Load Induced Blindness

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Although the perceptual load theory of attention has stimulated a great deal of research, evidence for the role of perceptual load in determining perception has typically relied on indirect measures that infer perception from distractor effects on reaction times or neural activity (see N. Lavie, 2005, for a review). Here we varied the level of perceptual load in a letter-search task and assessed its effect on the conscious perception of a search-irrelevant shape stimulus appearing in the periphery, using a direct measure of awareness (present/absent reports). Detection sensitivity (d') was consistently reduced with high, compared to low, perceptual load but was unaffected by the level of working memory load. Because alternative accounts in terms of expectation, memory, response bias, and goal-neglect due to the more strenuous high load task were ruled out, these experiments clearly demonstrate that high perceptual load determines conscious perception, impairing the ability to merely detect the presence of a stimulus—a phenomenon of load induced blindness.

Keywords: attention, perceptual load, distractors, awareness, inattentional blindness

To what extent does conscious perception depend on attention? This question has intrigued psychologists for several decades and has led to a long-standing debate between early and late selection views of attention. According to the early selection view, perception is a limited capacity process and therefore depends on the allocation of attention (Broadbent, 1958; Treisman, 1960, 1969). According to the late selection view, perception has unlimited capacity and proceeds automatically, independent of attention (e.g., Deutsch & Deutsch, 1963; Driver & Tipper, 1989; Norman, 1968; Tipper, 1985).

Initial attention studies employing the dichotic listening or selective looking paradigms reported that unattended stimuli frequently went unnoticed (e.g., Cherry, 1953; Moray, 1959; Neisser & Becklen, 1975; Rock & Gutman, 1981; see Lavie, 2006, for a review). These findings suggest that conscious perception depends on the allocation of attention, in line with the early selection view. However, since these findings were typically obtained in experiments assessing retrospective reports, they were criticized as merely reflecting memory failures (e.g., Deutsch & Deutsch, 1963). Online measures of perception in the dichotic listening paradigm, such as assessing the effects of the semantic content of unattended information on the speed of shadowing (e.g., Lewis, 1970) or on skin conductance (e.g., Corteen & Dunn, 1974), or assessing distractor identity effects on the speed of target classification responses (e.g., Eriksen & Eriksen, 1974; Gatti & Egeth, 1978), are not subject to the memory criticism and have produced evidence that unattended information is perceived, in line with the late selection view.

The discrepancy between these contrasting sets of results cannot be resolved in terms of differences arising due to the use of online and offline retrospective measures of perception, however, because some experiments employing online measures of perception have supported the early selection view. For example, Treisman and Geffen (1967; see also Treisman & Riley, 1969) found that when awareness reports of targets occurring in either channel (both attended and unattended) were assessed online in the dichotic listening paradigm, very few targets occurring in the unattended channel were reported, whereas most of those in the attended channel were. Conflicting results were even found between experiments using the same measure of distractor processing. For example, whereas Eriksen and Eriksen (1974) found evidence for unattended distractor perception using the response competition paradigm (thus providing support for the late selection view), Eriksen and Hoffman (1972), and later Yantis and Johnston (1990), used the same measure of response competition effects as that used by Eriksen and Eriksen and found no evidence for perception of the unattended distractors (e.g., those presented outside of the putative region of the attentional spotlight in Eriksen & Hoffman, 1972), thus supporting the early selection view.

These inconsistencies in the attention literature have led some to doubt that the early versus late selection debate can ever be resolved (e.g., Allport, 1993). However, a resolution has been proposed in the form of a hybrid of early and late selection views: the perceptual load model of attention (Lavie, 1995, 2000; Lavie, Hirst, De Fockert, & Viding, 2004; Lavie & Tsal, 1994). Lavie proposed that the level of perceptual load imposed by a task dictates whether early or late selection will occur. In her model, perception has a limited capacity (as with the early selection view) but proceeds automatically on all stimuli (as per late selection), whether relevant to the task at hand or not, until all capacity is consumed. This model leads to the prediction that task-irrelevant stimuli will not be perceived (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 a low level of perceptual load, any spare attentional capacity will spill over involuntarily, resulting in the perception of irrelevant stimuli (late selection).

A review of the early and late selection studies of visual attention provided support for these predictions (Lavie & Tsal, 1994). The tasks used in the studies that provided support for the late selection view typically carried a low level of perceptual load—for example, requiring the identification of just one target stimulus (e.g., Eriksen & Eriksen, 1974)—whereas the tasks that provided support for the early selection view typically involved a high level of perceptual load—for example, requiring search for a target among six items or more (Eriksen & Hoffman, 1972; Yantis & Johnston, 1990).

The predictions of perceptual load theory have also been supported by various behavioral and neuroimaging studies, as we briefly review below (see Lavie, 2005, for a more detailed review). Lavie and colleagues (Lavie, 1995, 2000; Lavie & Cox, 1997; Lavie & Fox, 2000) have demonstrated that response competition and negative priming effects on target reaction times (RTs) from irrelevant distractors can be found, as long as the task involves a low level of perceptual load (e.g., with a search display of just one item or with a simple feature detection task). Such effects are eliminated, however, when the task imposes a high level of perceptual load (e.g., with a search display of six items or with a task requiring a complex feature-conjunction discrimination). These findings have been replicated with meaningful 3D objects as distractors (Lavie, Ro, & Russell, 2003) and with distractors presented directly at fixation (Beck & Lavie, 2005).

Functional imaging studies investigating perceptual load theory have demonstrated that visual cortex activity related to the presence of task-irrelevant stimuli (e.g., V5/MT activity related to motion, parahippocampal activity related to images of places, and activity in retinotopic cortex related to the presence of flickering checkerboards) is attenuated under high perceptual load (e.g., Bahrami, Lavie, & Rees, 2007; O'Connor, Fukui, Pinsk, & Kastner, 2002; Pinsk, Doniger, & Kastner, 2003; Rees, Frith, & Lavie, 1997; Schwartz et al., 2005; Yi, Woodman, Widders, Marois, & Chun, 2004). Indeed, typically the neural signature of the irrelevant stimulus is eliminated entirely with high perceptual load.

However, despite the focus of the theory on the extent to which task-irrelevant stimuli are perceived, in all these studies the conclusions are based upon indirect measures, such as effects on target RTs or neural activity. Therefore, although these studies demonstrate that the degree to which task-irrelevant stimuli are successfully ignored is determined by the level of perceptual load of the task, in support of load theory and the resolution of the early and late selection debate that it proposes, they do not provide any direct evidence to support the claim that perceptual load determines whether task-irrelevant stimuli are consciously perceived.

