Research Report

ON THE EFFICIENCY OF VISUAL SELECTIVE ATTENTION:
Efficient Visual Search Leads to Inefficient Distractor Rejection

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Abstract—*The ability to ignore irrelevant peripheral distractors was assessed as a function of the efficiency in visual search for a target at the center of a display. Efficient target search, among dissimilar nontargets, led to greater distraction than inefficient search, among similar nontargets. This seemingly paradoxical result is predicted by the recent proposal (Lavie, 1995a) that irrelevant processing can be prevented only by increasing the load for relevant processing. Varying the set size of similar items in the central search task demonstrated that interference from irrelevant distractors was eliminated only with more than four relevant items. These results demonstrate how capacity limits determine the efficiency of selective attention, and raise questions about some standard assumptions of most visual search models.*

To what extent can selective attention lead to the prevention of irrelevant distraction? This is perhaps the most basic question in the study of attention. Ideally, focusing attention on relevant information should prevent processing of any irrelevant information. In practice, however, the efficiency of selective attention varies, and unwanted intrusions from irrelevant distractors cannot always be prevented (see Lavie & Tsal, 1994). In fact, the relationship between the efficiency of selection for relevant information and the successful rejection of irrelevant information remains unclear. One might expect efficient target selection to lead to successful distractor rejection. However, there are numerous demonstrations of interference from distractors in situations that should allow very efficient selection of the target (e.g., when target and distractors are widely separated from one another, Gatti & Egeth, 1978).

The efficiency of target selection has been extensively studied in the visual search task. Participants are requested to find targets among a varied number of nontargets, and search efficiency is assessed by plotting reaction time (RT) as a function of nontarget set size. Inefficient searches result in a monotonic increase for RT against set size. In cases in which this increase is substantial and linear, it is often suggested that a serial process of inspecting each item in turn was required to find the target. Such an outcome is often found when nontargets are highly similar to the target (e.g., Duncan & Humphreys, 1989), or when the target is different from the nontargets just in terms of its specific combination of features (e.g., conjunction search for a green *T* or a brown *X* target among brown *T*s and green *X*s), as established within the influential framework of feature integration theory (e.g., Treisman, 1991). By contrast, if the target can be distinguished from the nontargets on the basis of a distinctive feature (e.g., the target has a different color), then a "pop-out" result is often found, that is, RT is largely independent of set size (e.g., Treisman & Gelade, 1980, Wolfe, 1994). It is often concluded that such efficient searches allow a successful rejection of all irrelevant items.

However, it is questionable whether nontargets in such visual search tasks are strictly irrelevant items. One might claim that the nontargets are in fact all relevant for the search task, in the sense that the target is likely to appear at any of their positions, and thus has to be found among them. Indeed, Mack, Tang, Tuma, Kahn, and Rock (1992) have recently argued that all items are in fact attended during parallel search (i.e., the nontargets as well as the target). Thus, parallel searches may not indicate the successful rejection of all nontargets from any attention. Instead, such searches may simply reveal the efficiency with which attention can be divided across all of the search items in some feature-based tasks (Treisman, 1992).

Thus, our question remains. What determines the efficiency of rejection for distractors that are entirely irrelevant (such as distractors placed well outside the current search area)? According to a recent proposal (Lavie, 1995a, Lavie & Tsal, 1994), the efficiency of rejection for irrelevant distractors depends on the perceptual load involved in the relevant processing. Perception is considered to be an automatic and involuntary process, but with limited capacity. Perception is characterized as automatic in this approach not in the sense that it does not require attentional capacity, but in the sense that it is not subject to complete voluntary control. Thus, this model combines aspects of early-selection approaches to attention (i.e., limited capacity) with aspects of late selection (i.e., automaticity), suggesting a solution to the long-standing debate between these rival views. According to the new model, processing proceeds from relevant to irrelevant items until capacity runs out.[1] With a low load in relevant processing, spare capacity inevitably spills over to process irrelevant information, and hence may lead to distraction. Irrelevant processing can be prevented only when a high load in relevant processing exhausts capacity.

