the low load condition. For a mask, five hash symbols (#) occupying the same position as the five digits were then presented for 1000 ms followed by the fixation dot again for 500 ms. The target and distractor letters were then displayed (100 ms) followed by a mask (500 ms) and then a blank screen (1400 ms), during which time participants made their response to the search task. Next, but only during the detection blocks, the word 'spot?' (grey letters [RGB values: 125, 125, 125] subtending 0.9° by 0.7°) was presented for 3 s, during which the detection response was made, either present or absent ('S' or 'A' key). The detection response was followed by the presentation of the memory probe, which remained on screen for 4 s or until the participant pressed the '0', '1', '2', '3' or '4' key on the numeric keypad to indicate which number had followed the probe in the memory set. Incorrect search task and working memory task responses (including making no response) were followed by a beep (with a lower pitch beep for incorrect memory task responses).

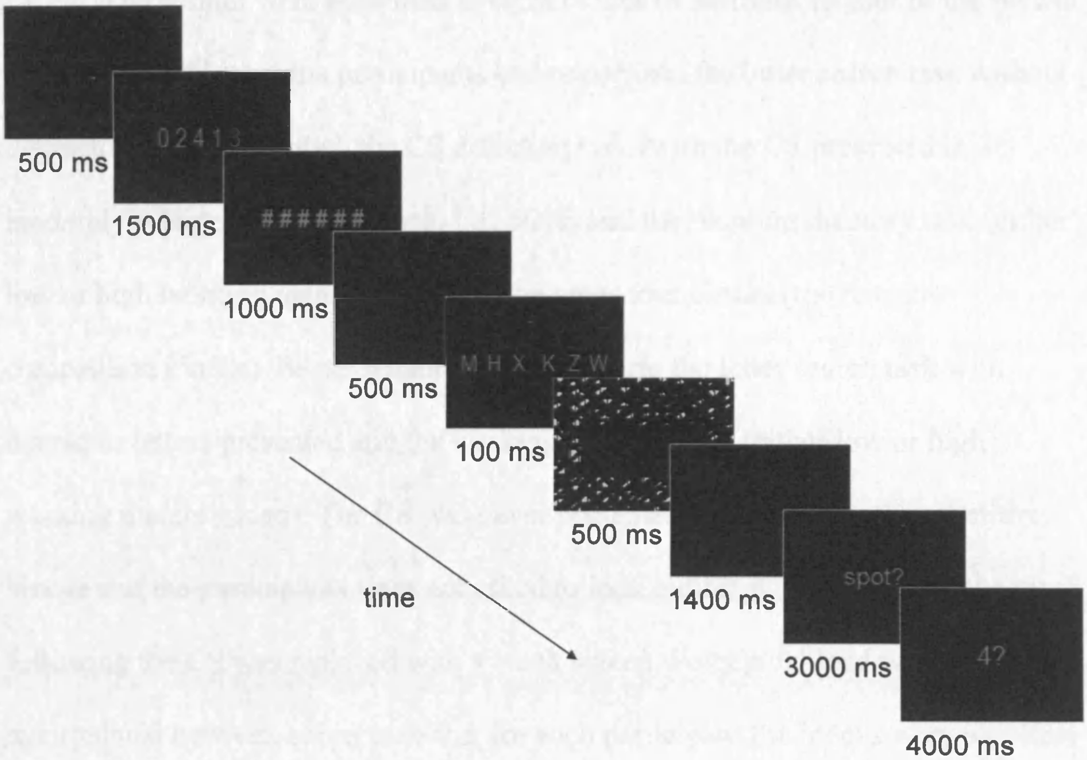

Figure 11. A schematic of the procedure in the detection blocks of Experiment 16.

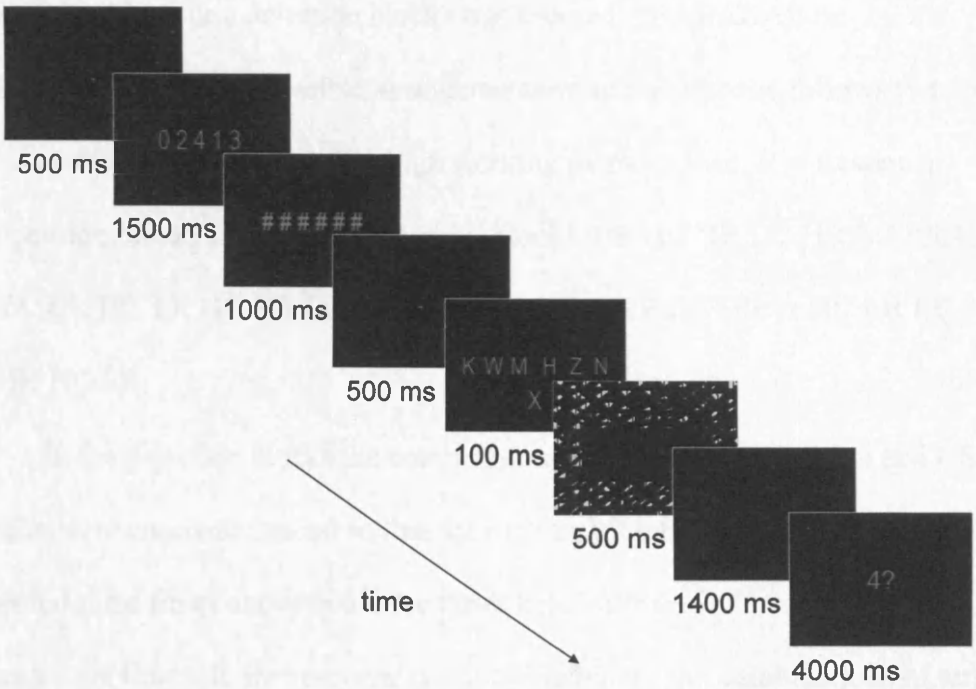

Figure 12. A schematic of the procedure in the response competition blocks of Experiment 16.

