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The role of perceptual load in inattentional blindness ☆,☆☆

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Abstract

Perceptual load theory offers a resolution to the long-standing early vs. late selection debate over whether task-irrelevant stimuli are perceived, suggesting that irrelevant perception depends upon the perceptual load of task-relevant processing. However, previous evidence for this theory has relied on RTs and neuroimaging. Here we tested the effects of load on conscious perception using the "inattentional blindness" paradigm. As predicted by load theory, awareness of a task-irrelevant stimulus was significantly reduced by higher perceptual load (with increased numbers of search items, or a harder discrimination vs. detection task). These results demonstrate that conscious perception of task-irrelevant stimuli critically depends upon the level of task-relevant perceptual load rather than intentions or expectations, thus enhancing the resolution to the early vs. late selection debate offered by the perceptual load theory.

Keywords: Perceptual load; Inattentional blindness; Awareness; Distracter; Conscious perception

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1. Introduction

Would focusing attention on a current task prevent the intrusion of task-irrelevant stimuli into awareness? This fundamental issue has intrigued psychologists for many years and has led to an enduring controversy between early selection views suggesting that attention can prevent irrelevant stimuli from reaching awareness (e.g., Broadbent, 1958; Neisser & Becklen, 1975) and late selection views proposing that attention does not affect perceptual awareness, but rather affects later processes such as response selection and memory (e.g., Deutsch & Deutsch, 1963; Tipper, 1985).

A possible resolution to this debate has been offered within a hybrid perceptual load model (Lavie, 1995, 2000). According to this model, focusing attention on a current task can prevent the perception of task-irrelevant stimuli (i.e., early selection) when the task-relevant processing involves a high level of perceptual load which consumes all available capacity. By contrast, when the processing of task-relevant stimuli involves only low perceptual load, any spare capacity spills over involuntarily to the perception of irrelevant stimuli (i.e., late selection).

Although the perceptual load model would clearly predict that irrelevant stimuli should not reach awareness under conditions of high perceptual load, this hypothesis has not been directly tested as yet. Previous evidence for the load theory has so far relied upon either indirect behavioral measures of the effects of distractors on target reaction times (RTs) or functional imaging experiments assessing neural activity in sensory cortices related to distractor perception (see Lavie, 2005, for review). However, with one exception (Rees, Frith, & Lavie, 1997), previous experiments have not examined whether load influences the entry of distractors into visual awareness.

For example, in a series of behavioral experiments, Lavie (1995; Lavie & Cox, 1997) assessed the effects of perceptual load on distractor processing within the response competition paradigm (Eriksen & Eriksen, 1974). Participants made speeded choice responses deciding whether a central target letter was one of two pre-specified letters while attempting to ignore a peripheral distractor letter. Distractor letters could be either congruent (e.g., distractor “X” for target “X”) or incongruent (distractor “X” for target “Z”) with the target. In some experiments, the perceptual load of this task was manipulated by increasing the number of letters among which the target appeared: In addition to the distractor, the target letter appeared either alone (low load) or among five other non-target letters (high load). In other experiments, perceptual load was manipulated by increasing the demands placed on attention for identical displays. For example, participants either detected presence/absence (low load) or (for the same stimuli) made a difficult size and position discrimination (high load). The results showed that distractor congruency with the target influenced target RTs in tasks of low perceptual load, but that such distractor effects were eliminated under high perceptual load. Lavie and Fox (2000) similarly found that distractors produced negative priming effects (i.e., they increased RTs when presented as targets in subsequent trials) in tasks of low perceptual load, but not in tasks of high perceptual load.

These studies clearly demonstrate that interference effects from distractors are reduced in tasks of high (compared to low) perceptual load. However, they cannot provide information about the effects of perceptual load on conscious perception of such distractors. Although the perceptual load model interprets the elimination of distractor effects on RTs by higher loads as reflecting an overall reduction in distractor perception (i.e., implying no conscious perception of distractors with high perceptual load), these effects are equally consistent with alternative interpretations proposing no role for perceptual load in determining conscious perception. For example, one could claim that perceptual load influences unconscious perceptual processes but has no effects on conscious perception. On such an interpretation, task-irrelevant distractors never enter awareness under either condition of load: distractor interference effects seen in conditions of low load merely reflect unconscious recognition of distractor-/target–response associations. Alternatively, one could also claim that distractors always enter awareness, regardless of load. With this interpretation, the reduction of distractor effects on RTs by higher perceptual loads reflects either an influence of load on post-perceptual processes such as response selection, or a dissipation of distractor effects during longer RTs for high load (but see Lavie & De Fockert, 2003; Lavie & Fox, 2000; for counter-evidence).

Functional imaging tests of the perceptual load theory demonstrate that activity in the visual cortex related to distractor presence is eliminated under high perceptual load. For example, Rees et al. (1997) showed that visual cortex activity related to moving (vs. stationary) distractors (e.g., in MT), was found in conditions of low task-relevant load (requiring detection of letter case in fixated target words) but was eliminated by high task-relevant load (involving a more complex word discrimination). Other studies found that visual cortex activity related to various other task-irrelevant stimuli (e.g., checkerboards, meaningful pictures) was significantly reduced, indeed typically eliminated, with increased perceptual load in a relevant task (Pessoa, McKenna, Gutierrez, & Ungerleider, 2002; Pinsk, Doniger, & Kastner, 2003; Schwartz et al., 2005; Yi, Woodman, Widders, Marois, & Chun, 2004).

The convergence of results from behavioral and imaging experiments makes an appealing case for the hypothesized role of perceptual load in distractor processing. It also clearly demonstrates that the perceptual load modulation of distractor processing is evident at multiple different levels and does not merely reflect effects on RTs (e.g., as stipulated in dissipation accounts). However, assessment of neural activity cannot provide information about subjective conscious experience and, as discussed above, neither can indirect behavioral measures (RTs).