Specifically, the effects of perceptual load on the neural activity related to task-irrelevant stimuli cannot support any direct conclusions about conscious perceptual experience. Indeed Bahrami, Lavie, and Rees (2007) recently showed that perceptual load can modulate V1 activity related to an invisible irrelevant stimulus that the participants did not consciously perceive. Furthermore, the measures of distractor effects on target RTs in the behavioral experiments, despite their prevalent use as an index of distractor processing in much of the early and late selection research, cannot support any direct conclusions about conscious perception, since one cannot deduce whether a participant was or was not conscious of the distractors on the basis of their RT to the target.

Indeed, the RT results can be construed either way. If the participants were not conscious of the distractors, then their effects on target RTs under conditions of low perceptual load can be explained by unconscious processing of stimulus–response associations. Conversely, if the participants were conscious of the distractors, the elimination of the distractor effects on target RTs under high perceptual load could be the result of post–perceptual response selection processes, although the argument that RT effects may have simply dissipated during the longer RTs in high load tasks is ruled out by the fact that distractor effects tend to increase rather than decrease with manipulations that increase task difficulty, and consequently RTs, without increasing perceptual load (for example, with manipulations of working memory load [Lavie, 2000; Lavie et al., 2004] or with manipulations that induce sensory limits rather than resource limits, e.g., involving extreme stimulus degradation that makes the target stimulus barely visible [Lavie & De Fockert, 2003]). While this body of research therefore provides convincing evidence that perceptual load determines the level of neural activity related to task-irrelevant stimuli and the extent to which distractors interfere with task performance, it is mute with regard to the question of whether the conscious perception of task-irrelevant stimuli is affected by perceptual load.

Only one study so far has investigated perceptual load while measuring participants' conscious perception of task-irrelevant stimuli. Cartwright-Finch and Lavie (2007) recently tested the effect of perceptual load on awareness 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 on the last trial was strongly dependent on the level of perceptual load of the task performed. The rate of awareness reports was considerably lower (typically around 40%–50% lower) in tasks of high perceptual load (involving either attention-demanding subtle perceptual discriminations or visual search for a letter among similar nontarget letters) than in tasks of low perceptual load (involving either simple color detection or visual search for a letter among very dissimilar nontarget letters). This study conclusively demonstrated that high perceptual load is far more likely than low perceptual load to produce inattentional blindness.

Inattentional blindness, however, may not necessarily reflect a lack of conscious perception. The retrospective measure of awareness used in this paradigm is taken after a task response and a surprise question, and so may well involve effects of rapid forgetting (Wolfe, 1999). Also, since both the presence of the extra stimulus and its physical appearance (e.g., color, shape, and location) are unexpected, it is possible that the extra stimulus is perceived but generates only a weak signal (see Barber & Folkard, 1972; Bashinski & Bacharach, 1980; Davis, Kramer, & Graham, 1983; Teichner & Krebs, 1974, for demonstrations of the effects of expectations on detection) that is easily wiped out of memory with the delay incurred by the task response and the processing of the surprise question. The effect of perceptual load on the likelihood of a participant's reporting awareness in the inattentional blindness paradigm may then, at least in part, reflect reduced encoding of the stimulus into memory instead of, or in addition to, reduced perception.

In the present study, we set out to examine the effects of perceptual load on conscious perception in a modified inattentional blindness paradigm in which an expected "critical" stimulus (CS) was presented in multiple trials. The participants were shown examples of this stimulus before starting the experiment, so that its appearance was known in advance. Conscious perception of the CS was measured online, with responses occurring straight after the task response or even immediately upon presentation (i.e., before the task response; see Experiment 3). Previously with the inattentional blindness paradigm there was no way to assess detection sensitivity, as the extra stimulus was presented only once per participant. Because here the CS was presented multiple times, the effects of perceptual load on detection sensitivity (d') and response bias (β) could be assessed. It follows directly from perceptual load theory that detection sensitivity will be reduced under conditions of high perceptual load, but response bias will be unaffected. Although this prediction is at the core of perceptual load theory it has not, as yet, been tested.

In addition, with the following experiments we also examined the specificity of the effect of perceptual load by addressing alternative accounts in terms of memory (Experiments 2 and 3), response prioritization or goal neglect (Experiment 4), strategy (Experiment 5), and general cognitive capacity limits (involving other processes such as working memory) as opposed to specific capacity limits in perception (Experiment 6).

Experiment 1

The purpose of Experiment 1 was to examine whether the perceptual load of a visual search task would determine the sensitivity of conscious detection of an extra stimulus that was irrelevant to the task. Participants were presented with a circle of letters on each trial and were asked to search for either of the target letters *X* or *N*. They were also asked to detect a small, meaningless gray figure (the 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 similarity between targets and nontargets in the circle of letters (e.g., Lavie & Cox, 1997). In the high perceptual load condition the nontarget letters were *H, K, M, W,* and *Z,* and in the low perceptual load condition they were all *O*s and were smaller than the target letter. 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 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.

Method

Participants. Sixteen participants were recruited at University College London (UCL) and were paid for their participation. One participant was excluded and 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 ($M = 24.9$, $SD = 4.4$), and there were 7 men. All of the participants in this experiment, as well as those in subsequent experiments, 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 an IBM compatible PC attached to a Sony 15" monitor. A viewing distance of 57 cm was maintained with a chin rest throughout the experiment. Six letters were presented, equally spaced (nearest contours 0.95° apart), in a circle of 1.7° radius that was centered at fixation. The background of the display was mid-gray (red/green/blue [RGB] values: 204, 204, 204), the CS was a darker gray (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 center so as not to mask the circle of letters. The target letter, a capital letter *X* or *N* (0.6° × 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° × 0.2° wide) 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 gray meaningless shape (0.3° × 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 (see Figure 1 for an example display).

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 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 nontarget 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 fixation dot was presented at the center 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
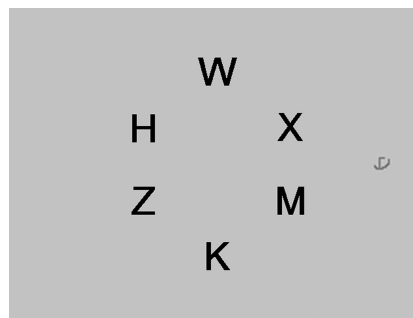

Figure 1. Example of the stimulus display used in the high perceptual load condition.

screen that lasted for 1.4 s (making a total of 2 s during which participants could make the search task response). A display with a question mark at the center was presented next for 100 ms. The participants were instructed to make the CS detection response upon the presentation of this question mark. This was followed by a blank screen for 1.9 s (making a total of 2 s during which participants could make the CS detection response). Both 2-s time windows elapsed regardless of whether a response was made or not made. Participants were instructed to make their search response as quickly and as accurately as possible and to indicate detection of the CS immediately following the presentation of the question mark. 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 hand. 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 CS detection.