The stimuli were presented in eight blocks of 72 trials. In four of the blocks (the detection blocks) the participants had to perform the letter search task without distractor letters presented, the CS detection task (with the CS presented in 36 randomly selected trials per block, i.e., 50%) and the working memory task (either low or high working memory load). In the other four blocks (the response competition blocks) the participants had to perform the letter search task with distractor letters presented and the working memory task (either low or high working memory load). The CS was never presented in the response competition blocks and the participants were not asked to look out for it. Additionally, the mask following the CS was replaced with a blank screen. Perceptual load was manipulated between-subjects so that for each participant the blocks were all either low or high perceptual load and were ordered in one of four possible arrangements in which the working memory load of the blocks was either ordered ABBAABBA or BAABBAAB and the task type of each block (i.e., whether it was a response competition block or a detection block) was ordered ABABABAB or BABABABA. The four possible arrangements were therefore as follows (where L = low working memory load, H = high working memory load, R = Response Competition block, and C = CS Detection block): LR HC HR LC HR LC LR HC, HR LC LR HC LR HC HR LC, LC HR HC LR HC LR LC HR or HC LR LC HR LC HR HC LR.

In the detection blocks the combinations of target letter position and CS position were counterbalanced so that for each target letter position the CS was presented three times above and three times below the line of letters and it was not presented six times. In the response competition blocks the combinations of target letter position and distractor letter position were counterbalanced so that for each target letter position the distractor letter was presented six times above the line of letters (three times congruent and three times incongruent) and six times below it (again, three times congruent and three times incongruent).

One low and one high working memory load practice block of 36 trials was undertaken before embarking on the eight experiment blocks followed by the control block, which contained half low working memory load trials and half high working memory load trials (making 72 trials). Participants were instructed to ignore the numbers and letters in the control block and to just report the presence or absence of the CS.

6.2.2 Results and Discussion

Working Memory Task. One way ANOVA on memory task mean RT (incorrect trials excluded) and error rate as a function of working memory load (low and high) across block types and perceptual load conditions revealed a main effect of working memory load. There was a longer mean RT and a greater number of errors on the memory task in the high working memory load condition (*M* RT = 1225 ms; *M* error rate = 12.4%) than in the low working memory load condition (*M* RT = 816 ms; *M* error rate = 1.8%), which confirmed that the manipulation of working memory load was effective, $F(1, 16) = 135.79$, $MSE = 10{,}452.80$, $p < .001$, $\eta_p^2 = .90$ for RT, $F(1, 16) = 18.99$, $MSE = 50.19$, $p < .001$, $\eta_p^2 = .54$ for error rate.

Letter Search. Incorrect search task trials and memory task trials were excluded from the RT analysis, as well as RTs over 1.5 s. A mixed model ANOVA with perceptual load as a between-subjects factor and working memory load as a within-subjects factor on mean search RT across block types was performed. There was a non-significant trend for a main effect of working memory load on mean search RT (*M* = 23 ms longer with high working memory load), $F(1, 15) = 4.15$, $MSE = 1131.14$, $p = .060$, $\eta_p^2 = .22$. Surprisingly, although there was a clear numerical trend for a longer mean RT in the high perceptual load condition (*M* = 831 ms) than low perceptual load condition (*M* = 737 ms), the main effect of perceptual load was not significant, $F(1, 15) = 1.00$, $MSE = 74{,}741.41$, $p = .333$, $\eta_p^2 = .06$. This appears to be due to two particularly slow participants in the low perceptual load condition (both with a mean search RT of over 900 ms). There was no interaction between working memory load and perceptual load, $F < 1$.

A similar mixed model ANOVA on search task error rate revealed no effect of working memory load (high working memory load *M* = 10.2%; low load *M* = 11.6%), $F(1, 15) = 3.04$, $MSE = 5.33$, $p = .102$, $\eta_p^2 = .17$, but a significant main effect of perceptual load: errors were more frequent in the high perceptual load condition (*M* = 13.8%) than the low perceptual load condition (*M* = 7.9%), $F(1, 15) = 5.18$, $MSE = 56.29$, $p = .038$, $\eta_p^2 = .26$. There was no interaction, $F < 1$.

Distractor Congruency Effects in the Response Competition Blocks. Trials in which either the search response or the working memory response were incorrect were excluded from the analysis, as well as RTs over 1.5 s. Mean search RT and error rate as a function of perceptual load, working memory load, and distractor congruency are presented in Table 16. To analyse the distractor congruency effects in the response competition blocks, a three way mixed model ANOVA on mean search RT with perceptual load as a between-subjects factor and working memory load and distractor congruency as within-subjects factors was performed. As with the ANOVA across blocks, there was no main effect of perceptual load, $F < 1$, although the main effect of working memory load did reach significance, $F(1, 15)$

= 4.70, *MSE* = 2631.09, p = .047, η_p^2 = .24, and there was no interaction of perceptual load with working memory load, $F(1, 15) = 1.36$, *MSE* = 2631.09, p = .262, η_p^2 = .08.

Table 16. Mean (and *SD*) Search RT and Error Rate as a Function of Perceptual Load, Working Memory Load and Distactor Congruency in Experiment 16.

	Working memory load					
	Low			High		
Distractor congruency	I	C	I - C	I	C	I - C
Perceptual load						
Low						
RT ms	738 (212)	682 (180)	56 (39)	804 (207)	700 (161)	104 (66)
Errors %	11.9 (8.1)	9.3 (8.0)	2.6 (4.4)	12.1 (6.9)	5.8 (3.5)	6.3 (6.6)
High						
RT ms	816 (166)	798 (151)	18 (32)	822 (196)	817 (175)	5 (56)
Errors %	14.2 (5.0)	10.9 (4.9)	3.4 (6.4)	14.0 (9.9)	12.4 (5.8)	1.6 (5.3)

