Psychonomic Bulletin & Review
2004, 11 (4), 697-702

Attentional set interacts with perceptual load in visual search

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In the present study, we examined the hypothesis that perceptual load is the primary factor that determines the efficiency of attentional selection. Participants performed a visual search task under conditions of high- and low-load. In line with the perceptual load hypothesis, presenting conditions of high- and low-load in separate blocks of trials resulted in processing of to-be-ignored stimuli only in the low-load condition (Experiment 1). However when high- and low-load conditions were randomly mixed in blocks of trials, the participants showed processing of to-be-ignored stimuli in both conditions, suggesting that high perceptual load is not necessarily sufficient to obtain perceptual selectivity (Experiment 2). An analysis of intertrial transition effects showed that on high-load trials, processing of to-be-ignored stimuli occurred only when the previous trial was a low-load trial. The results suggest that low perceptual load can engender broad attentional processing. On the other hand, when a high-load trial was preceded by another high-load trial, little processing of task-irrelevant stimuli was observed. The present results are discussed in terms of the interaction between expectancies and bottom-up factors in the efficiency of attentional selection.

The locus of attentional selection has been a hotly debated topic for several decades (e.g., Yantis & Johnston, 1990). According to early-selection theories (e.g., Broadbent, 1971, 1982; Treisman & Gelade, 1980), only a preliminary analysis of basic features can be conducted in parallel over the visual display. For determining the meaning of a stimulus, however, a second stage of limited capacity is needed. Selective attention controls which stimuli have access to the limited capacity stage and, thus, which stimuli are fully identified. Alternatively, late-selection theories (e.g., Bundesen, 1990; Deutsch & Deutsch, 1963) assume that all perceptual encoding, including identification, proceeds in parallel over the visual field. These theories claim that selection occurs "late" in processing, primarily in selecting between competing response tendencies arising from multiple stimuli (Allport, 1980). Over the last 40 years, the debate on the locus of visual selection has generated a great deal of empirical work, without one theory prevailing over the other (see, e.g., Johnson, McGrath, & McNeil, 2002; Kahneman & Treisman, 1984; Lavie, 1995, 2000; Lavie & Cox, 1997; Theeuwes, 1993; Yantis & Johnston, 1990).

We thank Chip Folk, Anne Hillstrom, Nilli Lavie, and Cathleen Moore for their excellent comments and suggestions on an earlier draft of this article. Correspondence concerning this article should be addressed to J. Theeuwes, Department of Cognitive Psychology, Vrije Universiteit, Van Der Boechorststraat 1, 1081 BT Amsterdam, The Netherlands (e-mail: j.theeuwes@psy.vu.nl).

Recently, Lavie and colleagues (Lavie, 1995, 2000; Lavie & Cox, 1997; Lavie & Tsal, 1994) have provided an elegant solution to this heated debate. Lavie has argued that the locus of visual selection may not be either early or late but may depend on the *perceptual load* imposed on the human information-processing system. Lavie argued that the capacity for perception is limited, but that within these limits, perception proceeds automatically. The extent to which a task consumes available resources determines whether task-irrelevant stimuli will be processed. With a high perceptual load, there is not enough capacity to process irrelevant stimuli. However, with a low perceptual load, task-irrelevant stimuli will receive excess attentional resources. The strong form of the perceptual load hypothesis is that the extent to which irrelevant distractors are processed does not depend on the participants' expectancies or intentions to ignore distracting stimuli, but, instead, on the attentional resources that remain after the processing of task-relevant stimuli.

