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Response Selection in Visual Search: The Influence of Response Compatibility of Nontargets

Peter A. Starreveld, Jan Theeuwes, and Karen Mortier
Vrije Universiteit

The authors used visual search tasks in which components of the classic flanker task (B. A. Eriksen & C. W. Eriksen, 1974) were introduced. In several experiments the authors obtained evidence of parallel search for a target among distractor elements. Therefore, 2-stage models of visual search predict no effect of the identity of those distractors. However, clear compatibility effects of the distractors were obtained: Responses were faster when the distractors were compatible with the response than when they were incompatible. These results show that even in parallel search tasks identity information is extracted from the distractors. In addition, alternative interpretations of the results in terms of the occasional identification of a distractor before or after the target was identified could be ruled out. The results showed that flat search slopes obtained in visual search experiments provide no benchmark for preattentive processing.

Visual search is one of the basic human skills: It is an activity that humans use on a daily basis. For decades, research has been devoted to unraveling the underlying processes of this activity. Following Neisser (1967), the prevailing view among theorists is that the visual search process consists of two stages. During the first stage, basic features (like curvature, color, and orientation) are extracted from the elements in the visual field. The stage is assumed to operate preattentively and without capacity limits: All items from the visual display are processed in parallel. According to Neisser, these "preattentive processes . . . produce the objects which later mechanisms are to flesh out and interpret" (p. 89). These later processes operate during the second stage, in which *focal* visual attention selects one item at a time for further processing. This stage is therefore characterized by severe capacity limitations, or, in Neisser's words, "an allotment of analyzing mechanisms to a limited region of the field" (p. 88). The idea of *selecting* or *filtering* (cf. Broadbent, 1958) a limited subset of the information available to the senses has been further developed by more recent theorists. For example, according to Treisman and colleagues (Treisman, 1999; Treisman & Gelade, 1980; Treisman & Sato, 1990), only the basic features present in the visual display are computed automatically. Visual attention, deployed in a serial manner, is necessary to bind those basic features together so that the conjunction of features (e.g., *tilted red*) can be computed, or objects can be recognized. For example, the identities of letters—which are conjunctions of basic curvature features—are only known to participants after the employment of visual attention (see also Duncan, 1979).

Peter A. Starreveld, Jan Theeuwes, and Karen Mortier, Department of Cognitive Psychology, Vrije Universiteit, Amsterdam, the Netherlands.

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Correspondence concerning this article should be addressed to Peter A. Starreveld, Department of Cognitive Psychology, Vrije Universiteit, Van der Boechorststraat 1, 1081 BT Amsterdam, the Netherlands. E-mail: pa.starreveld@psy.vu.nl

Similarly, Wolfe and colleagues (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) proposed a model in which basic features are extracted in parallel. In this *guided search* model, all activated basic feature representations contribute to activations in a retinotopic activation map. According to this model also, visual attention is necessary in order to recognize an item (e.g., Wolfe & Bennett, 1997; Wolfe, Klempen, & Dahlen, 2000). To find a target, "attention is deployed in order of decreasing activation. It shifts from peak to peak in the activation map until the target is found or until the search is terminated" (Wolfe, 1994, p. 209). For present purposes, it is important to note that the model considers only one location at a time: "Attention is only at one location or another" (Wolfe, 1994, p. 209).

A major source of evidence for such two-stage theories of visual search was derived from tasks in which the number of distractor elements was varied. Key findings from such studies are that when target and distractor differ in one basic feature (e.g., color), reaction times (RTs) are independent of the number of distractor elements (e.g., Mueller, Heller, & Ziegler, 1995; Treisman, 1988; Treisman & Gelade, 1980). Thus, flat slopes of the search functions relating RT to display size are obtained. Two-stage theories explain these flat slopes by assuming that for these tasks a decision about the presence or absence of the target can be made based on results of the first, parallel, processing stage. This mode of search behavior is labeled *parallel search*, or efficient search. In contrast, in tasks in which the target and the distractors differ in a conjunction of basic features (e.g., when a red tilted line has to be found among red vertical lines and blue tilted lines), the time to find a target element increases linearly as the number of distractor elements increases (e.g., Treisman & Sato, 1990). Thus, in this case, steep slopes of the search functions relating RT to display size are obtained. Two-stage theories assume that serial—attentional—processing of display elements has to occur for a decision about the presence or absence of the target. As a result, processing time increases when the number of distractor elements (and thus the set size of the to-be-searched elements) increases. This mode of search behavior is labeled *serial search*, or inefficient search.