As would be expected, there was a significant main effect of distractor congruency, such that mean RT was longer when incongruent distractors were presented (M = 795 ms) compared to when congruent distractors were presented (M = 749 ms), $F(1, 15) = 19.30$, *MSE* = 1839.55, p = .001, η_p^2 = .56. Furthermore, as expected, there was a significant interaction between perceptual load and distractor congruency, $F(1, 15) = 10.91$, *MSE* = 1839.55, p = .005, η_p^2 = .42, such that the response competition distractor effect was greater under low perceptual load (M RT difference between congruent and incongruent distractor conditions =

80 ms) than high perceptual load (*M* RT difference = 12 ms). There was no working memory load by congruency interaction, $F(1, 15) = 1.83$, $MSE = 704.21$, $p = .196$, $\eta_p^2 = .11$, but there was a significant three way interaction between working memory load, perceptual load and distractor congruency, $F(1, 15) = 5.75$, $MSE = 704.21$, $p = .030$, $\eta_p^2 = .28$, such that in the low perceptual load condition the distractor congruency effect was greater under high working memory load (*M* RT difference between congruent and incongruent distractor conditions = 104 ms) than low working memory load (*M* RT difference = 56 ms), $t(8) = 2.81$, $SEM = 17.22$, $p = .023$, but in the high perceptual load condition the distractor congruency effect in the high and low working memory load conditions was not significantly different (high working memory load *M* RT difference = 5 ms, low working memory load *M* RT difference = 18 ms), $t < 1$.

Since there was a main effect of working memory load on mean search RT, i.e., it was longer with high working memory load than low, it could be argued that the larger interference effect in the high working memory load condition was merely a side effect of the longer RT. However, when the ANOVA was repeated on the percentage increase in mean RT (i.e., (incongruent – congruent) / congruent), the interaction of perceptual and working memory load remained significant: there was a larger difference in percentage congruency effect between memory load conditions in the low perceptual load condition ($M = 14.5\%$ under high working memory load and 7.6% under low, giving a mean difference of 6.9%) than in the high perceptual load condition ($M = 0.1\%$ under high working memory load and 2% under low, giving a mean difference of 1.9%), $F(1, 15) = 6.73$, $MSE = 24.15$, $p = .020$, $\eta_p^2 = .31$.

The same analysis of variance model was used to analyse error rate. There was no main effect of perceptual load, $F(1, 15) = 1.30$, $MSE = 125.42$, $p = .273$, $\eta_p^2 = .08$, no main effect of working memory load, $F < 1$, and no interaction between them, $F < 1$. There was a significant main effect of distractor congruency: incongruent distractors produced more errors than congruent distractors ($M =$ 13.1% and 9.6%, respectively), as would be expected, $F(1, 15) = 11.28$, $MSE =$ 18.12, $p = .004$, $\eta_p^2 = .43$, and there was no interaction between perceptual load and distractor congruency, nor was there between working memory load and distractor congruency, both $F < 1$. Finally, although the three way interaction did not reach significance, the pattern of results was in line with those for mean RT: in the low perceptual load condition the distractor congruency effect was larger under high working memory load ($M = 6.3\%$) than low ($M = 2.6\%$), whereas in the high perceptual load condition the distractor congruency effect was comparable under high ($M = 1.6\%$) and low ($M = 3.4\%$) working memory load, $F(1, 15) = 2.19$, $MSE = 14.75$, $p = 0.159$, $\eta_p^2 = .13$.

CS Detection. Trials in which either the search response or the working memory response were incorrect were excluded from the analysis. Mean percentage detection and false alarm rates and mean *d'* and β as a function of perceptual load and working memory load are presented in Table 17.

These data were entered into three separate two way mixed model ANOVA with perceptual load as a between-subjects factor and working memory load as a within-subjects factor - one analysis for detection rate, one for *d'*, and one for β. As can be seen in Table 17, detection rate and *d'* were lower in the high perceptual load condition than in the low perceptual load condition, $F(1, 15) = 5.20$, $MSE =$ 393.18, $p = .038$, $\eta_p^2 = .26$ for detection rate, $F(1, 15) = 13.18$, $MSE = 1.87$, $p =$

.002, $\eta_p^2 = .47$ for *d'*, replicating the effect of perceptual load reported in the previous chapters.

Table 17. Mean (and *SD*) Percentage Detection and False Alarm Rates and Mean (and *SD*) *d'* and β as a Function of Perceptual Load and Working Memory Load in Experiment 16.

	Working memory load							
	Low	High	Low	High	Low	High	Low	High
Perceptual load	Detection rate %		False alarm rate %		*d'*		β	
Low	92.1 (12.9)	91.4 (10.4)	1.9 (2.3)	1.8 (2.1)	3.85 (0.95)	3.75 (0.92)	2.19 (1.94)	2.62 (1.78)
High	77.0 (12.8)	75.5 (20.8)	16.6 (22.9)	20.0 (23.3)	2.17 (1.09)	2.02 (1.08)	4.04 (3.35)	3.17 (4.38)

However, detection rate and *d'* were no different in the high and low working memory load conditions, $F < 1$ for both measures. There was also no interaction between perceptual load and working memory load for detection rate or *d'*, both $F < 1$.

β was not significantly different between the low and high perceptual load conditions, nor was it between the low and high working memory load conditions, both $F < 1$. The interaction between perceptual load and working memory load on β was also not significant, $F(1, 15) = 1.29$, $MSE = 2.81$, $p = .273$, $\eta_p^2 = .08$.

Note that the null effect of working memory load in the high perceptual load condition occurred even though detection rate and *d'* were not at ceiling as they were in the low perceptual load condition of this experiment, and in the previous experiment (which was exclusively low perceptual load). Thus, both Experiments 15 and 16 have demonstrated that detection is unaffected by working memory load, even when, in the high perceptual load condition of Experiment 16, detection performance is off the ceiling.