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 he or 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.

Results and Discussion

Letter search. Trials in which the search response was incorrect and those in which RT was greater than 1.5 s were excluded from the RT analyses in all of the experiments reported. One-way analyses of variance (ANOVAs) on mean search RT and mean search error rate in the low and high perceptual load conditions revealed that search RTs were significantly longer in the high perceptual load condition ($M = 766$ ms) than in the low perceptual load condition ($M = 593$ ms), $F(1, 14) = 8.68$, $MSE = 13,742.09$, $p = .011$, $\eta_p^2 = .383$ (two tailed, as is every statistical test in this article), and search error rates in the high perceptual load condition ($M = 11\%$) were significantly higher than in the low perceptual load condition ($M = 3\%$), $F(1, 14) = 58.27$, $MSE = 3.99$, $p < .001$, $\eta_p^2 = .806$. These results confirm that the perceptual load manipulation was effective.

CS detection. Mean percentage detection rate and false alarm rate, as well as mean d' were calculated, excluding trials in which the search response was incorrect. These are shown as a function of perceptual load in Table 1. One-way ANOVAs on these measures as a function of perceptual load indicated that detection rates were significantly lower in the high perceptual load condition than in the low perceptual load condition, $F(1, 14) = 15.06$, $MSE = 756.46$, $p = .002$, $\eta_p^2 = .518$. Mean d' in the high perceptual load condition was also significantly lower than that in the low perceptual load condition, $F(1, 14) = 15.44$, $MSE = 1.50$, $p = .002$, $\eta_p^2 = .524$.

Table 1

Experiment 1: Mean Percentage Detection Rate and False Alarm Rate and Mean d' for Critical Stimulus Detection as a Function of Perceptual Load

Perceptual load	Detection rate (%)	False alarm rate (%)	d'
Low	90	2	3.7
High	37	8	1.3

Response criterion (β) was not significantly different between the low load ($M = 5.5$) and high load ($M = 9.0$) conditions, $F < 1$.

There was no effect of the distance between the letter search target and the CS. Mean hit rate was 61% for near and 64% for far target-to-CS distance conditions, $F(1, 14) = 1.42$, $MSE = 96.13$, $p = .254$, $\eta_p^2 = .092$, and there was no interaction of load and distance, $F < 1$. There were no effects of distance in the rest of the experiments either ($p > .19$ in all comparisons of detection rates in the far and near target-to-CS distance conditions). The remainder of the results are therefore reported collapsed across distance conditions.

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 ($M = 17\%$ excluded) than from the low load condition ($M = 4\%$ excluded). 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 $= 37\%$; $M d' = 1.31$) than in the low perceptual load condition (M detection rate $= 90\%$; $M d' = 3.68$), $F(1, 14) = 14.00$, $MSE = 795.11$, $p = .002$, $\eta_p^2 = .500$, and $F(1, 14) = 11.90$, $MSE = 1.89$, $p = .004$, $\eta_p^2 = .460$ for detection rates and d', respectively.

In addition, to address possible carryover effects from a search task error on CS detection in the next trial, we reanalyzed the data, excluding any trial that immediately followed an incorrect search task trial, as well the incorrect search task trials themselves. The results remained unchanged: Detection rates and d' were very similar to those obtained in the main analysis (see Table 1), M detection rate $= 37\%$, $M d' = 1.36$ for the high perceptual load condition; M detection rate $= 91\%$, $M d' = 3.73$ for the low perceptual load condition, $F(1, 14) = 15.37$, $MSE = 734.42$, $p = .002$, $\eta_p^2 = .523$ for the effect of load on detection rates, and $F(1, 14) = 18.24$, $MSE = 1.24$, $p = .001$, $\eta_p^2 = .566$ for the effect of load on d'. Thus, the reduction in detection sensitivity in the high load condition was not caused by carryover effects from the larger number of search task errors in that condition.

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 $= 95\%$; $M d' = 3.36$) and high (M detection rate $= 98\%$; $M d' = 3.23$) perceptual load conditions, $F(1, 14) = 1.14$, $MSE = 36.96$, $p = .303$, $\eta_p^2 = .075$ for detection rates, $F < 1$ for d'. Clearly, the reduction in detection rate and sensitivity found with the high, compared with low, perceptual load experimental blocks was related to the actual performance of the search task, rather than the differences between the appearance of the displays in the load conditions.

These findings provide preliminary evidence for the hypothesis that the level of perceptual load in a task dictates whether any additional stimuli unrelated to the search task can be consciously detected.

Experiment 2

In Experiment 1, the manipulation of perceptual load was validated by the fact that the search task RTs in the high load condition were longer than those in the low load condition. However, because in Experiment 1 the time interval for the search response always elapsed (regardless of when the response was made), 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 of time between the search response and the detection response would also be equal.

In Experiment 2, therefore, the participants were forced to wait for 2 s after the presentation of the stimuli before responding to the search task. We anticipated that this delay would equate search task RTs in the low load and high load conditions. Unless the effect of perceptual load was due to the shorter time available in the high load condition to prepare for the detection response, the results of Experiment 2 should replicate those of Experiment 1.

Method

Participants. Sixteen new participants were recruited from UCL. One participant was replaced because her accuracy on the letter search task was lower than 65%; another 3 were replaced because they detected less than 75% of the CS in the control block; and another 1 was replaced because his mean letter search RT (787 ms) was over two standard deviations above the group mean (337 ms). The age range of those included was 19 to 28 years ($M = 23.5$ years, $SD = 3.3$ years), and there were 4 men.

Stimuli and procedure. The apparatus, stimuli, and procedure were the same as Experiment 1 except that the participants were instructed to make their response to the letter search task 2 s after stimulus presentation, at which point *X/N?* was presented for 100 ms. This was followed by a 1.9-s blank screen, during which time the participants made their search response. Immediately following the search response, a question mark was presented for 100 ms, indicating that the detection response could 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.

Results and Discussion

Letter search. As predicted, with the 2-s delay of the search response there was no longer a difference in search RTs 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 ($M = 21\%$) was, nevertheless, significantly higher than in the low perceptual load condition ($M = 3\%$), $F(1, 14) = 31.38$, $MSE = 39.60$, $p < .001$, $\eta_p^2 = .691$, demonstrating that despite the equal mean 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' for correct search trials only as a function of perceptual load are presented in Table 2. As can be seen in the table, detection rates and d' were again significantly lower in the high load condition, $F(1, 14) = 6.53$, $MSE = 883.98$, $p = .023$, $\eta_p^2 = .318$, and $F(1, 14) = 7.16$, $MSE = 1.61$, $p = .018$, $\eta_p^2 = .338$ for detection rates and d', respectively. Response criterion (β) was not significantly different between the low load ($M = 6.9$) and high load ($M = 7.3$) conditions, $F < 1$.