As discussed previously, flat slopes of search functions are interpreted as evidence showing that distractor elements in the corresponding experiments were only preattentively processed. Because identification of a display element involves attentive processing, two-stage theories of visual search predict that the identities of distractors should not affect the search time for a target in any search task in which flat search slopes are obtained. In the present study, this prediction was put to the test.

The prediction regarding the influence of distractor identity upon search efficiency that we derived for serial two-stage theories of visual attention contrasts with predictions of parallel theories of visual attention. According to the latter type of theory (e.g., McElree & Carrasco, 1999; Murdock, 1971; Rumelhart, 1970; Shaw & Shaw, 1977; Townsend & Ashby, 1983), all identities of the elements in the visual field are computed in parallel, so influences of distractor identity upon search efficiency are to be expected.

The fact that we derived clearly different predictions for serial two-stage models and parallel models is not trivial. It has long been known that the classic results of visual search tasks that we described earlier (flat search slopes for feature search and steep slopes for conjunction search) can easily be explained by both serial models and parallel models of visual search (e.g., Townsend, 1972). For parallel models, the explanation of flat search curves obtained for feature search is self-evident: Because information is accumulating in parallel, a decision can always be made at the same speed. The explanation of steep search functions seems to pose more of a problem for parallel theories. However, for example, Townsend already argued that parallel models that assume limited processing capacity can explain an increase in RTs with increasing number of distractors. When the information needed to make a comparison of an element with a target representation is complex, capacity limits may reduce the rate of information accumulation for each comparison. This lower rate ultimately translates to longer RTs (e.g., McElree & Carrasco, 1999; Murdock, 1971; Rumelhart, 1970; Shaw & Shaw, 1977; Townsend & Ashby, 1983). The assumption of limited capacity is not critical: Another class of parallel models assumes unlimited capacity in the amount of information accumulation. However, for these models, as the number of comparisons increases, so does the chance of making an error. Although such models (known as *confusability theories*) are mostly aimed at explaining accuracy data (e.g., Kinchla, 1974; Palmer, Ames, & Lindsey, 1993), they might be generalized to handle visual search results as well. Finally, dependent on the characteristics of the stimulus display, even implemented neural network models may produce both flat and steep search slopes (Humphreys & Müller, 1993).

The classic RT pattern produced by feature search and conjunction search tasks can thus be explained by both serial two-stage models and parallel models. Therefore, a different type of evidence is needed to help distinguish these types of models. To do so, McElree and Carrasco (1999) used a response–signal speed–accuracy trade-off procedure and argued that their results were best explained by a limited-capacity parallel model. In the present article, we show that the standard RT paradigm can also be used to directly test different predictions of serial two-stage models and parallel models of visual search. We describe the paradigm that we used next.

In most visual search experiments, only a target present/target absent response is required, and the identity of the distractors bears no relation to the present/absent response. However, a large body of literature exists in which experiments are described that use the fact that distractors can be associated to the required response. In flanker tasks, introduced by B. A. Eriksen and Eriksen (1974), participants respond to a target presented at a fixed location. The target is flanked by two distractors, which participants are instructed to ignore. In the flanker task, generally two responses are required that are based on the identity of the target. For example, when the target is an *A*, participants respond by pressing one of two keys; when it is a *T*, they press the other key. In this type of task, varying the relation between the distractors and the response has profound consequences for the obtained results. When the distractors are not associated with a response (target *A*, distractor *K*), RTs in a baseline condition are obtained. Relative to this baseline condition, RTs increase when distractors are associated to a different response than the one that is required for the target (target *A*, distractor *T*), an *interference* effect. Also, relative to the baseline condition, RTs generally decrease when distractors are associated with the same response (target *A*, distractor *A*, a *facilitation* effect; e.g., B. A. Eriksen & Eriksen, 1974; Taylor, 1977). In the remainder, we call the difference in RTs between the compatible and incompatible conditions a *congruency* effect. We use the term *compatibility* effect as a superordinate for the three effects mentioned.

In the present study, we introduced aspects of the flanker task in types of visual search tasks based on conjunction search tasks and feature search tasks. Like standard visual search tasks, participants always searched for a target among distractors. In addition, like flanker tasks, the target was always one of two letters that each required a different button-press response, and distractors could be associated with the same response, a different response, or with no response at all. Usage of this type of task has already proven to yield valuable results in the study of attentional capture by singletons (Theeuwes & Burger, 1998; see also Theeuwes, 1996).