As mentioned above, one imaging study (Rees et al., 1997) included an assessment of the effects of perceptual load on awareness. Rees et al. (1997) measured the subjective duration of a motion after effect caused by the irrelevant distractor-motion in their imaging task. They found that the duration of a motion after effect was significantly reduced when participants performed the high load task compared with the low load task. As this test involved participants directly reporting their subjective motion experience, the results are encouraging for our suggestion that perceptual load determines awareness. However, without further corroboration and extension to other measures of awareness, Rees et al.'s (1997) results remain confined to the case of motion after effects.

The purpose of the present study was therefore to directly examine the role of perceptual load in visual awareness, using a more general measure of awareness within the ''inattentional blindness'' paradigm (Mack & Rock, 1998). In a typical inattentional blindness procedure, an unexpected, task-irrelevant object appears either in the final ''critical trial'' of a small set of experimental trials (e.g., a square presented in the periphery while participants perform a line-length judgment on a cross-target at fixation, Mack & Rock, 1998; a triangle moving across the screen while participants attend to one of two subsets of moving shapes, Most et al., 2001), or for some duration during a continuous task (e.g., a woman with an umbrella passing by people playing a ball game while participants count the number of ball-passes made, Neisser, 1979; Simons & Chabris, 1999). Following the usual task–response on the critical trial, participants are asked to report whether they were aware of any extra task-irrelevant stimulus, or anything unusual on the screen. Findings show that participants often fail to notice the unexpected task-irrelevant stimulus. By contrast, the same stimulus is often detected on a following control trial in which participants do not perform the task but instead pay attention to whether there is any extra stimulus on the screen. This contrast has been taken to reflect blindness due to inattention hence the term ''inattentional blindness''.

Fully-attended control trials differ from experimental trials however, in several aspects that entail processes other than attention. First, the critical stimulus is expected on the control trials, and participants are likely to look for it intentionally (either due to explicit instruction to look for something extra in some studies, or due to the preceding awareness probe raising their expectations of something unusual). Thus, the comparison of control trials with experimental trials confounds effects of attention with effects of expectation and intention (see Braun, 2001). Second, awareness reports are made after a task–response and a surprise awareness question in critical trials, but can be made immediately following display presentation in control trials. Reduced rates of awareness in critical (vs. control) trials may therefore reflect greater rates of forgetting during the longer delay from display presentation until the awareness question in the critical (vs. control) trials. In other words, inattentional blindness may be conceptualized as ''inattentional amnesia'' (e.g., Wolfe, 1999).

Thus, the contrast of awareness between critical trials and control trials in previous studies cannot lead to clear conclusions about the pure role of inattention in the phenomenon of inattentional blindness and may, at least in part, reflect effects of expectation, intention and memory. The present study therefore also served to clarify the role of inattention in ''inattentional blindness''. To avoid the expectation and memory confound in this study, we did not compare rates of inattentional blindness between critical trials and control trials. Instead we compared rates of inattentional blindness between critical trials with different levels of attention available, as determined by manipulations of perceptual load in the relevant task. Awareness reports in the control trial were used solely as an exclusion criterion: participants that could not report the critical stimulus in the fully-attended control trial were excluded from analysis (thus ensuring that any failures to report the critical stimulus in the critical trial could not be explained by an inability to see that stimulus). In this way, our comparisons were not confounded with varying levels of expectation: the additional task-irrelevant stimulus in the critical trial is equally unexpected at both levels of perceptual load. ‘‘Inattention’’ was manipulated through varying perceptual load. Determining the relationship between inattentional blindness and perceptual load in this way will not only establish the role of perceptual load in awareness but will also allow us to confirm that reported ‘‘blindness’’ within the inattentional blindness paradigm is indeed due to inattention.

A role for general task difficulty, and hence a possible role for perceptual load, in inattentional blindness has been hinted at in two previous studies. An early study (reported in Neisser, 1979) using the ‘‘selective looking’’ paradigm found greater rates of awareness for an irrelevant stimulus (e.g., a woman with an umbrella walking across the screen whilst participants attend to a ball-game) in the third repetition of the same video clip compared with the first viewing. The increase in awareness with practice may result from a reduction in perceptual load following greater practice in the relevant task. However, Neisser’s (1979) report does not establish that task performance became any easier with practice, since results regarding task performance were not reported. Moreover, although practice is expected to reduce perceptual load, it is also expected to reduce load on other task-processes, including memory. In addition, practice is also expected to speed-up task–responses, and hence may have reduced the delay between stimulus presentation and the questioning of awareness (as awareness questioning always followed task–responses). Thus, the increase in rates of awareness reports with practice may simply reflect a lower likelihood of forgetting due to effects of practice on processes other than perceptual load.

Simons and Chabris (1999) varied task difficulty more directly. They asked participants either to count the number of ball-passes made between one of two teams of basketball players in a video-clip (‘‘easy task’’ condition), or to maintain two separate counts for the number of bounce passes and aerial passes (‘‘hard task’’ condition). Awareness for an unexpected ‘‘Gorilla-man’’ walking through the playing space was reported more often by participants in the easy task condition than participants in the hard task condition, in line with our load hypothesis. The particular difficulty manipulation used in this study however, was likely to have involved a greater tendency for eye movements in the hard task condition than the easy task condition, as the discrimination between aerial and bounce passes would benefit from looking up (for aerial throws) and down (for bounce passes) whereas monitoring all ball-passes can be made without this discrimination. Thus, since eye movements cause blur on the retina, the critical stimulus may simply have been less visible in the hard task (separate-count) condition. Moreover, maintaining two separate counts (as in the hard task condition) places a greater load on working memory than maintaining just one count (as in the easy task condition). Since encoding into long-term memory is known to be determined by the availability of working memory (Baddeley, 1986), lower awareness in the hard task condition may have been caused by a reduction in the encoding of critical stimuli into memory (where it had to be retained until the awareness question following the rest of the video clip and the report of the count). As such, the role of attentional load per se (e.g., without the potential effects of eye movements and working memory load) in determining awareness within this task remains unclear.