Applying this load hypothesis to the visual search situations described earlier leads to a somewhat counterintuitive prediction. More efficient search for a target (e.g., as typically found when the target has a distinctive feature) should result in the unintended processing of irrelevant distractors—that is, in less efficient resistance to distraction. Detecting a feature-target should impose only a low load on attention, and therefore spare capacity should be available to spill over to the processing of irrelevant distractors. By contrast, when search for the target imposes a higher load on attentional capacity (as in serial search tasks), then the search items should exhaust available capacity, thus preventing the processing of irrelevant items. This prediction of the load hypothesis is the exact opposite of the usual intuition that more efficient target selection (i.e., easier search) will lead to better distractor rejection (e.g., Duncan & Humphreys, 1989).

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[1] Relevancy of items may be determined by the priority set given in the instructions, by other top-down factors (e.g., expectations), or by bottom-up mechanisms of control (e.g., saliency). The crucial point here is that although priorities may be set in various ways, and attention may be directed to high-priority items first, processing will nevertheless proceed to low-priority items as well, as long as there is available capacity (e.g., under low loads, see a more extensive discussion in Lavie & Tsal, 1994).

GENERAL METHOD

To test any influence of search efficiency on the success of distractor rejection, we devised variations of visual search tasks which had the additional requirement that an irrelevant distractor, presented in the periphery outside the central search array, had to be ignored (see Fig. 1). Subjects searched for either of two possible target letters among the central nontarget letters, indicating which target was present. The identity of the peripheral distractor could be compatible with the target response (the same letter), incompatible (the alternative target letter), or neutral (with no response associations). We anticipated that any failure to ignore the distractor would result in interference on RT for incompatible versus neutral and compatible distractors (Eriksen & Eriksen, 1974). Our analyses focus on RT data, though similar patterns can be seen in accuracy for all our data figures.

Our question was whether interference from incompatible distractors would depend on the efficiency of the central search task. To manipulate search efficiency, we varied similarity between the central target and nontargets, plus the similarity within nontargets, to produce easy- and hard-search tasks (following Duncan & Humphreys, 1989). Search arrays with a single peripheral distractor were presented for 100 ms to preclude eye movements.

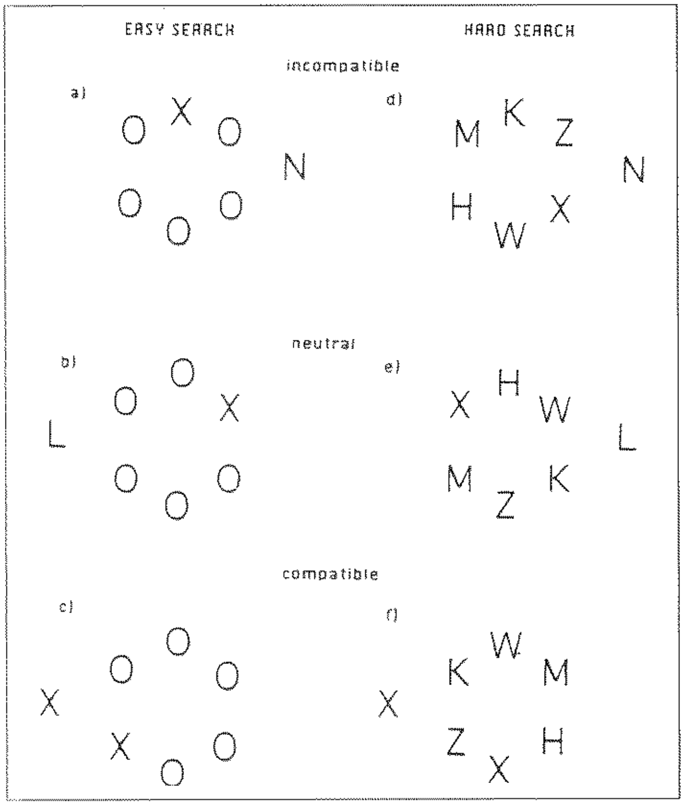

Fig. 1. Example displays from the easy-search (a–c) and hard-search (d–f) tasks in Experiment 1. Participants discriminated whether a target *X* or *N* was present in each central circle by pressing designated computer keys. In the easy search, the central nontargets were five *O*s. In the hard search, the central nontargets were heterogeneous letters that, like the target, were all angular (*K, H, V, Z, W*). A single peripheral distractor appeared 1.4° away from the nearest central letter on the left or right. This distractor could be incompatible with the central target (a and d), neutral (b and e), or compatible (c and f).