6.3 Chapter Conclusions

Whereas perceptual load significantly modulated detection rate and sensitivity, as it did in the experiments in the previous chapters, working memory load had no effect on detection in the experiments reported here; however, within the same experiment (Experiment 16), the previously reported finding that working memory load increases distractor interference effects on RTs (Lavie, 2000; Lavie et al., 2004; Lavie & De Fockert, 2005) was replicated in the low perceptual load condition, but not in the high perceptual load condition. Why this occurred is not clear; however, it is possible that search task responses were not made as quickly as possible in the high perceptual load condition for the modulation of distractor effects by working memory load to be revealed, which may have been the result of participants undertaking the high perceptual load version of the experiment easing off a little in the less highly demanding dual-task response competition blocks, in between the intense triple task detection blocks (working memory task, search task, and detection task). Participants in the low perceptual load condition may not have suffered as much in the triple task detection blocks as their high perceptual load counterparts, since the low load search task was very easy, and hence search RTs were speeded enough to show an effect of working memory load in the low perceptual load condition. Nevertheless, since the modulation of distractor interference effects by working memory load shown previously was not replicated with a high perceptual load search task, whether working memory load was actually manipulated in the high perceptual load condition is brought into question, although working memory task RTs and error rates were higher under high working memory load than low. Since under conditions of low perceptual load detection performance was close to ceiling, it remains theoretically possible that detection of task-unrelated stimuli can be modulated by working memory load.

Taken at face value, the results of the experiments in this chapter suggest that the effect of perceptual load on detection is unique and specific to perceptual load, since increasing working memory load (in as far as working memory task RTs and error rates were significantly higher under high working memory load than low) during performance of the search and detection tasks did not have an effect on detection rate or sensitivity. This finding rules out an account of the effects of perceptual load in terms of an increase in the demand on general cognitive capacity resources. Furthermore, the contrast between this finding and those of previous studies, that working memory load increases distractor-related neural activity and interference effects on behaviour (Lavie, 2000; Lavie et al., 2004; Lavie & De Fockert, 2005), potentially allows a more detailed understanding of the role working memory serves in the control of selective attention: only in situations in which task-irrelevant stimuli compete with the target for response selection will active executive control of selective attention (and hence working memory) be needed to minimize the processing of such distracting stimuli. Therefore, in such situations, rendering executive control unavailable by loading working memory results in greater distractor processing. On the other hand, when task-irrelevant stimuli do not compete with the target for response selection, and therefore can not produce interference, executive control is not required and the processing of such stimuli is unaffected by the level of load on executive control functions such as working memory.

Chapter 7

General Discussion

7.1 Overview of Findings

The experiments presented in this thesis have demonstrated the effect of perceptual load on conscious awareness. The rate and sensitivity (*d'*) of detection of a task-unrelated stimulus were reduced under high perceptual load compared to low perceptual load, indicating that participants were less likely to be aware of the stimulus when performing a task of high load. I have termed this phenomenon 'load induced blindness'. The effect was shown to not be due to differences in response criterion, search RTs, memory, goal-neglect, strategy, task difficulty or demand on general cognitive resources, but was indeed specifically due to load on perceptual processes. The effect extended to stimuli located at fixation as well as those in the periphery, although awareness was more likely for stimuli at fixation. In addition, a dissociation was found between the effects on conscious awareness of perceptual load and working memory load. Whereas perceptual load decreased awareness, working memory load had no effect on awareness. Although there have been many previous perceptual load studies, these experiments are the first to establish the effect of perceptual load on detection sensitivity.

7.1.1 Relation to Perceptual Load Research

The results provide the most compelling evidence so far that perceptual load modulates conscious awareness, and further considerably the resolution offered by the perceptual load theory for the early versus late selection debate. Specifically, the theory proposes that the demand on attention imposed by a task determines whether perception of task-unrelated information will occur: in situations of low perceptual load, task-unrelated stimuli are readily perceived since spare capacity 'spills over' to include them; in situations of high perceptual load they are not perceived since attentional capacity is consumed by the task stimuli, leaving none remaining to process any further information.

As discussed in the General Introduction, previous evidence for perceptual load theory has almost exclusively come from experiments employing indirect measures of perception, such as the degree to which distractors interfere with target RTs and error rates (e.g., Beck & Lavie, 2005; Jenkins et al., 2005; Lavie, 1995; 2000; Lavie & Cox, 1997; Lavie & Fox, 2000; Lavie, Ro, & Russell, 2003; Theeuwes et al., 2004), or the level of neural activity they elicit in visual cortex (e.g., Bahrami et al., 2007; O'Connor et al., 2002; Pessoa et al., 2002; Pinsk et al., 2003; Rees et al., 1997, 1999; Schwartz et al., 2005; Yi et al., 2004). No research has ever explicitly addressed the effects of perceptual load on conscious awareness, with one exception: Cartwright-Finch and Lavie (2007) assessed awareness reports using the inattentional blindness paradigm. Their results are therefore confined to the case of unexpected stimuli, and may have involved memory failure rather than conscious perception, as I discuss below. The findings of this thesis, however, fully support the prediction that perceptual load modulates conscious awareness of task-unrelated stimuli, and serve to further the resolution of the early and late selection debate by the perceptual load model.

7.1.2 Relation to Inattentional Blindness Research

Much previous research has attempted to show that a lack of attention leads to a lack of conscious awareness of task-unrelated stimuli: some presented an extra, unexpected object briefly with the task stimuli (while participants' attention was focused on the task), i.e., inattentional blindness (for example, Cartwright-Finch & Lavie, 2007; Downing et al., 2004; Mack & Rock, 1998; Newby & Rock, 1998).

Others presented a moving unexpected object during a long-presentation dynamic display of task stimuli, i.e., sustained inattentional blindness (for example, Most et al., 2000, 2001, 2005; Neisser & Becklen, 1975; Simons & Chabris, 1999). In both paradigms, after completing the critical trial, participants were asked if they had noticed anything extra in the display besides the task stimuli. Many participants failed to report the presence of the extra stimulus, even though they did notice it later when they did not have to perform a task, suggesting that the extra stimulus had not entered into their conscious awareness because their attention had been focused on the task, i.e., their attention had been elsewhere.