In the present study, we systematically varied the level of perceptual load in the relevant task while assessing the rates of awareness reports for a task-irrelevant stimulus presented on a final trial. Static displays were presented for only a brief duration (200 ms, or less in some experiments) in order to preclude alternative accounts for effects of perceptual load in terms of eye movements. As described earlier, increased perceptual load means either that the number of relevant items with different identities is increased (e.g., a search task with many items is harder than searching amongst relatively few) or that a more demanding perceptual task is carried out for the same number of items (for review see Lavie, 2005). Accordingly, in the following experiments we manipulated perceptual load both by increasing the number of letters (with different identities) in a visual search task, and by varying the demands of perceptual judgments; comparing a subtle length discrimination (high load) either with a more obvious length discrimination (low load, Experiment 3) or with a simple color detection on identical stimuli (low load, Experiment 1).

2. Experiment 1

In Experiment 1, we modified the conventional inattentional blindness cross-task procedure (Mack & Rock, 1998) to incorporate a manipulation of perceptual load. Participants in each condition of load were given identical series of central cross-targets with two arms of clearly different color (blue and green) and slightly different length. Participants in the low load condition performed a simple color discrimination task (indicating which cross-arm was blue), typically thought to impose low attentional load (e.g., Treisman & Gelade, 1980). Participants performing the high-load task were required to make subtle line-length discriminations (indicating which cross-arm was longer). This task should demand considerably more attentional resources than the low-load task (e.g., Bonnel, Possamamai, & Schmitt, 1987; Lavie, 1995), and has led to a reduction in distractor effects on RTs in previous load studies (for review see Lavie, 2000, 2005). An additional task-irrelevant outline black square (the critical stimulus) appeared in critical displays, and awareness for this stimulus was tested immediately following the task–response via direct questioning.

2.1. Method

2.1.1. Participants

Fifty-four visitors to the Science Museum, London (18–45 years) with normal or corrected-to-normal vision, participated in the experiment.

2.1.2. Apparatus and stimuli

The experiment was presented using E-Prime version 1.1 (Psychology Software Tools Inc.) on a PC connected to a 17 in. monitor (1024×768 screen resolution;

75% contrast). Viewing distance was fixed at 60 cm with a chin-rest. Stimulus displays were bitmap images created in Microsoft Paint and the background remained white throughout. Fixation was indicated by a black dot (0.15°). Target displays consisted of a cross at the center of the screen, with a shorter arm subtending 3.35° and a longer arm subtending 3.9°. One cross-arm was green (RGB values: 0, 234, 41) and the other was blue (RGB values: 0, 191, 255), with a black intersection between the two arms. On the sixth, critical trial, a black outline square shape (sides subtending 0.3°) was presented in addition to the cross-target. This critical stimulus appeared in one of four peripheral locations (counterbalanced between participants), all equidistant from fixation (the center of the cross) at 3.2° eccentricity, and positioned exactly half-way between two neighboring cross-arms. A mesh pattern consisting of straight black lines of different orientations against the white background was used as a visual mask.

2.1.3. Procedure

Each trial began with a small fixation dot (1500 ms) followed by a brief blank screen (96 ms), a cross-target display (110 ms), and finally, a visual mask (496 ms). A blank screen was then displayed while participants provided their appropriate verbal responses. All trials were initiated by pressing the space bar. Participants in the high load condition were asked to judge which arm of the cross was longer, whilst participants in low load were asked to decide which arm was blue (horizontal or vertical). Participants were instructed to fixate centrally throughout and to guess if they were unsure. Responses were entered by the experimenter.

Each participant completed six trials. The horizontal cross-arm was longer on half the trials (the vertical longer on the other half), with order being counterbalanced across participants. Independent of the line-length counterbalancing, the horizontal cross-arm was blue on half of the trials (green on the other half), with the vertical arm taking the opposite color. Therefore, displays in both conditions of load consisted of half "horizontal" correct and half "vertical" correct responses. On the sixth trial, the critical stimulus was presented and the cross-task response was made and entered by the experimenter as normal. Immediately following response entry, participants were asked whether they noticed anything else appearing on the screen that had not been there before. Participants responded verbally, giving details of the critical stimulus where possible. The critical trial was then repeated in a final control trial. Before this trial, participants were instructed to ignore the cross-target and instead, look for anything extra that appeared in the display. Awareness for the critical stimulus was measured immediately after trial-termination by direct verbal report as before. Only participants reporting awareness for the critical stimulus on these trials were included in the analysis.

2.2. Results

Participants who failed to report the critical stimulus in the final control trial were excluded from any further analysis (1), as were those who scored less than four trials correct (6). Note also that nearly all of the participants discarded due to low accuracy were in the high load group (5 of 6) whereas only one participant from the low load group was excluded for failing to perform the task. Also discarded were participants who gave ambiguous or uninterpretable responses (5) or participants who did not understand the awareness question following the critical trial (2). Remaining participants were divided equally between the low load (20) and high load (20) groups. All of the participants who reported awareness of the critical stimulus were also able to describe correctly its location and at least two of its major features (shape, size or color).

The number of errors made across trials in the two conditions of load indicates that the manipulation of perceptual load established in this experiment was effective. On average, participants in the high load group made more errors in experimental trials ($M = 17\%$ corresponding to 1.02 trials incorrect on average) than participants in the low load group ($M = 5\%$ corresponding to 0.3 trials incorrect on average).

Importantly, the results showed a clear effect of perceptual load on awareness reports. As can be seen in Fig. 1, fewer participants reported awareness of the critical stimulus under conditions of high perceptual load (2 of 20) than under conditions of low perceptual load (11 of 20), $\chi^2(1, N = 40) = 9.23$, $p < .002$ (two-tailed as in all other experiments reported). Thus, the level of perceptual load in a relevant task determined awareness for an additional task-irrelevant object: increasing the perceptual demands from a simple color discrimination (low load) to a more subtle length discrimination (high load) led to greater experienced inattentional blindness.