Evidence for the perceptual load hypothesis has come from a visual search task designed by Lavie and Cox (1997). In this task, participants responded to one target letter (X or N) among five nontarget letters presented in a circular configuration. A single distractor letter appeared outside the primary circular array. Relative to the target letter, the distractor letter could be compatible (i.e., the same as the target), incompatible (e.g., an X as a distractor while the target is an N), or neutral (L). In the high perceptual load condition, the nontarget letters were heterogeneous and shared features with the target letter, whereas in the low-load condition, the nontarget letters were homogeneous (they were all Os) and shared no features with the target letter. The high- versus low-load manipulation employed by Lavie and Cox was successful: In the low-load condition; mean reaction time (RT) was 480 msec, whereas in the high-load condition, mean RT was 720 msec. More important, in line with the perceptual load hypothesis, there was a flanker effect (i.e., longer RTs for the incompatible than for the compatible distractor trials) in the low-load, but not in the high-load, condition. The results are consistent with the notion that perceptual processing is automatic and not subject to top-down control.

Recently, however, employing the same paradigm as Lavie and Cox (1997), Johnson et al. (2002) showed that top-down control can override interference by irrelevant distractors in a low-load condition. Johnson et al. used an advance spatial cuing procedure and showed that, under conditions of focused attention, there was little evidence of the processing of irrelevant distractors even when processing load was low (Theeuwes, 1991; Yantis & Jonides, 1990).

The experiment we report here was designed to examine the role of attentional set on the locus of selection. Even though it is conceivable that the extent to which distractor stimuli are processed is completely determined by the perceptual load imposed by the task, it is also possible that distractor processing is determined by a combination of perceptual load and search strategies adopted by observers. In Experiment 1 reported by Lavie and Cox (1997), processing load was manipulated between blocks of trials. Thus, observers knew before each block of trials whether search would be difficult (search for an X or N among heterogeneous nontarget letters) or easy (search for an X or N among Os). As has been argued by Theeuwes (1992, 1994, in press), the extent to which an observer engages in serial focused attentional search or parallel divided attentional search is dependent on the task set or on participant strategies. Thus, if finding the target requires focused serial search, as is the case in the high-load condition, observers may be set to search serially, and this precludes the processing of irrelevant distractors (see e.g., Gibson & Peterson, 2001; Theeuwes, 1991, 2004). However, if the target letter pops out from the background, as is the case in the low-load condition (see, e.g., Figure 1, left panels), observers may set a wide attentional window to detect the target letter by means of parallel search. As was demonstrated by Theeuwes (1991, 1992, 1994; Yantis & Jonides, 1990) when attention is divided, irrelevant distractors capture attention and interfere with search.

In the present study, we investigated whether flanker interference results from perceptual load, as advocated by Lavie and Cox (1997), or whether it is also influenced by an attentional set *to expect* a high or a low perceptual load. Note that we use the term *expectancy*. However, whether such expectancy is due to a top-down attentional set or to