The first experiment was based on a study reported by Kaptein, Theeuwes, and van der Heijden (1995). These authors described experiments in which participants had to search for a colored target among distractors: some had the same color as the target and some had a different color.[1] The results showed an increase in RT with increasing numbers of same-color distractors, while there was no effect on RT when the number of different-color distractors increased (see also Egeth, Virzi, & Garbart, 1984). The authors interpreted these results as showing that participants performed a serial search among the elements that shared the color of the target. According to an interpretation in terms of serial two-stage models

[1] Keren (1976) obtained congruency effects in a very similar search task. However, because no set-size manipulation was used in the study reported by Keren, the obtained effects could have occurred because participants might not have been able to limit their search to the target-color subset. Francolini and Egeth (1980) also performed experiments with similar displays. Their results indicated that the elements of the nontarget color could be ignored (but see Driver & Tipper, 1989), just like those in the study of Kaptein et al. (1995). However, responses in their experiments were not related to the identity of the elements, but to their number. In addition, because of their Stroop-like manipulations, the identity of the target elements could in fact be incompatible with the response. Because of these differences with the present study, we do not discuss this study further.

of visual search, the elements of the nontarget color were only preattentively processed.

Kaptein et al. (1995) used a visual search task in which participants indicated the presence or absence of the target. The present Experiment 1 used a variant of this task. Each display contained one of two possible target letters, each requiring a different response. The target letter was always displayed in red and was accompanied by red distractors (other red letters) that never were targets in the experiment. In addition, the red elements were accompanied by green distractors that were related either to the same response (these letters were identical to the target letter except for their color) or to the other response. We varied both the number of red and the number of green distractors. On the basis of the results of Kaptein et al., we expected to obtain results that would show inefficient search among the red display elements and efficient search among the green distractors. When these results would obtain, we could then address the main issue of the experiment. Given efficient search among the green distractors, serial two-stage models of visual search predict that no compatibility effect induced by the green distractors should be obtained, whereas parallel models of visual search predict that clear compatibility effects of these distractors should be found.

Experiment 1

Method

Participants. Eight students from the Vrije Universiteit, Amsterdam, the Netherlands, took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. Participants were paid about $5 for their cooperation.

Materials. In all experiments reported in this article, stimuli were drawn on a computer screen with a resolution of 640 × 480 pixels. The letters were located on an imaginary circle drawn around the center of the display with a radius of 3.6° of visual angle, to control for visual acuity differences between different presentation locations (see, e.g., Anstis, 1974). The position of each element was randomly chosen, the only restriction being that distances between neighboring display elements were equal.

In the present experiment, the target letter was either a capital *A* or a capital *R*, displayed in red. Green distractors were also *R*s and *A*s. In the compatible condition, these letters were the same as the target letter; in the incompatible condition, they were different from the target. There were 2, 4, or 6 green distractors. In addition, there were 2, 4, or 6 red distractors. These distractors were randomly chosen from the set *B, E, G, H, K, N, S, T, U, Z.* Numbers of green and red distractors were factorially combined to yield nine different display constitutions ranging from 5 display elements (2 green distractors, 2 red distractors, and 1 target) to 13 display elements (6 green distractors, 6 red distractors, and 1 target). For all display constitutions, both target letters were used to create compatible displays and incompatible displays. Red and green distractors were equiluminant as determined by the flicker-fusion test. The height and width of the letters were about 0.67° and 0.47° of visual angle, respectively (font FR-25 of the Micro Experimental Laboratory [MEL] fonts; MEL Version 2.0; Schneider, 1988).

The experiment was preceded by a practice series in which the green distractors from the experimental displays were replaced with green letters randomly chosen from the set used for the red letters so that none of these distractors were compatible or incompatible with the response. Each of these displays was created 18 times, rendering 324 trials.

Apparatus. The experiment was programmed using MEL professional software (Version 2.0; Schneider, 1988). Presentation of the stimuli and collection of the data were performed using a fast IBM compatible PC. Participants rested their heads on a chin rest located at 85 cm in front of the computer screen.

Procedure. Participants were seated in a dimly illuminated booth. Participants were told that they would see both red and green letters, but they were only to respond to a red *A* or a red *R*, one of which would be present in each display. Participants had to press the *Z* key when they saw a red *A* and the *slash* key when they saw a red *R*. They were instructed to respond as quickly and accurately as possible. Instructions also stressed that participants should fixate on the fixation cross and that they should not move their eyes during the presentation of a trial.