We note that a relatively high level of inattentional blindness was seen in Experiment 1, even under conditions of low perceptual load (only 55% awareness). This could be explained by the marked difference in color and size between the attended

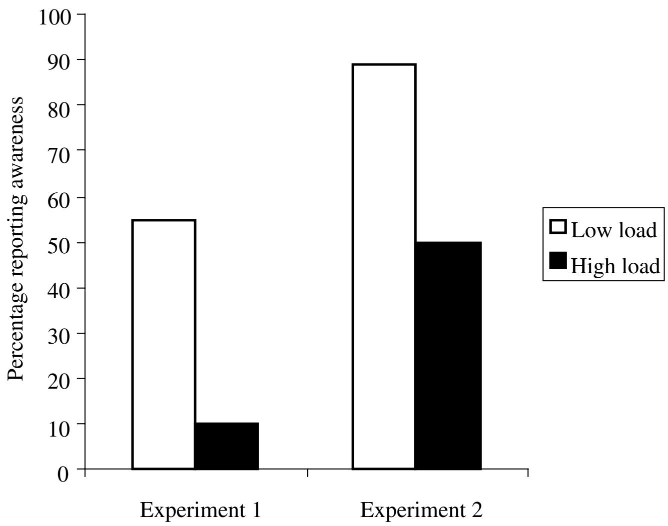

Fig. 1. Percentage of participants reporting awareness for the critical stimulus in low load and high load groups in Experiment 1 ($n = 40$) and Experiment 2 ($n = 36$).

stimuli (blue and green, subtending over 3°) and the critical stimulus (black, subtending 0.3°) reducing the task-relevance of critical stimuli (see Most et al., 2001; Most, Scholl, Clifford, & Simons, 2005). In Experiment 2 however, all stimuli (relevant targets and critical stimuli) were colored black, and all were of similar size. On the basis of the previous research by Most and colleagues, we expected this to elevate the overall level of awareness reported. Critically however, we predicted that the overall level of awareness should not alter the impact of perceptual load on inattentional blindness. Specifically, high perceptual load should increase rates of inattentional blindness even for a critical stimulus of the same color and size as the attended stimulus.

3. Experiment 2

In Experiment 2, we sought to generalize the effects of perceptual load on inattentional blindness across another manipulation of perceptual load, which varied the number of different identity items in the relevant task. Thus, the typical inattentional blindness cross-task was replaced by a visual search task. Participants were asked to search a circular array for a target letter amongst either five non-target letters (high load) or five place-holders (low load). A critical stimulus identical to that used in Experiment 1 was presented on the sixth trial in addition to the usual letter-target display, and awareness was assessed immediately following task–response entry. The critical stimulus was presented in the periphery (at 3.2° eccentricity) clearly separated from the letter circle (which had a radius of 1.6°) in order to avoid any effects of crowding or cluttering of the critical stimulus from target letters or place-holders. Numerous studies have demonstrated that the level of search load in such tasks determines the extent of distractor interference (e.g., Lavie, 1995; Lavie & Cox, 1997; Lavie & Fox, 2000). In all of these previous experiments however, distractor processing was inferred indirectly by measuring effects on target RTs. It will be interesting to discover here, whether the level of perceptual load in a search task can also dictate explicit awareness for an unexpected task-irrelevant stimulus measured with an inattentional blindness procedure.

3.1. Method

3.1.1. Participants

Forty-six Science Museum visitors (18–45 years) with normal or corrected-to-normal vision, participated in the experiment.

3.1.2. Stimuli

Fixation was indicated by a small black cross (0.2°). Target displays comprised black letters on a white background measuring 0.36° horizontally and 0.4° vertically at the fixed viewing distance of 60 cm. The target letter (either X or N) appeared once in each of six possible locations falling on an imaginary circle with a radius of 1.6°. The remaining five locations of the circular stimulus array were filled either by small black dot place-holders (low load) or by five non-target letters (U, F, S, P and J) the same size as target letters (high load). Non-target letters appeared randomly but with equal probability in each of the five empty spaces, and appeared 1.8° apart from center to center. On the sixth trial, a critical stimulus identical to that in Experiment 1, was presented 3.2° to the left or right of fixation in addition to the letter-target display. The critical stimulus was equally likely for each target position. The visual mask was the same as in Experiment 1.

3.1.3. Procedure

The letter displays were presented for 200 ms. Participants were asked to identify whether an "X" or an "N" appeared in each letter display. In the high load group, participants searched for this target amongst five other non-target letters, whereas in the low load, the letter appeared alone amongst five black dots. As before, six trials were presented. The correct target identification response was "X" for half the trials, and "N" for the other half. All possible permutations of target/position order were presented in a design fully counterbalanced across participants. Critical stimuli appeared on the left or right of the letter-circle with equal probability, and as before, a final control trial followed. All other aspects of the procedure were as in Experiment 1.

3.2. Results

Participants who scored less than four trials correct were excluded from any further analysis (4), as were those who failed to make a correct search response in the critical trial (2). Note again that all participants who were excluded due to low accuracy (either during non-critical or critical trials) were performing the high load task. Also discarded were participants who failed to report awareness for the critical stimulus in the final control trial (1), participants who gave uninterpretable responses (1), or participants who failed to understand the awareness question in the critical trial (2). Remaining participants were divided equally between low load (18) and high load (18) groups. All of the participants who reported awareness of the critical stimulus were also able to describe correctly its location and at least two of its major features (shape, size or color).

Error rates between the two conditions of load confirmed that the set size manipulation of perceptual load in Experiment 2 was effective. There were more errors on average during performance of a high load task ($M = 19\%$ corresponding to 0.17 trials incorrect on average) than during performance of a low load task ($M = 0\%$).

Importantly, the results showed that perceptual load played a crucial role in determining explicit awareness for a task-irrelevant stimulus. As with Experiment 1, conditions of high perceptual load led to significantly fewer awareness reports than conditions of low perceptual load. Even though most of the participants reported awareness of the critical stimulus under conditions of low perceptual load (16 of 18) in this experiment, high perceptual load significantly reduced the rate of awareness reports (to 9 of 18), $\chi^2(1, N = 36) = 6.42$, $p < .01$ (see Fig. 1). Experiment 2 thus generalizes the findings of Experiment 1 across different levels of visual similarity (in color and size) between the critical stimulus and attended task and hence different overall levels of awareness, as well as across different manipulations of perceptual load.