The results were unchanged when reanalyzed with the incorrect search task trials included (low load: M detection rate $= 85\%$, M $d' = 3.52$; high load: M detection rate $= 50\%$, M $d' = 1.95$), $F(1, 14) = 5.67$, $MSE = 876.25$, $p = .032$, $\eta_p^2 = .288$, and $F(1, 14) = 6.14$, $MSE = 1.61$, $p = .027$, $\eta_p^2 = .305$ for detection rates and d', respectively, and when both incorrect search task trials and any trial immediately following an incorrect search task trial were excluded (low load: M detection rate $= 86\%$, M $d' = 3.56$; high load: M detection rate $= 51\%$, M $d' = 1.94$), $F(1, 14) = 5.75$, $MSE = 876.91$, $p = .031$, $\eta_p^2 = .291$, and $F(1, 14) = 6.67$, $MSE = 1.56$, $p = .022$, $\eta_p^2 = .323$ for the load effect on detection rates and d', respectively.

CS detection in the control block was equivalent in the low perceptual load condition (M detection rate $= 97\%$, M $d' = 3.72$) and the high perceptual load condition (M detection rate $= 94\%$, M $d' = 3.49$), $F < 1$ for both detection rates and d', showing that the CS was easily and equally detected in both load conditions when there was no search task to perform.

Overall then, the results of Experiment 2 rule out an alternative account of the poorer CS detection in the high load condition in terms of there being less time available for decision making and preparation of the CS detection response in that condition than in the low load condition.

Experiment 3

Equating the time available for preparation of the detection response in Experiment 2 ruled out most of the potentially confounding effects of differential search task RTs in the low and high load conditions. However, since the detection response in Experiments 1 and 2 was made after the search task response, an account of the results in terms of a 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

Table 2

Experiment 2: Mean Percentage Detection Rate and False Alarm Rate and Mean d′ for Critical Stimulus Detection as a Function of Perceptual Load

Perceptual load	Detection rate (%)	False alarm rate (%)	d'
Low	86	2	3.53
High	48	5	1.84

perceptual load conditions, the participants' attention was more engaged in processing the search task during that interval in the high load condition 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 load condition 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—that is, before the search task response, rather than after it, as in the previous experiments.

Method

Participants. Twenty-two new participants were recruited from UCL. Two participants were replaced because their accuracy on the letter search task was below 65%, and 2 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 it, and to respond to the letter search task afterward. 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.

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 search task RT analysis, because making a detection response before the search response would have greatly delayed the search task RT. The perceptual load manipulation was again effective: Search task RTs were significantly longer in the high perceptual load condition ($M = 766$ ms) than in the low perceptual load condition ($M = 640$ ms), $F(1, 20) = 5.57$, $MSE = 15,728.47$, $p = .029$, $\eta_p^2 = .218$, and error rate in the high perceptual load condition ($M = 21\%$) was significantly higher than in the low perceptual load condition ($M = 6\%$), $F(1, 20) = 39.46$, $MSE = 31.36$, $p < .001$, $\eta_p^2 = .664$.

CS detection. Mean percentage detection and false alarm rates, and mean d' for correct search trials only as a function of perceptual load are presented in Table 3. As in the previous experiments, detection rates and d' were significantly lower in the high load than in the low load condition, $F(1, 20) = 5.44$, $MSE = 982.61$, $p = .030$, $\eta_p^2 = .214$, and $F(1, 20) = 6.01$, $MSE = 1.16$, $p = .024$,

Table 3

Experiment 3: Mean Percentage Detection Rate and False Alarm Rate and Mean d′ for Critical Stimulus Detection as a Function of Perceptual Load

Perceptual load	Detection rate (%)	False alarm rate (%)	d'
Low	72	2	3.10
High	41	1	1.98

$\eta_p^2 = .231$ for load effects on detection rates and d', respectively. Response criterion (β) showed a numerical trend toward a more stringent criterion in the high load condition ($M = 14.1$) than in the low load condition ($M = 7.7$), but this was not significant, $F(1, 20) = 2.69$, $MSE = 83.50$, $p = .117$, $\eta_p^2 = .119$.

The results were unchanged when reanalyzed with the incorrect search task trials included (low load: M detection rate $= 72\%$, M $d' = 3.13$; high load: M detection rate $= 41\%$, M $d' = 2.01$), $F(1, 20) = 5.73$, $MSE = 911.68$, $p = .027$, $\eta_p^2 = .223$, and $F(1, 20) = 6.57$, $MSE = 1.05$, $p = .019$, $\eta_p^2 = .247$ for detection rates and d', respectively, and when both incorrect search task trials and any trial immediately following an incorrect search task trial were excluded (low load: M detection rate $= 72\%$, M $d' = 3.09$; high load: M detection rate $= 43\%$, M $d' = 2$), $F(1, 20) = 4.84$, $MSE = 967.18$, $p = .040$, $\eta_p^2 = .195$, and $F(1, 20) = 5.89$, $MSE = 1.11$, $p = .025$, $\eta_p^2 = .227$ for load effects on detection rates and d', respectively.

CS detection in the control block, where participants did not perform the letter search task, was again equivalent in the low perceptual load condition (M detection rate $= 98\%$, M $d' = 3.65$) and the high perceptual load condition (M detection rate $= 96\%$, M $d' = 3.31$), $F < 1$ for the main effect of perceptual load on detection rates, $F(1, 20) = 1.40$, $MSE = 0.46$, $p = .250$, $\eta_p^2 = .066$ for the main effect of perceptual load on d', ruling out alternative accounts in terms of the differences between the appearance of the displays in the load conditions.

Experiment 3, therefore, replicated the perceptual load effect on CS detection found in Experiments 1 and 2, 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. Furthermore, reversing the order of responses so that the detection response came first did not have a significant effect on the modulation by perceptual load: A comparison of the results of Experiments 1 and 3 with a between-experiment ANOVA revealed no main effect of experiment, $F < 1$ for both detection rates and d', and no interaction of perceptual load and experiment for both the mean detection rates, $F(1, 34) = 1.28$, $MSE = 889.49$, $p = .265$, $\eta_p^2 = .036$, and for mean d', $F(1, 34) = 2.92$, $MSE = 1.30$, $p = .097$, $\eta_p^2 = .079$. This adds further support to the hypothesis that the level of perceptual load in a task determines conscious perception of stimuli unrelated to that task.

