Research Report

CUING INTERACTS WITH PERCEPTUAL LOAD IN VISUAL SEARCH

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Abstract—We tested the strong form of the perceptual-load hypothesis, which posits that the amount of perceptual load is the only factor determining whether attention can be effectively focused. Participants performed a visual search task under conditions of low and high load and with either a 100% valid spatial cue or no spatial cue. With no cue, participants showed evidence of processing to-be-ignored stimuli when perceptual load was low but not when it was high, consistent with the perceptual-load hypothesis. However, with a 100% valid spatial cue, participants showed little evidence of processing to-be-ignored stimuli, even when perceptual load was low. These results suggest that although perceptual load may be an important factor in attentional selectivity, load alone is not sufficient to explain how and when selective attention is effective.

Considerable research on human attention has examined how and when attention selects information for further processing. Early-selection theories propose that attentional selection occurs before information has been processed for meaning (e.g., Broadbent, 1958; Treisman, 1969), whereas late-selection theories assume information is selected after meaning has been determined (e.g., Deutsch & Deutsch, 1963). Data consistent with both approaches have fueled a heated debate (e.g., Johnston & Dark, 1986; Kahneman & Treisman, 1984; Lavie, 1995, 2000; Lavie & Cox, 1997; Lavie & Tsai, 1994; Yantis & Johnston, 1990).

Recently, researchers have proposed some alternatives to “pure” early- and late-selection theories that are consistent with a wide range of extant data. For example, Lavie and colleagues (Lavie, 1995, 2000; Lavie & Cox, 1997; Lavie & Tsai, 1994) have argued that attention researchers have been quarreling over a false dichotomy. They propose that volitional mechanisms assign priorities to stimuli and that demands on the cognitive system determine the extent to which low-priority stimuli are processed and thus whether data obtained are consistent with early- or late-selection theories (the perceptual-load hypothesis; Lavie, 1995, 2000). A key component of the perceptual-load hypothesis is an assumption regarding the automaticity of perceptual processing. In this approach, limited-capacity perceptual resources may be guided by a top-down system but must be deployed until consumed. As Lavie (2000) stated, “The extent to which the perception of irrelevant distractors can be prevented should thus depend on the perceptual load imposed by the processing of relevant information. Situations of low perceptual load will inevitably result in perception of irrelevant stimuli, despite the assignment of low priority to their processing” (pp. 176–177). Thus, the strong form of this claim is that if a primary task does not consume all available resources, then a participant will have no choice but to process irrelevant stimuli (i.e., selective attention will fail).

The paradigm used by Lavie and Cox (1997) to test the perceptual-load hypothesis was a visual search task with to-be-ignored locations flanking a circle of letters (to be attended). The circular configuration of six letters contained one target (X or N) and five distractor letters. This primary display was flanked by one letter that, relative to the target, could be compatible (i.e., same as the target), incompatible (e.g., an X when the target was an N), or neutral (L). Lavie and Cox found diminished flanker effects in conditions of high perceptual load (i.e., the five distractors were heterogeneous and shared few features with the target), compared with conditions of low perceptual load (i.e., the distractors were homogeneous and shared few features with the target). These data are consistent with the perceptual-load hypothesis, and important because this approach provides a parsimonious explanation for the extent and varied data related to the locus of attention effects.

Although Lavie and Cox’s (1997) findings are consistent with the strong form of the perceptual-load hypothesis, there is still an important question left unaddressed. Are there situations of low perceptual load in which attention can be successfully allocated in a top-down fashion? Yantis and Johnston (1990) have empirically demonstrated conditions in which top-down allocation of attention allows for the successful rejection of to-be-ignored stimuli in visual search tasks (see the next paragraph).

The experiment we report here was designed to test the strong form of the perceptual-load hypothesis. Specifically, we examined whether it is possible to find evidence of early selection in a low-perceptual-load task by optimizing other aspects of the design. The paradigm was a cued visual search task in which load (search type: easy search or hard search), cue (cue type: 100% valid cue or cue), and flanker (flanker type: compatible, neutral, or incompatible) were manipulated. A subset of the conditions in this experiment contained many of the design features Yantis and Johnston (1990) identified as optimal for early selection to occur—including a 100% valid spatial cue, a 200-ms cue-target stimulus onset asynchrony (SOA), and changed locus of attention on each trial.

If the strong form of the perceptual-load hypothesis is correct, early selection is possible only under conditions of high perceptual load, even when conditions are optimized (in a Yantis & Johnston, 1990, sense) by using a cue. However, if Yantis and Johnston are correct and early selection is possible using 100% valid cues with a sufficient cue-target SOA, then the effects of flanker compatibility should be diminished under valid-cue conditions, independent of load.