EXPERIMENT 1

Processing of irrelevant distractors was compared for efficient versus inefficient searches (see Fig. 1). Participants were emphatically requested to ignore the irrelevant distractor in every condition. Search task was blocked. Each participant underwent 10 blocks of 72 trials (5 blocks for each task, with task order counterbalanced across participants). The first block of each task was discarded as practice. Fourteen participants were tested.

A within-subjects analysis of variance (ANOVA) on mean RTs, with the factors of search task (two levels) and distractor compatibility (three levels), found a main effect of task, $F(1, 13) = 140.1$, $p < .001$. As expected (Duncan & Humphreys, 1989; Treisman, 1991), search was less efficient for a target among nontargets similar to it ($M = 720$ ms) than among nontargets dissimilar to it ($M = 478$ ms). There was a main effect of distractor compatibility, $F(2, 12) = 7.7$, $p < .01$, and this interacted with the search task, $F(2, 12) = 3.8$, $p < .05$. Analysis of simple effects revealed a significant compatibility effect in the easy-search task, $F(2, 12) = 9.3$, $p < .001$, but none in the hard-search task, $F(2, 12) = 2.5$, $p > .10$ (see Fig. 2).

Thus, a more efficient central search, in which target detection could be based on a distinctive feature (i.e., angular vs. curved shape) led to a less efficient rejection of the irrelevant peripheral distractor, as evidenced by larger interference effects. By contrast, the inefficient search (with central nontargets all similar to the target) led to an efficient rejection of the peripheral distractor; indeed, interference was eliminated in this condition.

EXPERIMENT 2

The next study tested further whether our result of increased distractor rejection with decreased search efficiency can indeed be at-

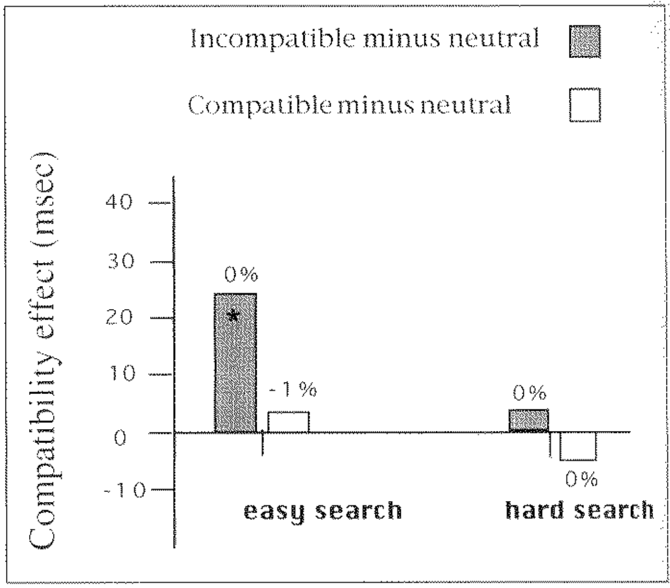

Fig. 2. Results from Experiment 1. Distractor compatibility effects on reaction times and on percentage of errors (noted above each bar) are shown for easy and hard searches. The asterisk indicates significance at $p < .01$.

tributed to the five central nontargets exhausting all attentional capacity when they are highly similar to the target. In Experiment 2, we examined the search function for this hard-search task by varying the number of similar nontargets. If every similar nontarget imposes an additional demand on attentional capacity, then RT should increase linearly with set size. The critical issue was whether distractor interference would be found at the smaller set sizes, and eliminated only when capacity was exhausted by the larger set sizes.