4. Experiment 3

The small number of trials presented to participants in Experiments 1 and 2 precluded the assessment of effects of perceptual load on task RTs. Although it is well-established that the visual search set size manipulation of perceptual load used in Experiment 2 produces slower RTs in high load compared to low load (e.g., Lavie, 1995; Lavie & Cox, 1997; Maylor & Lavie, 1998; Lavie & Fox, 2000; see Lavie, 2005, for review), the effects of the cross-task load manipulation on RTs are yet to be measured. In Experiment 3, we therefore presented long blocks of low load and high load trials (randomly intermixed, except for the final and penultimate trials, for which the level of load was counterbalanced across participants) using the cross-task of Experiment 1. In addition, awareness for the same critical stimulus as in Experiments 1 and 2 was assessed in the final trial, which was either a low load trial for one group of participants or a high load trial for a second group of participants. Importantly, as low load and high load trials were randomly intermixed within blocks, participants could not anticipate the level of load in any given trial. Thus, any effects of perceptual load on awareness in this experiment cannot be attributed to differences in strategy or in expectation of task difficulty between pure blocks of low load and high load trials.

Randomly intermixing trials of different loads requires the same task to be performed throughout to avoid confounding effects of task switching. All participants were therefore asked to judge which cross-arm was longer (horizontal or vertical) for each cross-target throughout the block. Targets in high load trials were identical to those used in Experiment 1 (i.e., involving a subtle line length difference). In low load trials, the long arm was the same as in high load trials, but the shorter arm was reduced to a much greater extent (i.e., producing a less perceptually demanding length discrimination). We expected this load manipulation to produce slower RTs in high load (vs. low load) trials, as well as fewer awareness reports when critical stimuli appeared on critical trials of high load (vs. low load).

4.1. Method

4.1.1. Participants

Fifty-seven respondents (18–35 years) to an advertisement for psychology experiments participated in this experiment. All reported normal or corrected-to-normal vision.

4.1.2. Stimuli

Stimuli were as for Experiment 1 with the exception of low load cross-targets. On low load trials, the longer arm of the blue–green cross-target subtended 3.9° (as on the high load trials) while the shorter arm subtended 1.25°, producing a clear difference in line length.

4.1.3. Procedure

The procedure was similar to Experiment 1 except that now, all participants were asked to judge which arm was longer on a series of colored cross-targets. Participants responded by pressing "H" for horizontal longer or "U" for vertical longer, as fast but as accurately as possible. A practice block of 32 trials preceded two blocks of 72 trials, with the critical stimulus (shape, size and locations as in Experiment 1) appearing on an additional critical trial at the end of the final block. In critical trials, a low load target was presented to one group of participants and a high load target was presented to a second group. The target on penultimate trials (i.e., the final non-critical trial preceding the critical trial) was either of the same level of load or of a different level of load as the target on final critical trials, and this was counterbalanced across participants. The levels of load in the rest of the trials were intermixed in random within each block. Arm length and arm color of critical trial targets were fully counterbalanced across participants, as was the critical stimulus position (top left, top right, bottom left, and bottom right). Awareness of the critical stimulus was tested by presenting the critical question on the computer screen immediately following entry of target responses. Participants entered their awareness response by pressing "Y" for Yes or "N" for No on the computer keyboard. Following awareness response entry, participants were asked to guess which shape out of four alternatives (see Appendix A) had appeared in the critical display and then to guess in which location it had appeared (top left, top right, bottom left or bottom right), regardless of their initial awareness response. These additional measures enabled us to verify the validity of participants' awareness reports. As in previous experiments, a final control trial was then presented in which participants simply had to look for anything extra in the repeated critical display. Responses to this control trial were verified in the same way as responses to the critical question.

4.2. Results

Data were excluded from participants who failed the visual control trial (8), participants who were familiar with the inattentional blindness phenomenon (2), or participants who were unable to correctly identify either the shape or the location of the critical stimulus following a "Yes" awareness response (4). In addition, one participant was discarded for failing to score above 55% correct in the high load trials, and 10 participants who failed to give a correct target response on the critical trial. Note that, as before, almost all of those making errors on the critical trial were performing the high load task (8 of 10) whereas only two participants made incorrect responses on critical trials of low load. There were 16 remaining participants in each condition of load.

The results supported our hypothesis while confirming that the load manipulation was successful. Non-critical trials of high perceptual load produced significantly slower RTs ($M = 685$ ms) and higher error rates ($M = 19\%$) than non-critical trials of low perceptual load (RT $M = 563$ ms; error $M = 6\%$, $t(31) = 7.4$, $p < .001$ for the RTs; $t(31) = 7.3$, $p < .001$ for the errors). RTs in critical trials were also significantly slower for participants viewing high load targets ($M = 687$ ms) than for participants viewing low load targets ($M = 512$ ms), $t(30) = 2.1$, $p < .04$.

Importantly, the rate of awareness reports for the critical stimulus was significantly lower under conditions of high perceptual load (6 of 16) than conditions of low perceptual load (13 of 16), $\chi^2(1, N = 32) = 6.35$, $p < .01$ (see Fig. 2). Participants reporting awareness were often able to correctly identify the critical stimulus shape from the four possible alternatives (9 of 13 correct in low load; 4 of 6 correct in high load), and nearly all correctly identified the location of the critical stimulus (12 of 13 in low load; 5 of 6 in high load). By contrast, participants who did not report awareness of the critical stimulus were typically unable to identify the shape or location in the high load group (7 of 10 incorrect shape guessed; 10 of 10 incorrect location guessed). Similarly, participants not reporting awareness were typically unable to identify the location in the low load group (3 of 3 incorrect), although two of the three unaware participants guessed the correct shape. Thus, awareness reports showed good correspondence with the forced-choice discrimination results, with the possible exception of better shape-guessing than detection in the low load group.