METHOD

Participants

Twenty-three undergraduates participated in one 50-min session either as part of a requirement for an introductory psychology course or for $7.50 in compensation. All participants reported having either normal or corrected-to-normal visual acuity and normal color vision.

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Apparatus and Stimuli

A microcomputer provided millisecond timing and controlled stimulus presentation and response acquisition. All stimuli were white letters appearing on a black background. Targets were the letters X and N; distractors were the letters K, M, Z, W, and H for the high-load condition, and the letter O for the low-load condition; and flankers were the letters X, N, and L. Each letter subtended approximately 1.5° of visual angle in height and 0.7° in width from the viewing distance of 60 cm. Letters were presented on an imaginary circle centered at fixation. The distance between the fixation point and the center of each letter was 4.2°; the center-to-center distance between letters was 3.2°. The distance between the fixation point and the center of the flanker was 5.0°; the center-to-center distance between the nearest letters and the flanker was 3.8°. The central cue was an arrowhead 0.67° long and 0.38° wide presented at fixation.

Procedure

Many aspects of the procedure and design are detailed in Figure 1. Each trial began with the presentation of the fixation cross. On no-cue trials, the fixation cross remained displayed for 1,000 ms. On valid-cue trials, the fixation cross was displayed for 800 ms and was followed by the cue for 200 ms. The search display remained on the screen for 100 ms and was then replaced by a black screen. Participants made a two-choice speeded response in which they indicated which of the two target stimuli (X or N) was present in the search display. They responded with the index finger of each hand, and the target-to-finger mapping was counterbalanced.

An audible tone was presented if a response was incorrect or not produced within 3.5 s. Participants were instructed to focus their attention on the cued location (valid-cue condition) or on the circular display of letters (no-cue condition), to ignore all stimuli outside the circular display, and to respond as quickly as possible while maintaining accuracy and without shifting their gaze from the center of the display.

Design

There were always six letters present in the search display, plus one flanking stimulus. The dependent measure was response time (RT). The target letter and its position were selected randomly for each trial. In the high-load condition, the order of the distractor letters was random. Participants completed 12 test blocks of 72 trials, for a total of 864 trials of recorded data. Participants were debriefed following the experiment.

Fig. 1. Examples of visual displays for the easy (a, c) and hard (b, d) search conditions. There was either no spatial cue (a, b) or a 100% valid central cue, an arrowhead correctly indicating the location (but not identity) of the target (c, d). Participants were to indicate which of two target letters (X or N) was presented on a given trial. In the easy condition, the distractor letters were all the letter O. In the hard condition, the letters K, M, Z, W, and H served as distractors. The flanking stimulus appeared equally often to the left or right of the main display and could be neutral (i.e., the letter L, as depicted in a and c), compatible (e.g., the letter N when the target was an N, as depicted in d), or incompatible (e.g., the letter N when the target was an X, as depicted in b).
Testing the Perceptual-Load Hypothesis

A three-way (2 × 2 × 3) within-subjects analysis of variance (ANOVA) was conducted to analyze the mean RT data from each participant; factors were load (low and high), cue type (valid cue and no cue), and flanker type (compatible, neutral, and incompatible). The mean RT and error rate in each condition are listed in Table 1. Alpha was set at .05 for all inferential statistics.

A main effect was obtained for each of the three factors. Low load resulted in significantly faster RTs than high load (537 ms vs. 638 ms, respectively), \( F(1, 22) = 120.25 \). Participants were significantly faster when presented with a valid cue (495 ms) than with no cue (679 ms), \( F(1, 22) = 177.94 \), and the flankers significantly influenced RT (RTs for the compatible-, neutral-, and incompatible-flanker conditions were 579 ms, 580 ms, and 603 ms, respectively), \( F(2, 44) = 17.73 \).

A significant interaction was found between load and cue type, \( F(1, 22) = 144.43 \), such that the benefit of a valid cue relative to no cue was greater in the high-load condition (500 ms vs. 775 ms) than in the low-load condition (490 ms vs. 584 ms). There was a significant load-by-flanker-type interaction, \( F(2, 44) = 4.47 \), with larger flanker effects under low-load (525 ms, 523 ms, and 562 ms) than under high-load (632 ms, 637 ms, and 643 ms) conditions. There was also a cue-type-by-flanker-type interaction, \( F(2, 44) = 6.67 \), with larger flanker effects under no-cue (667 ms, 667 ms, and 704 ms) than valid-cue (490 ms, 494 ms, 501 ms) conditions. Most important, the interaction among load, cue type, and flanker type was significant, \( F(2, 44) = 4.50 \). The no-cue RTs showed a considerably larger flanker effect for low-load than high-load conditions, a result that conceptually replicates Lavie and Cox’s (1997) results, whereas the valid cue caused a diminished flanker effect in the low-load condition, resulting in the significant three-way interaction (see Table 1).²