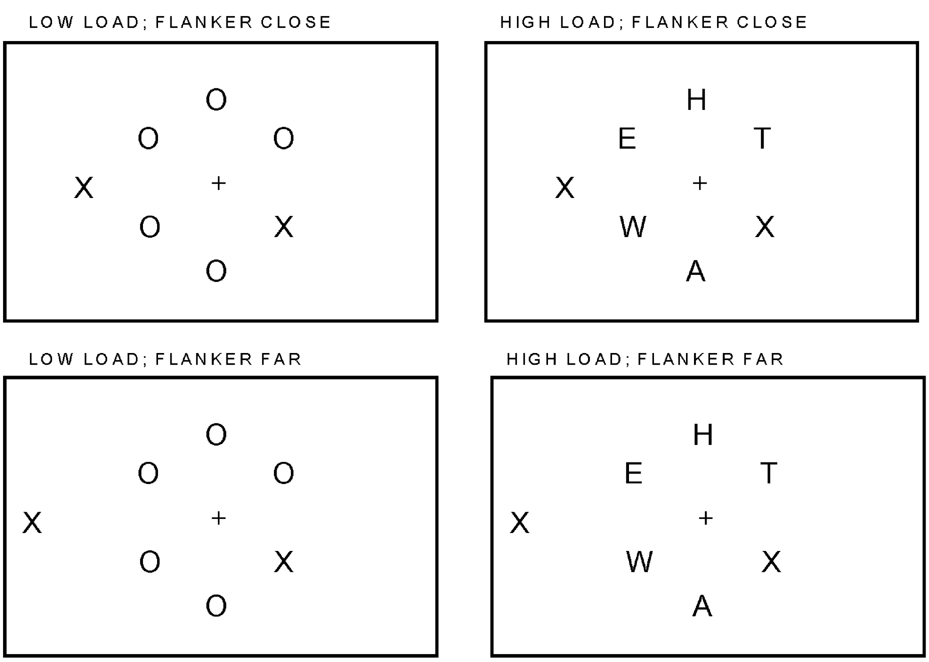

Figure 1. Examples of displays for low-load (left panels) and high load (right panels) search conditions. The flanker could be located close to (top panels) or far from (bottom panels) the primary search display. The participants were to indicate which of two target letters (X or *N*) was present on a given trial. In the low-load conditions, the nontarget letters were all Os. In the high-load condition, the letters E, H, T, W, and A served as nontarget letters. The flanker appeared equally often to the left or right, far from or close to the fixation cross. The flanker was either compatible (as in this example) or incompatible with the target letter (e.g., the letter *N* was a flanker, whereas the target was the letter X).

bottom-up task-set inertia (e.g., Allport, Styles, & Hsieh, 1994; Los, 1996; Maljkovic & Nakayama, 2000) is beyond the scope of the present investigation.

The task we used was very similar to that of Lavie and Cox (1997). Experiment 1 was basically a replication of Lavie and Cox, in which conditions of high and low load were presented in separate blocks of trials. In Experiment 2, high- and low-load conditions were varied randomly within blocks of trials. In addition, to increase uncertainty about where the distractor letter would appear, we presented the distractor letter close to the primary search display (at the same position as that in Lavie & Cox, 1997) or farther away. Spatial uncertainty was increased to ensure that the participants could not filter out the distractor location (cf. Theeuwes, 1991). If the perceptual load of a display determines whether or not distractor letters are processed, presenting high- and low-load conditions in mixed (Experiment 2) or in blocked (Experiment 1) conditions should not matter. If, on the other hand, attentional set to *expect* a high- or low-load display influences the extent to which task-irrelevant distractors are processed and, hence, a flanker effect is observed, mixed trial blocks that make it difficult to prepare an attentional set in advance might be expected to result in interference effects on both low- and high-load trials. However, sequential effects (e.g., high–high load trials resulting in a smaller interference effect than do low–high load trials) might be expected to be observed to the extent that attentional sets or strategies are carried over from one trial to the next (e.g., Maljkovic & Nakayama, 2000).

EXPERIMENT 1

Method

Participants. Eighteen university students with normal or corrected-to-normal vision took part in the experiment. The data from 2 participants were discarded because of high error rates (more than 25% errors in one of the conditions).

Apparatus and Stimuli. A microcomputer provided millisecond timing and controlled stimulus presentation and response acquisition. The stimuli were presented in white on a black background. Target letters were the letters X and N; distractor letters were E, T, H, A, and W for the high-load condition and the letter O for the low-load condition. Compatible or incompatible letters (X or N) served as flankers. At a viewing distance of 55 cm, each letter subtended 1.1º in height and 0.8º in width. The letters were presented at 45º, 90º, and 135º of arc on an imaginary circle of 3.1º radius. The center-to-center distance between the letters was 3.0º. The flanker was presented either left or right from the fixation point at an eccentricity of either 4.2º or 6.2º (center to center). In the close-flanker condition, the flanker appeared 1.6 º away from the nearest central letter (from edge to edge; closest contour).

Design and Procedure. The participants received 384 experimental trials. In separate blocks, they received 192 trials in the high- and 192 trials in the low-load condition. Half of the participants started with the high-load condition; the other half started with the low-load condition. There were equal numbers of compatible and incompatible trials and equal numbers of close and far flanker trials. There were 96 practice trials.