This experiment also allowed us to test an alternative account for the results of Experiment 1. Our manipulation of search efficiency in that study may have inadvertently influenced the relative similarity of the peripheral distractor to the central target in terms of its shape. Although the targets and peripheral distractors were kept identical across the easy- and hard-search tasks of Experiment 1, decreasing the similarity between the central target and nontargets for the easy search may have increased the relative similarity of the target to the distractor, as compared with the central nontargets (see Fig. 1). The greater interference in the easy search might then simply have arisen because the distractor was effectively more similar to the target. In Experiment 2, the relative similarity between all items remained constant across all the set sizes used. Thus, any effect of set size on the ease of ignoring the distractor can be attributed unambiguously to the increased search load, rather than to any increased similarity between target and distractor.

Method

Eighteen new participants were tested in 10 blocks of 96 trials. On each trial, the target *X* or *N* appeared with either zero, one, three, or five additional nontargets in the central array. (Nontargets were selected from the set of similar nontarget letters used in Experiment 1.) The central letters always appeared on the same imaginary circle, with equal spacing between adjacent central letters at all set sizes. The irrelevant peripheral distractor could be incompatible or neutral. The various set sizes were intermixed at random with equal probability in each block. The first two blocks were discarded as practice.

Results

As can be seen in Figure 3a, search performance varied systematically as a function of nontarget set size. This was confirmed in a one-way ANOVA on the mean RTs, which demonstrated a robust main effect for set size, $F(3, 15) = 103.6$, $p < .01$. The average search slope for the highly linear RT function was 43 ms per item. Slopes of this order are typically taken to indicate a serial or inefficient search, requiring focused attention to every search item. The important point for the present purposes is that the compatibility effect of the peripheral distractor interacted significantly with search set size, $F(3, 15) = 6.5$, $p < .01$. As can be seen in Figure 3b, incompatible distractors produced significant interference at all set sizes, with the exception of a set size of six. This outcome cannot be attributed to any variation of relative similarity between target and peripheral distractor, as this was held constant across set size. Instead, the results suggest that only when capacity limits are exceeded or exhausted can efficient distractor rejection be obtained (as previously suggested by Lavie, 1995a, 1995b).

It is noteworthy that the results did not show any graded decrease in distractor processing at intermediate set sizes. Instead, there was an abrupt decrease in distractor interference when the central load exceeded four items (see Fig. 3b). This result may imply that capacity limits are reached only when more than four items require focused attention. This is consistent with several previous studies reporting in other contexts that capacity limits with letter tasks are reached at about four to five items (e.g., Fisher, 1982; Kahneman, Treisman, & Gibbs, 1992; Pylyshyn, Burkell, Fisher, & Sears, 1994; Yantis & Jones, 1991). We conclude that attention has capacity limits, yet can accommodate more then one item.