**DISCUSSION**

The present study used a visual search paradigm to evaluate two approaches to determining the locus of attentional selection. Specifically, we tested a strong form of Lavie and colleagues’ (Lavie, 1995, 2000; Lavie & Cox, 1997; Lavie & Tsal, 1994) perceptual-load hypothesis, which asserts that perceptual load alone determines whether early or late selection occurs. In several respects, the manipulated variables had the expected effects on behavior. Participants were faster to identify the target in the low-load versus the high-load conditions, indicating that the manipulations associated with load were effective. The effectiveness of the cue was demonstrated both by the main effect of cue type and by the interaction between cue type and load (demonstrating that the valid cue was particularly helpful for the high-load

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1. Diedrichsen, Ivry, Cohen, and Danziger (2000) found an interaction between the side of flanker presentation and side of response in simple flanker displays (involving a centrally presented and fixated target and two flanking stimuli). We added flanker-response congruence (i.e., whether the side of flanker presentation and side of response were the same or different) as a factor in the ANOVA in order to determine if this effect occurred in our more complex displays. There was no main effect or interaction involving flanker-response congruence, and because this issue is tangential to the main thrust of our arguments, we report the three-way ANOVA here.

2. Pilot data indicated that error rates were unacceptably high when display durations were brief enough to preclude eye movements, so there is a potential nonattentional explanation of the interaction among load, cue type, and flanker type that must be addressed. Consider the possibility that in the valid-cue conditions participants shifted their gaze to the cued location despite being explicitly instructed not to move their eyes during a trial. On some trials these eye movements would result in the flanker being further from fixation, potentially weakening the flanker effect through nonattentional means and generating the three-way interaction. To test this alternative account, we performed a second ANOVA limited to the conditions in which the target was in the closest and furthest locations relative to the flanker (the 2, 4, 8, or 10 o’clock positions as depicted in Fig. 1). If participants were shifting their gaze to the cued location, then the distance between the cued location and the flanker location should mediate the flanker effect. Thus, we conducted a four-way (2 × 2 × 3 × 2) within-subjects ANOVA to analyze the mean RT data from each participant, with load (low and high), cue type (valid cue and no cue), flanker type (compatible, neutral, and incompatible), and distance (target close to or far from the flanker) as factors. As before, there were main effects of load, cue type, and flanker type; two-way interactions between load and cue type, load and flanker type, and cue type and flanker type; and a three-way interaction among load, cue type, and flanker type (all ps < .03). However, there was no main effect of distance, nor did distance participate in any interactions (all ps > .10). These results are inconsistent with an explanation based on eye movements and strongly suggest an attentional explanation for these data is required.
task). And last, the to-be-ignored flanking stimuli did in fact influence RTs (as seen by the main effect of flanker). Thus, the employed methodology successfully showed load and cue effects.

We compared the ability of the perceptual-load hypothesis and Yantis and Johnston’s (1990) approach to account for data obtained under low and high perceptual load, with and without a valid spatial cue. The data from the no-cue conditions replicate the results Lavie and Cox (1997) obtained and are consistent with the perceptual-load hypothesis, as are an array of data from other paradigms (Lavie, 2000). However, the present data suggest that early selection occurred in a low-load situation (the low-load, valid-cue condition), and this finding is problematic for the strong form of the perceptual-load hypothesis.

It is difficult to explain these findings with a strong form of the perceptual-load hypothesis. Clearly, the load manipulation was sufficient, given the findings from the no-cue conditions. One way to salvage the strong form of this theory is to claim that the addition of a cue made search more difficult. The argument would be that the cue increased perceptual load, making the valid-cue, low-load condition a high-load situation, which would cause a diminished flanker effect. The fact that RTs were considerably faster in the valid-cue than in the no-cue conditions refutes this explanation, however. Thus, our results indicate that selective attention is possible even under low-load conditions, and this finding is problematic for the strong form of the perceptual-load hypothesis. This approach cannot explain the data patterns presented here without some adjustment to allow for a more powerful influence of top-down attention allocation factors.

The results of the present study are consistent with Yantis and Johnston’s (1990) theory of modified early selection, which predicts effective early selection under ideal cuing conditions. However, it is important to note that not all the results obtained in this experiment can be explained with an unmodified version of this approach either. Yantis and Johnston offered no explanation as to how search condition (easy vs. hard) affects locus of selection. The results of Lavie and Cox (1997) and those of the present experiment indicate that perceptual load is an important factor determining the effectiveness of selective attention. Yantis and Johnston’s approach does not account for load as operationally defined in this article. Clearly, a simple and parsimonious explanation of selective attention is at best elusive. The present results are consistent with the argument that there are a variety of factors that influence attentional selectivity, an important one of which is perceptual load.

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