Each trial began with the presentation of a fixation cross for 1,000 msec followed by the search display (see Figure 1), which was presented for 200 msec (see Figure 1). If an X was presented, the observers had to press the "z" key; if an N was presented, the observers pressed the "/" key. When an error was committed, an audible tone was presented for 300 msec. The participants received feedback about their performance (RT and error rates) every 48 trials. The participants were instructed to respond to an X or an N appearing in the primary search array. They were instructed to maintain fixation on the central cross.

Results

The mean RT and error rate in each condition are listed in Table 1. Alpha was set at .05 for all inferential statistics. A low load resulted in significantly shorter RTs than did a high load [532 vs. 693 msec; $F(1,15) = 93.6$, $MS_e = 8{,}887$]. A flanker far from the primary array resulted in shorter RTs than did a flanker close to the primary array [599 vs. 626 msec; $F(1,15) = 14.5$, $MS_e = 1{,}544$]. The participants were significantly faster when the flanker was compatible with the target than when it was incompatible with the target [597 vs. 627 msec; $F(1,15) = 25.4$, $MS_e = 1{,}123$]. There was a significant interaction of type of flanker (compatible vs. incompatible) and load [high vs. low; $F(1,15) = 23.8$, $MS_e = 411$]. In the high-load condition, the compatibility effect was only 13 msec, whereas in the low-load condition it was 47 msec. There was also an interaction between flanker position (close vs. far) and flanker type [compatible vs. incompatible; $F(1,15) = 11.9$, $MS_e = 1{,}143$], so that the flanker compatibility effect was larger when the flanker was close to the primary display (flanker compatibility effect of 50 msec) than when the flanker was farther away from the primary display (flanker compatibility effect of 10 msec). Table 1 provides additional planned comparisons in order to specify the flanker compatibility effects under high- and low-load conditions.

Error rates were low (5.3%). There were more errors in the high load than in the low-load condition [7.2% vs. 3.4%; $F(1,15) = 13.7$, $MS_e = 32.7$], and there were more errors when the flanker was incompatible than when they were compatible [6.7% vs. 3.9%; $F(1,15) = 19.5$, $MS_e = 14.6$]. None of the interactions was reliable. Error rates

Table 1
Experiment 1: Mean Response Time (RT, in Milliseconds) and Error Rate (ER, in Percentage) for Each Condition

	Compatible		Incompatible		Incompatible − Compatible	
Load	RT	ER	RT	ER	RT	ER
High	687	5.7	700	8.7	13	3.0*
Low	508	2.1	555	4.9	47*	2.8*

*$p < .05$.

mimicked the effects of RT, suggesting that the RT effects are not due to speed/accuracy tradeoffs.

Discussion

In Experiment 1, a visual search paradigm very similar to that in Lavie and Cox (1997) was used. Particular aspects of the results we report here are similar to those reported in this earlier study. Our low-load condition had a mean RT of 532 msec, which is slightly higher than the mean RT for the low-load condition (478 msec) reported by Lavie and Cox. Like Lavie and Cox, we found a large flanker compatibility effect in the low-load condition of 47 msec, which is comparable to the 38 msec reported by Lavie and Cox.

Our high-load condition was also similar to the high-load condition used by Lavie and Cox (1997). In their study, the mean RT in the high-load condition was 720 msec, which is similar to our high-load mean RT of 693 msec. In the present experiment, we found a nonsignificant compatibility effect in the high load condition of 13 msec, which is similar to the nonsignificant compatibility effect of 9 msec reported by Lavie and Cox. Note, however, that like Lavie and Cox, even in the high-load condition, this effect was marginally significant ($p = .073$). Overall, the present experiment shows that we were successful in creating high- and low-load conditions that resulted in large compatibility effects in the low-load condition and a small compatibility effect in the high-load condition. The conditions created and the results obtained are very similar to those obtained by Lavie and Cox.

EXPERIMENT 2

In Experiment 2, we used exactly the same high- and low-load conditions as in Experiment 1, except that we presented these conditions in mixed blocks of trials.