It is somewhat surprising that the overall mean detection rate in this experiment (56%) was lower than in Experiment 1 (63%), considering that the detection response was now prioritized by being made first, before the search response. This may reflect that 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. It is important to note, however, that 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 cannot serve as an alternative account of the effect of perceptual load on detection.

Experiment 4

In Experiment 3, alternative accounts of the results in terms of memory failure were countered by having the detection response first, before the search response, thereby 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 4, therefore, the order of responses was restored to that of Experiments 1 and 2, with the detection response following the search response.

In all the experiments so far the CS was presented in 17% of trials and participants made a detection response only if they had spotted the CS, and simply made no response if it was absent. This may have increased the likelihood that detection task performance suffered to some extent from some form of "goal-neglect" (Duncan, Emslie, Williams, Johnson, & Freer, 1996). In other words, people may have simply neglected to respond to the detection task on some occasions, and this would be more likely to occur when the search task was more demanding, as in the high load condition.

There is some evidence against a simple form of such response-neglect in the previous experiments, as the reduction in detection rate in the high load condition was typically accompanied by a higher rate of false alarms (and hence could not be accounted for by an overall reduction in the rate of detection responses in the high load condition). Nevertheless, to minimize any effects of an overall deprioritization of the detection task, we presented the CS in 50% of the trials in Experiment 4 and requested that participants make a detection response (either *present* or *absent*) on every trial. 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.

Method

Participants. Sixteen new participants were recruited from UCL. Five participants were replaced because their accuracy on the letter search task was below 65%; another 4 were replaced because they detected less than 75% of the CS in the control block; and 2 were replaced because their mean search RT was two standard deviations either 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 5 men.

Stimuli and procedure. The apparatus, stimuli, and procedure were the same as in 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 (2) in each of the letter circle positions (6), either without or with the CS in each position (6). In the high perceptual load condition there were also 144 randomly selected nontarget arrangements. The control block used half of the displays from the first block and half from the second block. Participants were instructed to press the *A* key when the CS was absent and the *S* key when it was present.

Results and Discussion

Letter search. As in the previous experiments, longer search RTs and a greater number of errors were found in the high perceptual load condition ($M = 870$ ms and $M = 24\%$) than in the low perceptual load condition ($M = 533$ ms and $M = 11\%$), $F(1, 14) = 64.69$, $MSE = 7026.05$, $p < .001$, $\eta_p^2 = .822$ for the RTs, and $F(1, 14) = 12.24$, $MSE = 54.17$, $p = .004$, $\eta_p^2 = .466$ for the error rates.

CS detection. The mean percentage detection and false alarm rate and mean d' for correct search task trials only as a function of perceptual load are presented in Table 4. As can be seen in the table, the effects of perceptual load on detection rates and d' were replicated in Experiment 4, $F(1, 14) = 15.32$, $MSE = 208.34$, $p = .002$, $\eta_p^2 = .523$ for detection rates, and $F(1, 14) = 19.58$, $MSE = 0.64$, $p = .001$, $\eta_p^2 = .583$ for d'. Response criterion (β) did not differ between the low load ($M = 2.2$) and high load ($M = 3.5$) conditions, $F < 1$.

The results were unchanged when reanalyzed with the incorrect search task trials included (low load: M detection rate $= 91\%$, M $d' = 3.28$; high load: M detection rate $= 63\%$, M $d' = 1.56$), $F(1, 14) = 13.68$, $MSE = 225.11$, $p = .002$, $\eta_p^2 = .494$, and $F(1, 14) = 18.37$, $MSE = 0.65$, $p = .001$, $\eta_p^2 = .567$, respectively, and when both incorrect search task trials and any trial immediately following an incorrect search task trial were excluded (low load: M detection rate $= 93\%$, M $d' = 3.34$; high load: M detection rate $= 68\%$, M $d' = 1.89$), $F(1, 14) = 13.54$, $MSE = 171.99$, $p = .002$, $\eta_p^2 = .492$, and $F(1, 14) = 15.64$, $MSE = 0.54$, $p = .001$, $\eta_p^2 = .528$ for the load effect on detection rates and d', respectively.

CS detection in the control block was again equivalent in the low perceptual load condition (M detection rate $= 98\%$, M $d' = 3.97$) and the high perceptual load condition (M detection rate $= 97\%$, M $d' = 3.69$), $F(1, 14) = 1.00$, $MSE = 5.06$, $p = .334$, $\eta_p^2 = .067$ for the main effect of perceptual load on detection rates, and $F(1, 14) = 1.93$, $MSE = 0.15$, $p = .187$, $\eta_p^2 = .121$ for the main effect of perceptual load on d', showing that the CS was easily and equally detected in both load conditions when there was no letter search task to perform.

These results clearly demonstrate that perceptual load determines conscious perception even when the CS has a considerably higher probability, appearing in 50% of trials rather than 17% as in the previous experiments, and when task priority is greater as participants now respond to the detection task on every trial.

Experiment 5

The purpose of Experiment 5 was to determine whether the effect of perceptual load on detection can be replicated in a design

Table 4

Experiment 4: Mean Percentage Detection Rate and False Alarm Rate and Mean d' for Critical Stimulus Detection as a Function of Perceptual Load

Perceptual load	Detection rate (%)	False alarm rate (%)	d'
Low	92	5	3.38
High	64	15	1.61

in which low and high perceptual load trials are randomly intermixed within a block. 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. This has been adopted in several studies (Brand-D'Abrescia & Lavie, 2007; Cartwright-Finch & Lavie, 2007; Lavie & Cox, 1997; Lavie & Fox, 2000; Theeuwes, Kramer, & Belopolsky, 2004), each successfully ruling out differential strategies as an alternative explanation of the perceptual load effect. As in Experiment 4, the probability of CS presentation was 50% for each condition of perceptual load, and the participants made a detection response on every trial (either *present* or *absent*).

Method

Participants. Twenty-two new paid UCL participants were recruited. Three participants were excluded and replaced because their accuracy on the letter search task was lower than 65%, and 2 were replaced because they detected less than 75% of the CS 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 in Experiment 4 except that low and high perceptual load trials were randomly intermixed within each block. The CS was presented on 50% of trials as in Experiment 4, and participants made the detection response (either *present* or *absent*) upon the presentation of the word *spot?* The first time interval for the search response elapsed regardless of whether a response was made or not, whereas the second time interval for the detection task terminated on response. A counterbalanced set of 144 different stimulus displays, employed across two blocks of 72 trials, consisted of each load condition (2), each of the target letters (2) in each of the letter circle positions (6), either without or with the CS in each position (6). In the high perceptual load condition there were also 72 randomly selected nontarget arrangements. The control block used half of the displays from the first block and half from the second block.