The session started with the presentation of a practice series. If participants made more than 10% of errors in this practice series, then the practice series was repeated. Two experimental series then followed. Each series consisted of 2 (targets) × 3 (number of red elements) × 3 (number of green elements) × 2 (conditions) × 9 (repetitions), to equal 324 trials. Participants received a short break after 81 trials in each series. During these breaks, the computer showed participants their mean RTs and number of errors on the preceding block, which they wrote down. After each series, the experimenter checked these figures to monitor participants' performance. A maximum of 3 participants were tested concurrently. During the experiment, each participant was monitored by a video camera.

Each trial involved the following sequence. First, a fixation cross appeared in the middle of the screen. After 700 ms, the stimuli were added to the screen. Then, after 200 ms, the screen was erased. A stimulus duration of 200 ms was chosen because previous research has shown that such display durations do not allow effective eye movements (e.g., Rayner, Slowiaczek, Clifton, & Bertera, 1983). Next, the participant responded by typing one of two keys. If the response was correct, this triggered the next trial. If it was incorrect, a tone was sounded for 100 ms, after which the computer presented the next trial. Finally, if the participants did not respond within 2 s, the response was scored as wrong. The experiment took about 45 min.

Results

Correct responses that took longer than 1,100 ms were removed and treated as errors. This accounted for 0.73% of the trials. All remaining RTs for correct responses were used for the calculation of the means for the compatible and incompatible conditions for each of the nine display constitutions. In Figure 1, these means and the corresponding mean numbers of errors are plotted, showing the differences between the compatible and incompatible conditions for each number of red elements (within a graph) and for each number of green elements (between graphs).

Mean RTs were analyzed by a 3 × 3 × 2 analysis of variance (ANOVA), with the number of red elements, the number of green elements, and compatibility as within-participant variables. The effect of compatibility was significant, $F(1, 7) = 47.8$, $p < .01$, $MSE = 650$. Participants responded slower in the incompatible condition than in the compatible condition. The effect of the number of red elements was also significant, $F(2, 14) = 158.3$, $p < .01$, $MSE = 781$. Finally, the effect of the number of green distractors was significant, $F(2, 14) = 20.1$, $p < .01$, $MSE = 334$. Participants' RTs increased as the number of red and green elements increased. Most important, neither the second-order interactions nor the third-order interaction was significant (all *p*s $>$ .20).

The effects of the variables number of red elements and number of green elements can be further analyzed by determining the slope of the search functions. Because no interactions with the other variables were obtained, least-square slope estimates were calcu-