The extra stimulus, however, was always unexpected in the critical trial and expected in the later control trial: hence it was not possible to disentangle the effect of not attending to it from the effect of not expecting it. Braun (2001) has suggested that a failure to expect or anticipate the presence of a supra-threshold stimulus (such as that used in the inattentional blindness paradigm) could lead to blindness of that stimulus, in the same way that near-threshold stimuli in psychophysical experiments typically require a degree of familiarity to be consciously perceived – sometimes hundreds of trials. The comparison of the critical and control trials in inattentional blindness experiments therefore confounds attention with expectation. In some studies, however, a comparison was made between different conditions in the critical trial, rather than between the critical and control trials (e.g., low and high perceptual load in Cartwright-Finch & Lavie, 2007; CS to target similarity in Most et al., 2001). In such cases attention is not confounded with expectation, but the results are limited to the case of awareness of unexpected stimuli. The methodology I have used here, however, precludes expectation as a confound, and does not limit the results to the case of unexpected stimuli, since the participants anticipated the appearance of the CS during the experiment.

Another confound of inattentional blindness is memory failure, or 'inattentional amnesia' as Wolfe (1999) has termed it. The presence of the extra stimulus in the critical trial may have been forgotten rather than not perceived, since the response as to whether it had been consciously perceived or not came a short while after presentation – after consideration of a task and making a response to that task, and also after the unexpected questioning that would have caused surprise and required verbal processing - all of which could have strongly affected the participants' ability to remember the presence of the extra stimulus. As Wolfe (1999) has pointed out, a commonality of inattentional blindness experiments is that questioning about the extra stimulus occurs some time after the visual representation and iconic memory of the stimulus has dissipated. He suggests that attention is the gateway to memory rather than perception, and therefore unattended stimuli may well be perceived, but will be instantly forgotten, hence 'inattentional amnesia'.

An alternative account of inattentional blindness in terms of memory failure has been proposed by Moore (2001; Moore & Egeth, 1997): the participants may have perceived the extra stimulus but not encoded it into memory. In a similar vein to Wolfe (1999), Moore suggests that while a subset of perceptual processes are engaged by unattended stimuli, the outputs of those processes require attention to be encoded into memory for subsequent report.

The methodology I have employed goes a considerable way to countering memory failure accounts, since there was no unexpected question causing surprise and requiring verbal processing of the question itself, and therefore the delay between task response and detection response was shorter than in inattentional blindness experiments. However, in only one experiment was the detection response made immediately after CS presentation and was there no intervening search response to be made first (Experiment 4). The effect of perceptual load was not significantly reduced in this experiment, and furthermore, overall detection rate was no better than previously, suggesting that there is no memory component to the effect of perceptual load on conscious awareness. Given that detection responses were made immediately in Experiment 4, an 'inattentional amnesia' account of load induced blindness can be ruled out: unlike with inattentional blindness experiments, participants would have been able to make a decision about the presence or absence of the CS during the presentation of the actual stimulus and the associated representation in iconic memory. An account in terms of the CS being perceived but not being encoded into memory can also be precluded: if a participant could not report the presence of the CS upon presentation, they must have not been consciously aware of it at the very moment it was reflected onto the retina. It must be noted, however, that manipulations employed in later experiments intended to raise the priority of the detection task, such as increasing the frequency of CS presentation (Experiments 5 and 7), requiring that a response is made when the CS is absent as well as present (Experiments 6 and 7), and increasing the location certainty of the CS (Experiment 8), were not implemented in Experiment 4 in addition to the reversal of the order of responses. This manipulation was also intended to raise the priority of the detection task, as well as allow the detection response to be made immediately upon CS presentation; however, since these other manipulations were not implemented in Experiment 4, it is possible that the priority of the detection task remained low in this experiment, and this could account for the difference in detection performance between conditions rather than perceptual load. If this were the case, the results of later experiments in which the priority of the detection task was raised but the order of responses reverted to the detection response coming after the search response could still be explained by the inattentional amnesia hypothesis. Since there was no reduction in the size of the effect of perceptual load when the aforementioned manipulations designed to raise detection priority were implemented, however, there is no reason to suppose that low detection priority was at work in Experiment 4.

A further advantage of the experimental design I have used over the typical inattentional blindness paradigm is that changes in detection sensitivity could be compared to changes in response criterion. In all of the experiments reported, response criterion did not vary across conditions of perceptual load and so could also be ruled out as a confound or even as a component of the effect.

7.1.3 Differences In Search RT

In many previous perceptual load studies showing reduced distractor effects under high perceptual load compared to low, high load search RTs were longer than low load search RTs (Lavie, 1995; Lavie & Cox, 1997). An account of these results in terms of a dissipation of distractor effects within the longer high perceptual load RTs is possible, although this argument is countered by the fact that manipulations that increase task difficulty, and consequently RTs, without increasing perceptual load, e.g., working memory load (Lavie, 2000; Lavie et al., 2004), or stimulus degradation (Lavie & De Fockert, 2003), produce an increase in distractor effects rather than a decrease. Although in this thesis perception was assessed via a measure of detection rather than effects on target RTs, it was nevertheless important to rule out an account of the effect of perceptual load on detection sensitivity in terms of the slower high load search RTs. The experiments in Chapter 2 have excluded such an account by replicating the results with designs in which the interval between the search response and the detection response was made equal (Experiment 2), and in which search responses were delayed so that mean search RT was the same in the two conditions of load (Experiment 3).

7.1.4 Detection Priority

In Chapter 3, the effect of perceptual load on awareness persisted with four different manipulations designed to raise the priority of the detection task, thereby ruling out goal-neglect type accounts of the results. The degree to which detection sensitivity was reduced by high perceptual load remained the same, even though response criterion became lower (i.e., there was an increase in present responses - both hits and false alarms).

Given that the manipulations employed in Chapter 3 affected the way participants responded to the detection task (i.e., by lowering response criterion), it is clear that these manipulations did produce the desired effect: the priority of detection was increased. It is impossible to know without further experimentation, however, whether detection could have been prioritised any further, for example, by providing feedback for errors of detection. If so, it is still possible that the effect of perceptual load on detection sensitivity may at least in part be due to the detection task being of lower priority in the high perceptual load condition than low perceptual load condition.