Results and Discussion

Letter search. As in the previous experiments, search RTs were significantly longer (high load $M = 857$ ms, low load $M = 674$ ms) and error rates significantly higher (high load $M = 21\%$, low load $M = 6\%$) in the high perceptual load condition than in the low perceptual load condition, $F(1, 21) = 199.96$, $MSE = 1844.82$, $p < .001$, $\eta_p^2 = .905$, and $F(1, 21) = 90.68$, $MSE = 28.29$, $p < .001$, $\eta_p^2 = .812$ for RTs and error rates, 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' for correct search trials only as a function of perceptual load are presented in Table 5. As can be seen in the table, detection rates and d' were again significantly lower in the high load than in the low load condition, $F(1, 21) = 4.61$, $MSE = 145.89$, $p = .044$, $\eta_p^2 = .180$, and $F(1, 21) = 4.65$, $MSE = 0.17$, $p = .043$, $\eta_p^2 = .181$ for the load effect on detection rates and d', respectively. Response criterion (β) was not significantly different between the low load ($M = 1.8$) and high load ($M = 2.2$) conditions, $F < 1$.

The results were unchanged when reanalyzed with the incorrect search task trials included (low load: M detection rate = 85%, M

Table 5

Experiment 5: Mean Percentage Detection Rate and False Alarm Rate and Mean d' for Critical Stimulus Detection as a Function of Perceptual Load

Perceptual load	Detection rate (%)	False alarm rate (%)	d'
Low	87	13	2.70
High	79	10	2.43

$d' = 2.59$; high load: M detection rate = 78%, M $d' = 2.33$), $F(1, 21) = 6.53$, $MSE = 99.35$, $p = .018$, $\eta_p^2 = .237$, and $F(1, 21) = 5.33$, $MSE = 0.13$, $p = .031$, $\eta_p^2 = .202$ for detection rates and d', respectively, and when both incorrect search task trials and any trial immediately following an incorrect search task trial were excluded (low load: M detection rate = 89%, M $d' = 2.79$; high load: M detection rate = 80%, M $d' = 2.48$), $F(1, 21) = 5.42$, $MSE = 152.88$, $p = .030$, $\eta_p^2 = .205$, and $F(1, 21) = 6.62$, $MSE = 0.16$, $p = .018$, $\eta_p^2 = .240$ for load effects on detection rates and d', respectively.

CS detection in the control block, in which participants did not perform the letter search task, was again equivalent in the low (M detection rate = 92%, M $d' = 3.46$) and high (M detection rate = 92%, M $d' = 3.72$) perceptual load conditions, $F < 1$ for the main effect of perceptual load on detection rates, $F(1, 21) = 3.35$, $MSE = 0.23$, $p = .081$, $\eta_p^2 = .138$ for the main effect of perceptual load on d'.

Overall, the results of Experiment 5 replicated the effect of perceptual load on detection with a design in which the level of load was randomly intermixed within blocks. Since this design precludes any strategy-based accounts of the results, the replication of the effect of perceptual load in this experiment clearly indicates that the effect of perceptual load on detection does not necessitate the adoption of any particular strategy. This conclusion concurs with the previous demonstrations that high perceptual load can eliminate distractor interference effects (e.g., Brand-D'Abrescia, & Lavie, 2007; Lavie & Cox, 1997; Lavie & Fox, 2000; Theeuwes et al., 2004) and induce a greater rate of inattentional blindness (Cartwright-Finch & Lavie, 2007), even when low and high levels of perceptual load are randomly intermixed within blocks.

The effect of perceptual load on detection in this experiment (a reduction in d' of 0.3) was, however, smaller than that of the previous experiments. (Compare, for example, this reduction in d' of 0.3 with the reduction of 1.8 obtained in Experiment 4, which had the most comparable procedure but used a blocked load design.[1]) This reduction in the effect of load in Experiment 5 may indicate the contribution of a strategy component to the effect of perceptual load in the previous experiments, or it may be due to other factors involved in the change to an intermixed load design in this experiment. First, because Experiment 5 had the same number of trials in total as in each of the previous experiments (to keep the same overall level of practice in the task), this meant that

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[1] Although the numerical trend suggests a reduction in the effect of load between Experiments 4 and 5, this could not be ascertained statistically because within-subjects (Experiment 5) and between-subjects (Experiment 4) manipulations of the same independent variable (load) cannot be entered into a single ANOVA.

it had only half the number of trials per load condition compared with the previous experiments. With the smaller number of trials per condition of load, Experiment 5 had weaker power to detect any load effect. Second, intermixing the levels of perceptual load in a block provides a weaker manipulation of perceptual load as a result of carryover effects from one level of load to the other. In fact, it is likely that such carryover effects would increase the level of load in the low perceptual load condition due to a lack of a full "clear out" of perception from the high load trials. In line with these suggestions, the effect of perceptual load on the search RTs was indeed smaller in this experiment compared with that in Experiment 4, and the reduction in this effect appears to be specifically due to an increase in the search RTs in the low perceptual load condition ($M = 674$ ms) compared with Experiment 4 ($M = 533$ ms). (In the high perceptual load condition, the mean RT was only 13 ms faster in Experiment 5 than in Experiment 4.) Therefore, because the effect of perceptual load on the search task was also smaller in this experiment, this may have been responsible for the weaker effect on detection.

In conclusion, it is unclear whether the reduction in the effect of perceptual load in Experiment 5 was due to its weaker power with the reduced number of trials per condition or to carryover effects weakening the effect of perceptual load on search performance and thereby on detection as well, or whether this reduction in the effects of load indicates a strategy component. We note that as alternative accounts of the effects of perceptual load in terms of strategy have been clearly ruled out when other measures of distractor processing and awareness were used (e.g., Cartwright-Finch & Lavie, 2007; Lavie & Cox, 1997), the contribution of strategy that the present results may allude to appears to be specific to the search plus detection task used here.

Experiment 6

So far we have focused on the effect of perceptual load on conscious perception. An important dissociation in load theory is between the effects of perceptual load and working memory load on selective attention (Lavie, 2000; Lavie et al., 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 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 other task-unrelated material during task performance, the processing of low priority, task-irrelevant distractors is increased.

Evidence for this dissociation has come from studies demonstrating that in contrast to 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).

As with the vast majority of the research on perceptual load, however, the behavioral evidence that working memory load increases distractor processing is currently limited to indirect measures (e.g., distractor effects on target RTs) that cannot lead to any definitive conclusions regarding conscious perception. In Experiment 6, we therefore sought to examine the effects of working memory load on the conscious perception of stimuli that are irrelevant to the search task.