Potential carry-over effects from the level of load in penultimate trials on RTs or awareness reports in (final) critical trials were also examined. Although there was a numerical trend for a larger load effect on RTs (high-load RTs minus low-load RTs) in critical trials preceded by the same level of load ($M = 193$ ms for load effect on RTs) than by a different level of load ($M = 153$ ms for load effects on RTs) a 2×2 between-participants ANOVA on critical trial RTs with the factors of critical trial load (high vs. low) and level of load across critical and penultimate trials (same

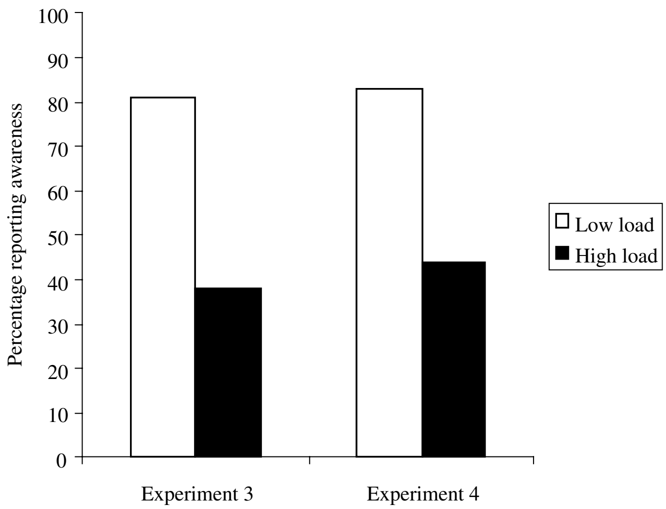

Fig. 2. Percentage of participants reporting awareness for the critical stimulus in low load and high load groups in Experiment 3 ($n = 32$) and Experiment 4 ($n = 36$).

vs. different) showed that this numerical trend for an interaction was not significant ($F < 1$).

The effects of load on awareness were also similar irrespective of the level of load on the preceding trial (although, as with the RTs, awareness reports showed a small trend for larger load effects when the critical and penultimate trials were of the same level of load). The rate of awareness decreased from seven of eight in the low-load group to two of eight in the high load group when critical trials were preceded by the same level of load, and from six of eight in the low-load group to four of eight in the high load group when critical trials were preceded by a different level of load.

Overall then, results in Experiment 3 clearly demonstrate an effect of load on awareness that cannot be attributed to effects of expectation of task-difficulty or effects of strategy, which might be established during performance of low load vs. high load tasks in the block designs of Experiments 1 and 2.

5. Experiment 4

Experiment 3 clearly replicated the typical effects of perceptual load on target RTs, with slower RTs in conditions of high perceptual load compared with conditions of low perceptual load. Although the measure of awareness we used in Experiment 3 (i.e., via Yes/No reports) was not based on RTs, it might have been affected by slowing of task responses under higher perceptual load. Such slowing of responses would introduce a longer delay from presentation of the critical display until the awareness questioning (as this always followed task responses) in conditions of high load compared with low load. This in turn could increase the likelihood of blindness due to forgetting during the longer delay. In other words, there may be a greater likelihood of inattentional amnesia (Wolfe, 1999) in high load rather than low load trials.

This criticism might also apply to Experiments 1 and 2: although participants were not requested to make speeded task–responses, it remains possible that the load manipulation in these experiments produced slower target RTs in high load (vs. low load) trials, and hence, a longer delay between critical stimulus presentation and awareness questioning during high load (vs. low load) tasks. Indeed, a test on 16 participants (all students at University College London) with a 48-trial block of each condition of visual search load used in Experiment 2, and without the instruction to make speeded responses, confirmed that RTs were longer in the high load ($M = 615$ ms) than the low-load condition ($M = 512$ ms), $t(15) = 7.03$, $p < .0001$.

It was therefore important to rule out an alternative account for effects of perceptual load in terms of greater inattentional amnesia (rather than greater inattentional blindness) due to the longer delay with slower task responses in high load compared with low load. This was the purpose of Experiment 4. In this experiment we modified the design of Experiment 2 in an attempt to equate the delay between display presentation (plus the task–response) and questioning about awareness across tasks of low and high load. To this end, we now introduced a 1-s delay from presentation of the task stimulus and mask, until the task–response could be made.

One long block of randomly intermixed low-load and high-load trials was run with awareness being tested on one final critical trial at the end of the block. In this way, we could obtain reliable measures of RT. In addition, this could establish effects of visual search load on awareness that cannot be explained by differences in strategy or expectation of task-difficulty between low-load and high-load trials. As there were no carry-over effects of load order found between critical and penultimate trials in Experiment 3, trial load order was fully randomized in this experiment.

5.1. Method

5.1.1. Participants

Thirty-nine undergraduate students from University College London were paid to participate in this experiment.

5.1.2. Stimuli

Stimuli were identical to those in Experiment 2.

5.1.3. Procedure and design

The procedure was similar to Experiment 2. Participants again searched for a target letter (X or N). However, targets could appear either in low load displays (target with five place-holders) or high load displays (target with five other distractor letters) which were randomly intermixed within the block. Participants were instructed to enter their responses as fast as they could via key-presses but only upon the presentation of a question mark, and not before. The question mark display appeared 1000 ms after termination of the mask. A practice block of 24 trials preceded a single experimental block of 102 trials with the critical stimulus (the same as Experiment 2) displayed on the final trial. The last trial was either of low load (for one group of participants) or of high load (for another group of participants). Letter target identity and position were fully counterbalanced across participants, as was critical stimulus location (left or right of fixation). Awareness of the critical stimulus was assessed using the same procedure as Experiment 3. A final control trial was included as in Experiment 3.

5.2. Results

Data were discarded from participants failing to notice the critical stimulus on the control trial (2). In addition one participant was discarded because they could identify neither shape nor location correctly after giving a "Yes" aware response on the critical trial. There were 18 remaining participants in each of the load groups.