7.1.5 Strategy

Several previous perceptual load studies have ruled out differential search task strategies as a confound by replicating the effect of perceptual load with a design in which trials of different levels of load are presented in a randomly intermixed order, so that the level of perceptual load in a trial could not be known in advance (Lavie & Cox, 1997, and Theeuwes et al., 2004, using the response competition paradigm; Cartwright-Finch & Lavie, 2007, using the inattentional blindness paradigm). In the same way, the experiments in Chapter 4 ruled out a strategy based account of the results using a design with randomly intermixed load trials. However, the difference in detection sensitivity between perceptual load conditions in these experiments was reduced, suggesting that there may have been a strategy component to the effect. Reducing the probability of CS presentation (Experiment 11) did not alleviate this weakening of the perceptual load effect.

It is puzzling, however, that the reduction in the effect of perceptual load was as much the result of poorer detection sensitivity in the low load compared to previous experiments, as it was the result of improved detection sensitivity in the high load. Because of this, it is unlikely that a low perceptual load strategy or a high perceptual load strategy was adopted for both conditions of load in the intermixed experiments – more likely that an intermediate strategy was employed that yielded detection sensitivity somewhere between the previous levels in the low and high perceptual load conditions. Alternatively, since the reduction of detection sensitivity in the low load in the intermixed design was entirely due to an increase in false alarms (detection rate was no lower than in the blocked design), perhaps the experience of guessing that the CS had been present in the high load led to more guessing in the low load than had occurred previously.

Although this thesis does not rule out a strategy component of the effect of perceptual load on conscious awareness, clearly strategy could not account for the whole effect, as it persisted with an intermixed design. Future experiments, however, may find that the effect of perceptual load disappears if an intermixed design is combined with further manipulations designed to increase the priority of detection (i.e., if in addition to increasing CS frequency and requiring present/absent detection responses, the order of search and detection responses is reversed, or the location certainty of the CS is increased).

7.1.6 Load Induced Blindness at Fixation

The experiments in this thesis have demonstrated that detection of a task-unrelated stimulus located directly at the point of fixation is modulated by perceptual load, but is superior to detection of a stimulus located in the periphery (Chapter 5). The first finding illustrates the pervasiveness of the effect of perceptual load on conscious awareness across the retina: both foveal and peripheral objects can be overlooked. The second finding adds to previous research showing that performance on perceptual tasks is superior for stimuli presented at fixation than in the periphery, for example, with letters (Anstis, 1974), vernier offsets (Weymouth, 1958), and gratings (Rovamo, Virsu, & Nasanen, 1978; Virsu & Rovamu, 1979). In every case, however, performance was equated across the visual field by scaling the sizes of the stimuli according to the cortical magnification factor (e.g., Cowey & Rolls, 1974; Rovamo & Virsu, 1979). Since equating visibility by size-scaling eliminates the effect of eccentricity, such findings are explained in terms of the considerable physiological superiority of the fovea. However, a foveal advantage despite size-scaling of stimuli was demonstrated in the experiments reported in this thesis, in line with Wolfe et al. (1998), who found an eccentricity effect with scaled stimuli in a visual search paradigm, such that targets closer to fixation were identified more rapidly than those at further eccentricities, and with Beck and Lavie (2005), who showed that fixated distractors exerted greater interference effects than those in the periphery, with a response competition paradigm using scaled distractor letters. This thesis therefore extrapolates non-visibility based eccentricity effects to include conscious awareness as well as search performance and distractor interference.

The finding that stimuli at fixation are more likely to reach awareness than stimuli in the periphery, together with the work of Wolfe et al. (1998) and Beck and Lavie (2005) suggests that over and above the well-documented perceptual superiority of the fovea, there is a greater attentional weight for objects located there. This prioritisation of the processing of foveal stimuli over stimuli located elsewhere on the retina results in those stimuli being identified more quickly and accurately, being more capable of causing distraction, and being more likely to enter conscious awareness, as has been shown in this thesis.

Such an assertion stands in direct opposition to Mack and Rock's (1998) conclusion that there is greater inhibition of fixated stimuli than peripheral stimuli. This was based on research showing more frequent inattentional blindness for stimuli at fixation (Mack & Rock, 1998). However, as I suggested in the introduction to Chapter 5, Mack and Rock's methodology confounded task demands with stimulus location (as did Goolkasian's, 1999), whereas with the experiments in this thesis the task demands were identical across CS location conditions. However, given that in Mack and Rock's (1998) experiments the CS was unexpected, whereas here the CS was always expected, it remains possible that there is greater inhibition of unexpected stimuli at fixation and greater awareness of expected stimuli at fixation. Future research should examine this possibility by reassessing inattentional blindness at fixation and in the periphery, while ensuring that task demands are equal across CS location conditions.

7.1.7 Working Memory Load

The findings of this thesis suggest two dissociations: one between the effects of perceptual load and working memory load on conscious awareness; the other between the effect of working memory load on awareness and on distractor interference effects on target RTs (Chapter 6).

Several previous studies have documented that loading working memory produces the opposite effect to loading the perceptual system, i.e., distractor interference effects are increased rather than eliminated. This effect has been shown with a response competition paradigm (De Fockert, Rees, Frith, & Lavie, 2001; Lavie, 2000; Lavie, Hirst, De Fockert, & Viding, 2004) and an attentional capture paradigm (Lavie & De Fockert, 2005), and furthermore, neural activity related to distractor processing has been shown to be greater under conditions of high working memory load than low (De Fockert et al., 2001). However, no such effect of working memory was found on detection rate or detection sensitivity in the experiments reported in Chapter 6, although the increase in distractor interference effects under high working memory load reported previously was only replicated in the low perceptual load condition and not in the high perceptual load condition, rendering the null effect of working memory load in the high perceptual load condition, in which detection performance was off-ceiling, somewhat questionable.