To this aim, we interleaved the visual search and detection task with a working memory task similar to that used in previous studies showing the effects of working memory load on distractor processing (e.g., Lavie et al., 2004). 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 task. Participants had to retain the digit(s) in working memory while performing the search and detection task 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.

Method

Participants. Twelve new participants were recruited from UCL. One participant was replaced because he detected less than 75% of the CS in the control block, and another was replaced 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 4 men.

Stimuli and procedure. The stimuli and procedure for the visual search and detection task were the same as those used in the low perceptual load condition of Experiment 4. 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 $0.7° \times 0.5°$, and were centered on the screen, in a row when there were six digits (high load condition). The memory probe digit had the same color and dimensions as the memory set digits and was also centered 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 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 $4° \times 1.4°$ patch of random noise (black and gray) 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 a blank screen (1.4 s), during which time participants made their response to the search task. Next, the word *spot?* (presented in black letters subtending $0.9° \times 0.7°$) was presented until the CS detection response was made (either present or absent, *S* or *A* key). The CS detection

response was followed by the presentation of the memory probe, which remained on screen until participants made their memory 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 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 displays of stimuli, with equal likelihood of each of the target letters (2), in each of the letter circle positions (6), either without or with the CS in each position (6). 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.

Results and Discussion

Working memory task. Longer RTs and a greater number of errors in the high working memory load condition (*M* RT = 1296 ms, *M* error rate = 15%) than in the low working memory load condition (*M* RT = 1028 ms, *M* error rate = 8%) confirmed that the manipulation of working memory load by memory set size was effective, $F(1, 11) = 17.93$, $MSE = 24{,}116.41$, $p = .001$, $\eta_p^2 = .620$ for the RTs, $F(1, 11) = 8.24$, $MSE = 33.99$, $p = .015$, $\eta_p^2 = .428$ for the error rates.

Letter search. RTs and error rates on the search task were no different in the high working memory load condition (*M* RT = 848 ms, *M* error rate = 3%) and the low working memory load condition (*M* RT = 842 ms, *M* error rate = 5%), $F < 1$ for the RTs, and $F(1, 11) = 1.17$, $MSE = 11.59$, $p = .304$, $\eta_p^2 = .096$ for the error rates. This has often been the case in previous working memory load studies: Working memory load typically has a selective effect on distractor processing with no general increase in overall RTs and error rates 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 6 shows mean percentage detection and false alarm rates and mean d' as a function of working memory load. 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 rates and d'. Response criterion (β) was also the same in the low working memory load ($M = 0.9$) and high working memory load ($M = 0.9$) conditions, $F < 1$.

Table 6
Experiment 6: Mean Percentage Detection Rate and False Alarm Rate and Mean d' for Critical Stimulus Detection as a Function of Working Memory Load

Working memory load	Detection rate (%)	False alarm rate (%)	d'
Low	91	11	3.13
High	89	10	3.11

The results were unchanged when reanalyzed with both the incorrect search task trials and incorrect working memory task trials included (low load: *M* detection rate = 91%, *M* d' = 3.07; high load: *M* detection rate = 89%, *M* d' = 3.04; $F < 1$ for both) and when any trial following an incorrect search task trial was excluded as well as the incorrect search task trials themselves (low load: *M* detection rate = 91%, *M* d' = 3.13; high load: *M* detection rate = 89%, *M* d' = 3.10), $F(1, 11) = 1.40$, $MSE = 20.08$, $p = .261$, $\eta_p^2 = .113$, and $F < 1$, for detection rates and d', respectively.

In the control block, in which participants did not perform the letter search task or working memory task, there was also no difference between the low working memory load (*M* detection rate = 97%, *M* d' = 3.53) and high working memory load conditions (*M* detection rate = 96%, *M* d' = 3.31), $F < 1$ for detection rate, and $F(1, 11) = 1.93$, $MSE = 0.15$, $p = .193$, $\eta_p^2 = .149$ for d', as expected.

Thus, in contrast with the consistent reduction in the detection rate and sensitivity of detection with high, compared with low, perceptual load in Experiments 1 through 5, Experiment 6 demonstrated that detection is unaffected by working memory load. This finding is important in two respects. First, the contrast 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 general task difficulty (see Lavie & De Fockert, 2003, for further support for this claim) 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.

Second, the contrast between our finding that the conscious perception of a search-unrelated stimulus is unaffected by working memory load and the previous findings that working memory load increases distractor interference effects on RT as well as distractor-related neural activity (Lavie, 2000; Lavie & De Fockert, 2005; Lavie et al., 2004) provides an important clarification of the role working memory serves in the control of selective attention.[2] The critical stimulus used here was a low contrast meaningless shape that could not compete with the search target for selection, because 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 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 Lavie, 2000, and Lavie et al., 2004) or because they were more visually salient than the target (i.e., in the attentional capture paradigm used by Lavie & De Fockert, 2005, the distractor was a color singleton presented during a shape search task), or in some

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[2] The contrast in susceptibility to the effects of working memory load between noninterfering task-unrelated stimuli and distracting stimuli was also directly established in another experiment (Macdonald, 2008). In this experiment, when stimulus displays were used that were similar to those of Experiment 6, but either the CS was presented (in some of the blocks) or a distractor letter that was congruent or incongruent with the target was presented (in the other blocks), working memory load significantly increased distractor interference effects but again had no effect on CS detection.

cases both (e.g., De Fockert et al., 2001, used distractor faces that were not only related to the task response—i.e., they were congruent or incongruent with the target response—but were also likely to have been more salient than the word targets).

The contrast between the effects of working memory load on these different types of stimuli therefore suggests that active executive control of selective attention by working memory is needed only in competitive situations: When stimuli irrelevant to the search or discrimination task compete with the target for selection, active executive control of selective attention is engaged in order to prevent the selection of such stimuli. Hence, loading working memory results in increased interference because executive control is no longer able to manage selective attention as effectively. However, the processing of irrelevant stimuli that do not compete with the target for selection is unaffected by working memory load, because 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 et al., 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 center of the display. As such, they would not have competed with the target for selection and 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.

Finally, it is important to note that the manipulation of working memory load via the active maintenance of digits in memory employed here, 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, because 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.

General Discussion

Our experiments have demonstrated the effect of perceptual load on conscious perception. High, compared with low, perceptual load in a letter search task consistently reduced participants' ability to detect the presence of a shape stimulus presented in the periphery that was unrelated to the search task. Moreover, the effect of perceptual load was found on both measures of detection accuracy (hit rates) and sensitivity (d') and was never accompanied by an effect on response bias (β). The effects of perceptual load therefore indicate that participants were less likely to be aware of the search-irrelevant stimulus when performing a search task of high perceptual load—a phenomenon of load induced blindness.