Method

All the conditions were randomized within blocks of trials. The participants received 384 trials. In total, there were 17 participants. The data of 1 participant were discarded because of a high error rate (>25%).

Results and Discussion

The mean RT and error rate in each condition are listed in Table 2. There were main effects for each of the three factors. A low load resulted in significantly shorter RTs than did a high load [558 vs. 711 msec; $F(1,15) = 135.7$, $MS_e = 5{,}537$]. A flanker far from the primary array resulted in shorter RTs than did a flanker close to the primary array [622 vs. 647 msec; $F(1,15) = 24.3$, $MS_e = 772$]. The participants were significantly faster when the flanker was compatible with the target than when it was incompatible with the target [618 vs. 651 msec; $F(1,15) = 98.1$, $MS_e = 359$]. A significant interaction was found between flanker position (close vs. far) and flanker type [compatible vs. incompatible; $F(1,15) = 13.4$, $MS_e = 615$], so that the flanker compatibility effect was larger when the flanker was close to the primary display (flanker compatibility effect of 49 msec) than when the flanker was farther away from the primary display (flanker compatibility effect of 18 msec). The interaction of type of flanker (compatible vs. incompatible) and load (high vs. low) failed to reach significance [note, however, that the interaction was marginally significant; $F(1,15) = 4.2$, $MS_e = 589$, $p = .057$]. Table 2 provides additional planned comparisons in order to specify the flanker compatibility effects under high- and low-load conditions. As is clear from this analysis, there were reliable compatibility effects both in the high- and low-load conditions.

Error rates were low (6.6%). Main effects were obtained for each of the three factors. There were more errors in the high-load than in the low-load condition [8.8% vs. 4.4%; $F(1,15) = 29.7$, $MS_e = 21.1$], there were more errors when the flanker was close than when it was farther away [8.0% vs. 5.2%; $F(1,15) = 23.9$, $MS_e = 10.8$], and there were more errors when the flanker was incompatible than when it was compatible [7.8% vs. 5.5%; $F(1,15) = 25.8$, $MS_e = 6.8$]. A significant interaction was found between flanker position (close vs. far) and flanker type [compatible vs. incompatible; $F(1,15) = 11.9$, $MS_e = 13.3$], so that the flanker compatibility effect in terms of errors was larger when the flanker was close to the primary display (flanker compatibility effect of 4.5% errors) than when the flanker was farther away from the primary display (flanker compatibility effect of 0.2% errors). Error rates mimicked the effects of RT, suggesting that the RT effects were not due to speed/accuracy tradeoffs.

In the present experiment, we randomly mixed high- versus low-load trials. In an additional intertrial transition, analysis we addressed the question of whether there were any systematic flanker compatibility effects of switching from one condition to another (e.g., switching from high to low load and vice versa). Table 3 presents the results of additional planned comparisons for the specific switching conditions. As is clear from this analysis, when the previous trial was high load and the current trial was high load,

Table 2
Experiment 2: Mean Response Time (RT, in Milliseconds) and Error Rate (ER, in Percentage) for Each Condition

	Compatible		Incompatible		Incompatible − Compatible	
Load	RT	ER	RT	ER	RT	ER
High	700	7.8	724	9.9	24*	2.1*
Low	537	3.2	579	5.7	42*	2.5**

$^*p < .05$. $^{**}p < .01$.

Table 3
Mean Response Time (in Milliseconds) for Repeated and Switched Trials in the High- (H) and Low-Load (L) Conditions in Experiment 2

Load	Compatible	Incompatible	Incompatible − Compatible
High			
Repeated trial (from H to H)	699	713	14
Different trial (from L to H)	701	736	35*
Low load			
Repeated trial (from L to L)	538	574	36*
Different trial (from H to L)	536	583	47*

*$p < .05$.

there was no significant flanker compatibility effect. However, when the previous trial was low load and the current trial was high load, a large and reliable flanker compatibility effect was found. In case of a low load, regardless of whether the same trial was repeated or switched, there was always a reliable flanker compatibility effect.