Nevertheless, these findings are important in two respects. Firstly, the disparity between the effect of perceptual load and the null effect of working memory load rules out an alternative interpretation of the reduction of detection sensitivity under high perceptual load in terms of simple task difficulty, and strengthens the claim that the effect of perceptual load on conscious awareness is specifically due to increased demand on attentional capacity, rather than increased demand on some general cognitive capacity resource. This specificity is consistent with a previous demonstration (Lavie & De Fockert, 2003) that a source of task difficulty other than perceptual load does not produce the same effect: degrading the appearance of the target stimulus increased task difficulty and resulted in an increase in distractor effects, whereas perceptual load increased task difficulty but decreased distractor effects. Lavie and De Fockert's (2003) study, however, assessed the perception of distractors via response competition; this thesis therefore extrapolates the finding that perceptual load has a specific effect among sources of task difficulty, to direct measures of awareness.

Secondly, the contrast between these results showing that conscious awareness of a task-irrelevant stimulus is unaffected by working memory load, and the previous finding that working memory load increases distractor interference effects on RTs (De Fockert et al., 2001; Lavie, 2000; Lavie et al., 2004), potentially provides an important clarification of the role working memory serves in the control of selective attention. The task-irrelevant stimulus used here was a low-contrast meaningless shape that evidently would not compete with the search target for selection, since it was unrelated to the search task responses and was less visually salient than the target. By contrast, increased distractor interference with high working memory load has been found here and in previous studies (De

Fockert et al., 2001; Lavie, 2000; Lavie & De Fockert, 2005; Lavie et al., 2004) with distractor stimuli that were strong competitors for target selection, either because they were response-related (i.e., congruent or incongruent with the task response, as in this thesis and in Lavie, 2000, and Lavie et al., 2004) or because they were more salient than the target (i.e., in the attentional capture paradigm used by Lavie and De Fockert (2005), the distractor was a colour singleton presented during a shape search task), or in some cases both (e.g., De Fockert et al., 2001, used distractor faces that were not only related to the task response, but were also likely to have been more salient than the word targets). As such, the contrast between the effects of working memory load on these different types of task-unrelated stimuli suggests that active executive control of selective attention by working memory is only needed in competitive situations: when task-unrelated stimuli compete with the target for attention (if they are particularly salient) or for response selection (if they are response-related), or both, active executive control of selective attention is engaged in order to inhibit the processing of such stimuli. Hence, loading working memory results in increased interference since executive control is no longer able to manage selective attention as effectively. Conversely, the processing of task-unrelated stimuli that do not compete with the target for selection is unaffected by working memory load, since executive control processes are not required to prevent them from causing interference in the first place.

This interpretation accommodates previous findings that the neural activity related to task-irrelevant stimuli is affected by perceptual load but not by working memory load (e.g., Yi, Woodman, Widders, Marois, & Chun, 2004). In this study, the task-irrelevant stimuli (images of places presented in the background) were unrelated to the task responses concerning the identity of a face in the centre of the display. As such, they would not have competed with the target for selection, hence active executive control would not have been required to reduce the extent to which they were processed. Loading working memory would therefore have no effect.

A different explanation of the dissociation between the effect of working memory load on awareness and on distractor effects, is that the effect of working memory load may occur too late to affect awareness: the increase in distractor interference could reflect effects on later response selection processes rather than on perception per se. De Fockert et al.'s (2001) data may appear at first sight to be inconsistent with this interpretation, in that the increase in neural activity in the fusiform face area related to the presence of face distractors under high load compared to low load seems to imply greater perception; however, the increase in neural activity could reflect response-selection processes or a greater activation of the face category of objects rather than increased perception of the particular face distractor.

Finally, it is important to note that the manipulation of working memory load via the active maintenance of digits in memory employed in this thesis, as well as in the previous working memory load and distractibility studies by Lavie and colleagues, would not have involved any load on visual short-term memory, since active maintenance of verbal material is mediated by phonological rehearsal (Conrad, 1964; Posner & Keele, 1967). Visual short-term memory involves a passive form of maintenance that does not draw on active executive control (Baddeley, 1986). Indeed, high visual short-term memory load has recently been found to reduce conscious awareness (Todd, Fougnie, & Marois, 2005). This finding is in line with the notion that representations in visual short-term memory are analogous to visual perception, leading to the prediction that the effect of visual short-term memory load would be similar to that of perceptual load. This prediction could be tested with the methodology used in this thesis by manipulating visual short-term memory load and measuring detection sensitivity of the task-unrelated stimulus.

7.1.8 Capacity Limits

The principal finding of this thesis, that the detection sensitivity of task-unrelated stimuli is reduced under conditions of high perceptual load, contradicts the traditional view that early perceptual processes such as detection are capacity-free, and hence do not depend on the allocation of attention (Bonnel, Stein, & Bertucci, 1992; Braun & Sagi, 1990; 1991; Posner & Boies, 1971; Shaw, 1984).

Bonnel, Stein, and Bertucci (1992) claimed that whereas a perceptual discrimination (e.g., between a luminance increment and decrement) depends on the allocation of attention, detection (e.g., of a luminance increment) is an automatic process in the sense that it is capacity-free. However, Bonnel and colleagues' study compared the effects of instructions to allocate attention differentially between two stimuli (e.g., 80% to one source of light and 20% to another) and did not address the effects of perceptual load on attention as I have in this thesis.

Somewhat more relevant are the findings from experiments that assessed the effects of attention on detection by comparing performance in single and dual-task conditions. In a series of studies, Braun and Sagi (1990; 1991, see also Sagi & Julesz, 1985a; 1985b) found that detection of an oddball that forms a texture break in a homogenous background (i.e., a vertical line among tilted lines), did not show a performance decrement under dual-task conditions (in which the detection task was combined with a central task requiring the discrimination of the orientation of a stimulus). When the detection task was replaced with a second discrimination task of stimuli in the background, however, performance of this task did suffer. Braun and Sagi (1990) therefore concluded, similarly to Bonnel et al. (1992), that whereas perceptual discrimination depends on the allocation of attention, detection of an element that forms a texture break does not.