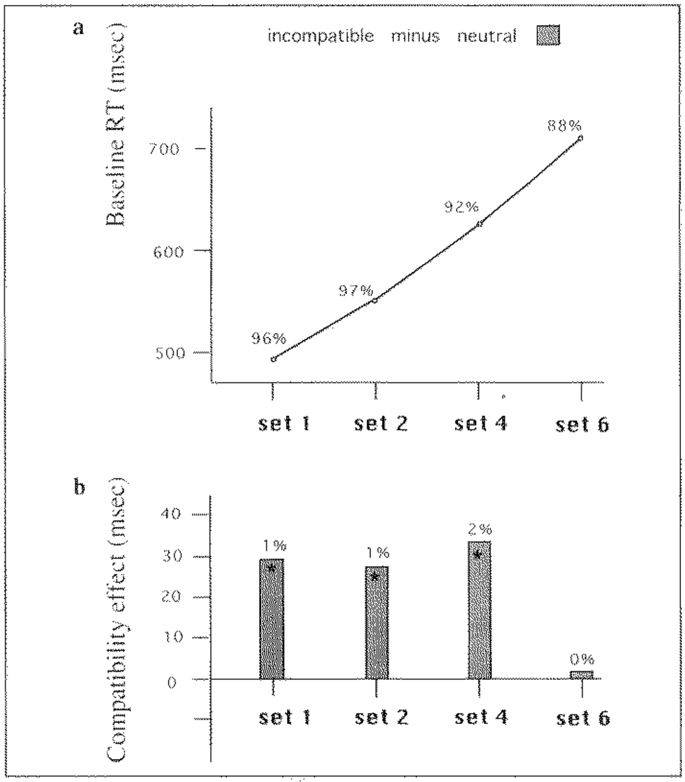

Fig. 3. Results from Experiment 2. Mean reaction time (RT) for the baseline condition (i.e., with a neutral distractor) is plotted as a function of size of the search set in (a). Distractor compatibility effects on RTs and on percentage of errors (noted above each bar) are shown in (b). The asterisks indicate significance at $p < .01$.

GENERAL DISCUSSION

We find that efficient search tasks lead to inefficient rejection of distractors. In both experiments, we obtained interference effects from a peripheral distractor only in the easier searches. In Experiment 1, distractor interference was present when the search involved nontargets dissimilar to the target (easy search); it was eliminated when the search nontargets were similar to the target (hard search). Experiment 2 demonstrated that it is the number of nontargets in the hard-search task that determines distractor rejection. As long as the number of items in the relevant display does not exceed capacity, then irrelevant distractors are not rejected from processing, despite the observers' intentions to ignore them. It is only when perceptual capacity is exhausted by the processing of items that are relevant for the search (i.e., search target and search nontargets) that irrelevant distractors can be excluded from further processing. Thus, rejection of irrelevant distractors under high relevant loads is considered a natural and inevitable consequence of relevant processing consuming the available capacity, and thereby not leaving any spare capacity for irrelevant processing.[2]

These results corroborate Lavie's proposal (1995a; Lavie & Tsal, 1994) that perceptual load in relevant processing is a major determinant of the processing of irrelevant distractors. Lavie (1995a) also found that distractor interference was always present under situations of low perceptual load and was eliminated by higher loads. Several manipulations of load converged on this conclusion, and these involved increases in the processing requirements for identical displays (e.g., detection vs. difficult identification tasks for the same stimulus) as well as variations in the number of relevant items. In addition, Lavie (1995b) demonstrated that whether distractors interfere does not depend solely on overall RT in the central task, but rather on whether performance in that task is critically limited by attentional factors, as here. If the central task is made harder simply by limiting the quality of the stimulus input, so that no amount of attention can compensate for this, then more distractor interference rather than less interference is observed (Lavie, 1995b). Thus, the present pattern of results depends specifically on attentional load.

Our studies extend this point to the case of efficient versus inefficient search tasks, and confirm the seemingly paradoxical prediction that a more efficient search should lead to less efficient rejection of irrelevant distractors. Although this outcome follows readily from the load hypothesis, because the easier searches should leave some spare capacity available to spill over to the critical distractor, the observed outcome is not predicted by current models of visual search (e.g., Duncan & Humphreys, 1989; Humphreys & Muller, 1993; Treisman, 1991; Wolfe, 1994). In present form, these models all equate more efficient visual search with a better rejection of every item other than the target, contrary to the result found here for the irrelevant distractor. Of course, the search models were not devised for selective attention situations in which items at particular locations should be consistently ignored, as in the present studies. The models could be extended to accommodate the present findings by incorporating our key point, namely, that any spare capacity automatically spills over to irrelevant items, even when a target can be readily found.

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[2] This conclusion implies a passive form of distractor rejection (see also Neisser, 1976) as opposed to an active process of rejection using some inhibition mechanisms (e.g., negative priming; see Tipper, 1985). Active inhibition is in fact predicted in our account only for situations in which distractors cannot be rejected from perception in an automatic-passive fashion (i.e., under low loads; see Lavie & Fox, 1997).