The results confirmed that RTs in the low load ($M = 335$ ms) and high load ($M = 334$ ms) trials were successfully equated in this experiment, although there were more errors in high load (5%) than low-load (2%) trials, $t(35) = 4.09$, $p < .001$, in line with an effective manipulation of load. Despite equal reaction times (as well as greater practice during a longer block and performance of high- and low-load trials in one randomly intermixed block), rates of awareness were significantly reduced by high perceptual load (Fig. 2), as in previous experiments. Fifteen out of 18 participants reported awareness of the critical stimulus in low load compared with eight out of 18 in high load, $\chi^2(1, N = 36) = 5.90$, $p < .02$.

Importantly, as low-load and high-load RTs were equated in this experiment, the effect of load on awareness reports found is immune to alternative accounts in terms of greater memory decay on trials of high (vs. low) load during the typically longer reaction times. Notice also that despite the stimulus presentation to awareness probe delay always exceeding 1 s, most participants reported awareness under conditions of low perceptual load. These findings together undermine the "inattentional amnesia" account for inattentional blindness at least for the current setup.

As with Experiment 3, the forced-choice shape and location judgments showed good correspondence with the detection reports. Participants reporting awareness of critical stimuli were generally able to correctly identify its shape (13 of 15 in low load; 7 of 8 in high load) and location (15 of 15 in low load; 8 of 8 in high load), whereas unaware participants could not identify shape (3 of 3 incorrect in low load; 9 of 10 incorrect in high load) or location (2 of 3 incorrect in low load; 10 of 10 incorrect in high load) correctly.

6. General discussion

The present research shows that the level of perceptual load in a current task determines whether a task-irrelevant stimulus will enter visual awareness or not. When load is increased in the relevant task (either through a greater number of items among which the target has to be found in search tasks as in Experiments 2 and 4; or through the cross-task typically used in inattentional blindness studies requiring a more subtle perceptual discrimination as in Experiments 1 and 3) more participants fail to notice the presence of an additional task-irrelevant stimulus appearing on a final trial, exhibiting inattentional blindness.

The results converged across load manipulations that did not vary the appearance of the display (Experiment 1) and load manipulations that did not vary the task (but instead either varied the number of items in the display, Experiments 2 and 4; or varied the difficulty of a discrimination judgment, Experiment 3). This convergence of results across different manipulations rules out alternative accounts of load effects in terms of any confound (e.g., different display appearance or different task performance between conditions of load) that each manipulation alone may have carried.

In addition, effects of perceptual load on awareness were found in both the cross-task and the visual search task when the level of load was varied randomly from trial to trial within a block (Experiments 3 and 4) and when the level of load on critical and penultimate trials was fully counterbalanced across participants in each of the load groups. Thus, the results cannot be explained by differences in the strategies set-up during blocks of high vs. low load, or by participants expecting, and preparing for, a certain level of task difficulty in the critical trial. Finally, effects of perceptual load on awareness were also found when reaction times in high load and low load were equated (Experiment 4). This finding rules out an alternative explanation of the results alluding to memory effects of the longer delay between stimulus presentation and awareness questioning caused by the slower target-responses in higher loads. Moreover, the addition of a 1-s delay in Experiment 4 had no apparent effect on the rates of awareness, which were still very high under conditions of low perceptual load. The present study therefore undermines the "inattentional amnesia" account (Wolfe, 1999) proposed for inattentional blindness.

Importantly, the modulation of inattentional blindness by different levels of load found in this study cannot be explained by the variation of intentions or expectations across conditions. In the present experiments, the critical stimulus was equally task-irrelevant and equally unexpected across all conditions of perceptual load. These results therefore offer compelling evidence that the availability of attention for the processing of a task-irrelevant stimulus, as varied by perceptual load, determines whether that stimulus reaches conscious perception.

As such, the present results provide the strongest behavioral evidence so far that perceptual load plays a critical role in determining conscious perception. Perceptual load theory has proposed that a consideration of the role of task-relevant perceptual load in determining task-irrelevant processing can resolve the early vs. late selection debate regarding the influence of attention on perception. In this theory, task-irrelevant stimuli are perceived in situations of low perceptual load when the relevant task leaves spare capacity for their processing, but not in situations of high perceptual load where all available capacity is consumed. Previous research has convincingly demonstrated that the level of perceptual load in the relevant task determines the degree of distractor interference (on RTs), as well as neural activity in visual cortex related to distractor perception. However, with one exception (in the case of subjective duration of the motion after effect; Rees et al., 1997), previous research did not explicitly address the effects of perceptual load on conscious perception. The present findings support the prediction that perceptual load determines conscious perception of task-irrelevant stimuli as directly measured by participants' awareness reports. This further strengthens the resolution offered by the perceptual load model to the early vs. late selection debate regarding the perception of ignored stimuli.

In addition, the present findings make a significant contribution to the understanding of the phenomenon of inattentional blindness. Although attention is held to play a key role in this phenomenon, as stipulated in the term "inattentional blindness", there has been surprisingly little previous research investigating the pure effects of attentional availability and correspondingly "inattention" on awareness. For example, two studies explored the effects of spatial separation between the critical stimulus and the target stimulus (Newby & Rock, 1998; see also Most, Simons, Scholl, & Chabris, 2000). Two other studies explored the effects of stimulus type with the assumption that biologically meaningful stimuli (e.g., body silhouettes, happy faces) capture attention and hence suffer less inattentional blindness (Downing, Bray, Rogers, & Childs, 2004; Mack, Pappas, Silverman, & Gay, 2002). As there were no direct manipulations of attention in these studies however, causal inferences about the role of attention in awareness cannot be drawn from these results.