This conclusion was contested, however, by Joseph, Chun, and Nakayama (1997), who replicated Braun and Sagi's (1991) findings, i.e., the lack of a detection performance decrement in dual-task conditions, with a task involving detection of an oddball line (e.g., a line tilted at 45° among other lines tilted at 315°), and a central task involving an orientation discrimination, but found that detection did suffer from a dual-task decrement when combined with a demanding RSVP letter task rather than the orientation discrimination task. These results mirror those presented in this thesis, in that only a demanding task of high perceptual load produced a decrement in detection performance. It is clear, therefore, that a greater demand on attention can result in reduced detection performance in line with perceptual load theory and the findings of this thesis. The conclusion drawn from Joseph et al.'s (1997) study, however, is confined to the comparison of detection performance in single and dual-task conditions. It is important to note that such conditions differ not only in the level of load on attention, but also in terms of the logistics involved in performing two tasks simultaneously. Such a comparison is therefore confounded by non-attentional processes such as making an additional response (in the dual-task condition), memory (due to the delay caused by the need to make one task response before the other in the dual-task condition) and goal-neglect (due to performing two tasks simultaneously in the dual-task condition). By contrast, the experiments presented in this thesis involve a task that remains the same in all respects other than the perceptual load of the search task, and demonstrate that the level of load on attention, as distinct from any effects of memory, goal-neglect, response criterion, strategy or task difficulty, can determine the simple ability to detect the presence of a stimulus. This research, therefore, not only elucidates the role of perceptual load in conscious awareness, but also resolves the important issue of whether early perceptual processing, involving mere stimulus detection, is subject to capacity limits.

7.2 Further Research

There are several directions for further research that arise directly from the results presented in this thesis.

7.2.1 Different Load Manipulations

Perceptual load was always manipulated in the same way in this thesis. This method involved increasing load by adding non-target stimuli to a search task that remained the same in both low and high load conditions. Perceptual load could also be manipulated by requiring different tasks to be performed with the same stimuli, for example, with an RSVP stream on which a single feature (low load) or conjunction of features (high load) search task can be performed (e.g., Schwartz et al., 2005). Alternatively, the cross task of Cartwright-Finch and Lavie (2007) could be used, in which participants are asked either to determine which cross arm is blue (low load), or determine which cross arm is longer (high load), with the same cross stimulus. A replication of load induced blindness with either of these manipulations would demonstrate the generality of the effect of perceptual load on awareness.

7.2.2 Type of Stimulus

To some extent, load induced blindness may depend on the type of task-unrelated stimulus presented. The image of a face, for example, may always enter conscious awareness irrespective of the level of perceptual load of the task. This proposition stems from recent suggestions that faces are prioritised for processing over other objects and may even be perceived automatically (Austen & Enns, 2000; Downing, Bray, Rogers, & Childs, 2004; Jenkins, Lavie, & Driver, 2003; Ro, Russell, & Lavie, 2001). Other types of meaningful stimuli may also automatically enter awareness: emotional pictures, words, or the participant's name, for example. Future research could investigate such claims.

The experiments reported here examined the conscious awareness of task-unrelated stimuli in static displays. A further test of the effect of perceptual load on conscious awareness could be with dynamic displays. A lack of awareness of moving stimuli in dynamic displays has already been demonstrated with the sustained inattentional blindness paradigm (e.g., Most et al., 2000, 2001, 2005; Simons & Chabris, 1999). Such experiments are, however, susceptible to confounds in terms of expectation and memory. A demonstration of load induced blindness with dynamic displays would therefore be more conclusive.

7.2.3 Unconscious Processing of the CS

When the appearance of the CS does not enter conscious awareness in the high perceptual load condition, it may nevertheless produce effects on behaviour due to unconscious processing. Such effects may be detectable by indirect measures. Previous perceptual load studies using indirect measures have shown that distractor effects are reduced under high perceptual load (e.g., Lavie, 1995); however, this only tells us that the identity of the distractor was not processed, it does not tell us that participants were not consciously aware of the presence of the distractor. Indeed, there may be measurable effects associated with the mere presence of a distractor (like a filtering cost, as per Treisman, Kahneman, & Burkell, 1983) rather than its identity, that would remain observable under high perceptual load (although Forster and Lavie [2008] showed that the RT decrement associated with the presence of an additional stimulus was reduced under high perceptual load; however, they did not produce evidence that the participants were not consciously aware of the distractor). In the same way, the CS may produce a slight slowing of search RT, even when it does not enter conscious awareness. It was not feasible to assess such a claim in this thesis due to an insufficient number of critical trials. A future experiment would have to involve a large number of critical trials in order to obtain reasonable measures of mean search RT when the CS was not presented and correctly rejected, and mean search RT when the CS was presented and missed.

7.2.4 Cross-Modal Load Induced Blindness

An ongoing debate concerns whether attentional resources are pooled across modalities or whether they are modality-specific (Allport, Antonis, & Reynolds, 1972; Broadbent, 1958; Driver & Spence, 1998; Duncan, Martens, & Ward, 1997; McLeod, 1977b). It is therefore of theoretical interest to investigate whether load induced blindness can occur cross-modally. This could be achieved by measuring detection of a task-unrelated stimulus presented to one modality while increasing perceptual load in an alternate modality. For example, visual awareness could be assessed while increasing perceptual load in the auditory domain. Conversely, it may be possible to demonstrate load induced deafness due to high perceptual demand in a visual task. In principle, such experiments could involve any pairing of the five modalities.

7.3 Conclusion

In summary, this thesis has established the role of perceptual load in determining conscious awareness. The results support the hypothesis that conscious perception (including the mere detection of the presence of a stimulus) depends on the allocation of limited capacity attention, and that exhausting attention in a high perceptual load task reduces conscious awareness of task-unrelated stimuli, with the failures of detection leading to load induced blindness. The results create new avenues for research: some have been addressed in this thesis, e.g., comparing awareness at fixation versus in the periphery, or establishing the effect of working memory load on awareness, others may be addressed by future research.

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