GENERAL DISCUSSION

The crucial claim of the perceptual load hypothesis is that "perceptual load plays a causal role in determining the efficiency of selective attention" (Lavie, 1995, p. 463). It has been argued that "perceptual load in relevant processing is a major determinant of the processing of irrelevant distractors" (Lavie & Cox, 1997, p. 398). Lavie (1995) and Lavie and Cox (1997) have shown that "distractor interference was always present under situations of low perceptual load and was eliminated by higher loads" (Lavie & Cox, 1997, p. 398).

The present study shows that perceptual load cannot be the only factor determining selectivity. In Experiment 1, high perceptual load prevented the processing of irrelevant distractors. In Experiment 2, exactly the same perceptual load could not prevent the processing of irrelevant distractors. By presenting high- and low-load conditions in blocks of mixed trials, a reliable compatibility effect was found in the high-load condition. If perceptual load had been the only factor determining perceptual selectivity, the compatibility effects should have been the same in the two experiments.

Our intertrial transition analysis provides some notion as to why flanker interference effects were found in the high-load condition. A reasonable assumption is that participants "expect" the same trial type (i.e., high or low load) to be repeated. If the current trial is high load and the next trial is high load, selection is efficient, and little flanker interference is found. These conditions are identical to those producing our results in Experiment 1 when high- and low-load trials were presented in different blocks (as in Lavie & Cox, 1997). However, if a low-load trial is followed by a high-load trial, flankers are processed and cause interference. In this case, one may argue that the strategy used to process the stimuli on the low-load trial, a broad attentional window in which to detect the target letter by means of parallel search (Theeuwes, 1991, 1992, 2004), was carried over to the subsequent high-load trial, resulting in the processing of the flanker, thereby producing a substantial compatibility effect.

Our intertrial analysis shows that for low-load trials, an intertrial change has less of an effect. If a focused attention strategy from a high-load trial transfers to a low-load trial, one would expect less flanker interference. However, we observed a large interference effect regardless of whether the previous trial was high or low load. This implies that attentional set plays a lesser role when perceptual load is low. Thus, in this case, processing may be more strongly influenced by the nature of the display elements, in accord with the perceptual load hypothesis. That is, under conditions of low load, processing is more stimulus driven, since the target and the distractor stand out against a homogenous background. As has been shown by Theeuwes (2004) when elements are highly salient, processing occurs in a bottom-up fashion, and irrelevant singletons capture attention.

Even though in Experiment 2 the interaction between load (high/low) and compatibility just failed to reach significance, it should be noted that there was a compatibility effect of only 24 msec in the high-load condition and a 42-msec effect in the low-load condition. The observation that a low load gives stronger flanker interference than does a high load is consistent with the perceptual load hypothesis, since Lavie and Cox (1997) have demonstrated that increasing perceptual load reduces the flanker interference.

However, even though a reduced flanker interference in a high-load condition is indeed consistent with the perceptual load hypothesis, it should be realized that the interference effect was *not* reduced in the high-load condition when the trial changed from a low-load to a high-load trial. Indeed, in this condition, the flanker interference was very similar to and equally robust as (35 msec) the one reported in the low-load condition. Even though perceptual load plays an important role, it is clear from this analysis that *expectancy* also plays an important role in modulating the effect of irrelevant flankers.

In summary, in line with Lavie and Cox (1997), we have shown that perceptual load is an important factor in determining the effectiveness of selective attention. In low-load conditions, selective attention fails, except under ideal spatial-cuing conditions (Johnson et al., 2002). Furthermore, in low-load conditions, expectancies appear to play little role, and processing is driven in a bottom-up manner.

However, under high-load, expectancies appear to play an important role in determining the extent of processing of display elements.

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(Manuscript received November 6, 2002;
revision accepted for publication August 5, 2003)