Perhaps the most intensive effort to relate inattentional blindness to attention was made by Most and colleagues. In a series of studies, greater rates of awareness were found for critical stimuli that were more visually similar to attended targets along task-relevant dimensions (e.g., in luminance or shape, Most et al., 2001, 2005). These results appear to provide an awareness analogue of "contingent attentional capture" (whereby greater attentional capture effects are found (on search RTs) for "singleton" items that share a feature with the target, e.g., Folk, Remington, & Johnston, 1992). However, effects of similarity between critical stimuli and targets on awareness may also be explained as direct effects of priming (driven by expectations of particular target features) on detection thresholds for the critical stimuli. Because critical stimuli that are more similar to the target are more likely to activate the target template (than critical stimuli that are dissimilar to targets), they would also be more readily detected. Such effects of priming on detection thresholds may not necessarily entail greater allocation of attention to the critical stimuli; rather, for the same level of activation and attention (or inattention), primed critical stimuli might be detected more often than unprimed critical stimuli due to lower detection thresholds for primed stimuli.

Finally, as we discussed earlier, although Simons and Chabris (1999) have shown greater inattentional blindness during performance of a harder counting task, the potential increase in eye movements (reducing critical stimulus visibility) and working memory load (reducing its encoding into memory) with the harder task (vs. the easier task) condition precludes a clear conclusion on the pure role of attentional load in awareness from their results.

Thus, the present study is the first to directly and systematically vary the level of demand that the task-relevant processing places on attention specifically (as distinct from expectation, working memory, and eye movements), and hence the level of inattention for task-irrelevant stimuli. The demonstration that reports of awareness or "blindness" critically depend on the extent to which the relevant task exhausts attentional capacity (under high perceptual load) and so leaves little or no capacity for irrelevant processing, provides strong and unequivocal evidence for the critical role of attention in inattentional blindness.

Appendix A

Critical stimulus and foils in the forced-choice guessing tasks used in Experiments 3 and 4.

References

Baddeley, A. (1986). *Working memory*. New York: Oxford University Press.

Bonnel, A., Possamamai, C. A., & Schmitt, M. (1987). Early modulations of visual input: A study of attentional strategies. *The Quarterly Journal of Experimental Psychology, 39A*, 757–776.

Braun, J. (2001). It's great but it's not necessarily about attention. *Psyche: An Interdisciplinary Journal of Research on Consciousness, 7*, 06.

Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon Press.

Deutsch, J., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review, 70*, 80–90.

Downing, P. E., Bray, D., Rogers, J., & Childs, C. (2004). Bodies capture attention when nothing is expected. *Cognition, 93*, 27–38.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a non search task. *Perception & Psychophysics, 16*, 143–149.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 1033–1040.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 451–468.

Lavie, N. (2000). Selective attention and cognitive control: dissociating attentional functions through different types of load. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII* (pp. 175–194). Cambridge, MA: The MIT press.

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences, 9*, 75–82.

Lavie, N., & Fox, E. (2000). The role of perceptual load in negative priming. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1038–1052.

Lavie, N., & De Fockert, J. W. (2003). Contrasting effects of sensory limits and capacity limits in visual selective attention. *Perception & Psychophysics, 65*, 202–212.

Lavie, N., & Cox, S. (1997). On the efficiency of visual selective attention: Efficient visual search leads to inefficient distractor rejection. *Psychological Science, 8*, 395–398.

Mack, A., & Rock, I. (1998). *Inattentional blindness*. Cambridge, MA: The MIT Press.

Mack, A., Pappas, Z., Silverman, M., & Gay, R. (2002). What we see: Inattention and the capture of attention by meaning. *Consciousness and Cognition, 11*, 488–506.

Maylor, E. A., & Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. *Psychology and Aging, 13*, 563–573.

Most, S. B., Scholl, B. J., Clifford, E. R., & Simons, D. J. (2005). What you see is what you set: Sustained inattentional blindness and the capture of awareness. *Psychological Review, 112*, 217–242.

Most, S. B., Simons, D. J., Scholl, B. J., & Chabris, C. F. (2000). Sustained inattentional blindness: The role of location in the detection of unexpected dynamic events. *Psyche: An Interdisciplinary Journal of Research on Consciousness, 6*(14).

Most, S. B., Simons, D. J., Scholl, B. J., Jimenez, R., Clifford, E., & Chabris, C. F. (2001). How not to be seen: The contribution of similarity and selective ignoring to sustained inattentional blindness. *Psychological Science, 12*, 9–17.

Neisser, U. (1979). The control of information pickup in selective looking. In A. D. Pick (Ed.), *Perception and its development: A tribute to Eleanor J. Gibson* (pp. 201–219). Hillsdale, NJ: Erlbaum.

Neisser, U., & Becklen, R. (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology, 7*, 480–494.

Newby, E. A., & Rock, I. (1998). Inattentional blindness as a function of proximity to the focus of attention. *Perception, 27*, 1025–1040.

Pessoa, L., McKenna, M., Gutierrez, E., & Ungerleider, L. G. (2002). Neural processing of emotional faces requires attention. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 11458–11463.

Pinsk, M. A., Doniger, G. M., & Kastner, S. (2003). Push–pull mechanism of selective attention in human extrastriate cortex. *Journal of Neurophysiology, 92*, 622–629.

Rees, G., Frith, C. D., & Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science, 278*, 1616–1619.

Schwartz, S., Vuilleumier, P., Hutton, C., Maravita, A., Dolan, R. J., & Driver, J. (2005). Attentional load and sensory competition in human vision: modulation of fMRI responses by load at fixation during task-irrelevant stimulation in the peripheral visual field. *Cerebral Cortex, 15*, 770–786.

Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception, 28*, 1059–1074.

Tipper, S. P. (1985). The negative priming effect: Inhibitory effects of ignored primes. *The Quarterly Journal of Experimental Psychology, 37A*, 571–590.

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 112*, 97–136.

Wolfe, J. M. (1999). Inattentional amnesia. In V. Coltheart (Ed.), *Fleeting memories* (pp. 71–94). Cambridge, MA: The MIT Press.

Yi, D.-J., Woodman, G. F., Widders, D., Marois, R., & Chun, M. M. (2004). Neural fate of ignored stimuli: dissociable effects of perceptual and working memory load. *Nature Neuroscience, 7*, 992–996.