The results were replicated when RTs for low and high perceptual load search tasks did not differ (Experiment 2) and when the

detection response was made immediately upon stimulus presentation, before the search response (Experiment 3). The results were also unchanged when the priority of the detection task was raised by increasing the frequency of CS presentation from 17% to 50% and by requesting participants to make either a present or an absent response so that a detection response had to be made on every trial (Experiment 4). Furthermore, the effect of perceptual load persisted with a design that rules out a strategy-based account of the results in which high load and low load trials were randomly intermixed within blocks (Experiment 5). The effect of perceptual load on conscious perception was therefore not due to differences in search task RTs, memory, strategy, or goal-neglect and deprioritization of the detection task, but was indeed specifically due to load on perceptual processes.

The results provide the most compelling evidence so far in support of the claim that the level of perceptual load in a task determines the extent to which any additional task-irrelevant stimuli are consciously perceived. This claim is one of the central tenets of load theory and is critical for the resolution load theory proposes for the early and late selection debate. Previous tests of the theory have not directly tested this prediction, however. As we briefly reviewed in the introductory section, although perceptual load theory has stimulated a great deal of behavioral and neuroimaging research, previous experiments have assessed perception with popular but indirect measures such as distractor effects on RTs and distractor-related neural activity. The only previous study that directly assessed the effects of perceptual load on conscious perception (Cartwright-Finch & Lavie, 2007) used the inattentional blindness paradigm. The results of that study are therefore confined to the case of unexpected stimuli and are open to alternative accounts in terms of potential effects of load on response bias or memory.

Working Memory Load

Experiment 6 confirmed the specificity of the effect of perceptual load on conscious detection: Increasing working memory load during performance of the search and detection task in Experiment 6 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 our finding that working memory load does not affect the perception of stimuli unrelated to the search task, and those of previous studies (see also footnote 2) showing that working memory load increases distractor-related neural activity and interference effects on behavior (De Fockert et al., 2001; Lavie, 2000; Lavie & De Fockert, 2005; Lavie et al., 2004), allows a more detailed understanding of the role working memory serves in the control of selective attention: Only in situations in which distracting stimuli compete with the target for selection will active executive control of selective attention by working memory be needed to minimize distractor interference effects. In such situations, rendering executive control unavailable to the task 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 cannot 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.

This account explains the apparent discrepancy between results showing that working memory load determines the processing of competing distractor stimuli (e.g., De Fockert et al., 2001; Lavie & De Fockert, 2005; Lavie et al., 2004) and results showing that working memory load does not affect the processing of task-irrelevant stimuli (e.g., Yi et al., 2004). Whereas the positive effects of working memory load were found in experiments using salient, competing distractors, the null effects of working memory load were found in experiments in which the task-irrelevant stimuli did not compete with the target for selection.

Detection as a Capacity-Limited Process

Our finding that detection sensitivity to a stimulus unrelated to the search task is reduced under conditions of high perceptual load (while response bias is unchanged) suggests that even simple presence/absence detection is subject to capacity limits and therefore depends on the allocation of attention.

Research into the question of the extent to which detection depends on the allocation of attention or may instead be a capacity-free process that is independent of attention has produced mixed results. Studies that have used attentional cuing paradigms typically found effects of spatial cuing on detection RT (showing both costs for unattended positions and benefits for attended positions; e.g., Posner, 1980; Posner, Snyder, & Davidson, 1980), and therefore suggested that detection depends on the allocation of attention. However, RT effects may simply reflect the adoption of a more liberal response criterion at the cued location and hence cannot directly inform about the role of attention in the perceptual processes involved in detection.

Studies that can isolate the effects on detection accuracy from those on response bias (e.g., using either the signal detection method or two-alternative forced choices) can be more informative in this regard. Unfortunately they have not produced consistent results. A series of experiments by Graham and colleagues (e.g., Davis et al., 1983; Graham, Kramer, & Haber, 1985) reported no effects of cuing on detection accuracy when two-interval forced choices were measured. In contrast, some studies using signal detection analysis have reported an enhancement of detection sensitivity for cued, compared with uncued, locations, with no effect on response bias (e.g., Bashinski & Bacharach, 1980; Brawn & Snowden, 2000). Others, however, have found an effect of attentional cuing on response bias alone, with no effect on detection sensitivity (e.g., Muller & Findlay, 1987), and others still have found an effect on both detection sensitivity and response bias (Downing, 1988; Hawkins et al., 1990; Luck et al., 1994; Muller & Humphreys, 1991; Smith, 1998).

Experiments addressing whether detection is a capacity-limited process by investigating the effect of the display set size have also produced mixed results (contrast, for example, the results of Palmer, 1990, with those of Palmer, Ames, & Lindsey, 1993). In addition, many have suggested that the effects of spatial cuing or display set size on detection sensitivity merely reflect reduced noise with smaller set sizes or cued stimuli (e.g., Duncan, 1980; Muller & Findlay, 1987; Muller & Humphreys, 1991; Pelli, 1985; Shaw, 1982; Sperling, 1984; Sperling & Dosher, 1986).

Research using the dual-task method is more relevant to the present study. However, this research has not reached a consensus either. Bonnel, Stein, and Bertucci (1992) claimed that whereas a perceptual discrimination (in their case between a luminance increment and decrement) depends on the allocation of attention, detection (of a luminance increment) 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 we have. 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 (a vertical line among tilted lines) did not show a performance decrement under dual-task conditions (in which the detection task was combined with an orientation discrimination task). When the detection task was replaced with a second discrimination task, however, performance did suffer. Braun and Sagi (1990) therefore concluded, similar 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 our own, in that only a demanding task of high perceptual load produced a decrement in detection performance, supporting the conclusion that a greater demand on attention can result in reduced conscious perception, in line with perceptual load theory. The conclusion drawn from Joseph and colleagues' 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 nonattentional processes such as making an additional response per trial (in the dual-task condition), memory (due to the delay caused by making one task response after the other in the dual task condition), and goal neglect (due to performing two tasks simultaneously). By contrast, our experiments 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 bias, strategy, or task difficulty, can determine perceptual sensitivity even for the simple ability to detect whether a stimulus is present or absent.

As such, these results provide the most direct evidence in support of the perceptual load hypothesis that conscious perception (even mere detection of stimulus presence) depends on the allocation of limited capacity attention and that exhausting attention in a high perceptual load task eliminates conscious perception of task-irrelevant stimuli, with the failures to detect the stimulus's presence leading participants to experience load induced blindness.

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