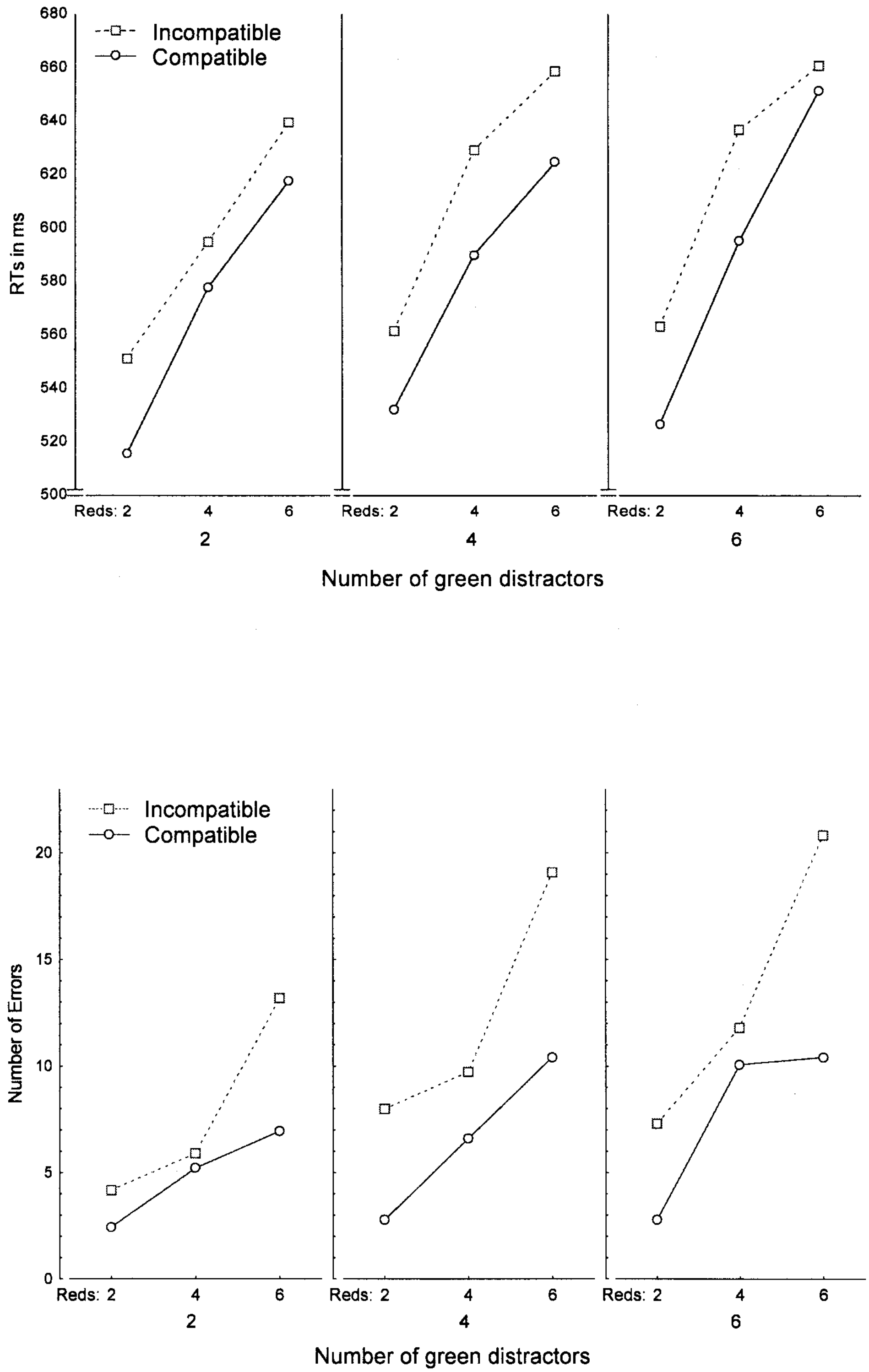


Figure 1. Mean reaction times (RTs) and mean numbers of errors for the incompatible and compatible conditions of Experiment 1 for each number of red elements (within a graph) and for each number of green elements (between graphs).

lated based on participants' mean RTs for the number of red elements averaged over the number of green elements and over the two conditions. For the red elements, the average slope of the linear fits was 25.1 ms per item. Similarly, the average slope of the linear fits based on participants' mean RTs for the green elements averaged over the number of red elements and over the two conditions was only 5.7 ms per item.

The error analysis showed comparable results. Errors were analyzed using the same 3 × 3 × 2 ANOVA. The effect of compatibility was significant, $F(1, 7) = 8.6$, $p < .05$, $MSE = 92$. The effect of the number of red elements was significant, $F(2, 14) = 19.6$, $p < .01$, $MSE = 49$. The effect of the number of green elements was also significant, $F(2, 14) = 7.8$, $p < .01$, $MSE = 30$. Finally, only the interaction between the number of red elements and compatibility reached significance, $F(2, 14) = 6.6$, $p < .01$, $MSE = 21$. Inspection of Figure 1 shows that this interaction was due to the effect of compatibility being especially large when six red elements were present in the display. In conclusion, no speed–accuracy trade-offs were apparent in the error data.

Discussion

In the experiment, the mean slope of the search function for the number of green elements was only 5.7 ms. This small number is generally taken to signify that the green elements were only preattentively processed (e.g., Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Enns & Rensink, 1990; Treisman & Gormican, 1988). In addition, the slope for the search function among the red elements was 25.1 ms. This finding is generally interpreted as showing inefficient serial search (e.g., Horowitz & Wolfe, 1998). Taken together, the experiment replicated the results of Kaptein et al. (1995) because the results showed that participants were able to reduce their searches to a color-defined subset. In addition, the experiment extended these results to a task in which participants searched for letters (see also Egeth et al., 1984). In terms of two-stage models of visual search, the results showed that visual attention was only deployed to the red elements and not to the green elements (see also Kaptein et al., 1995). Nevertheless, the results showed a clear effect of compatibility of the green distractors for all numbers of red elements used in the experiment. This latter result was not predicted by two stage models of visual search, but is in accordance with predictions of parallel models.

In terms of two-stage models of visual search, in the present experiment the target element was found by a serial deployment of attention among the red display elements. Thus, on an average trial, attention would have been deployed to several red elements at several locations. Although it is assumed that visual attention can move between positions instantaneously (e.g., Sagi & Julesz, 1985; Sperling & Weichselgartner, 1995), there is still debate about whether visual attention has effect on intermediate locations when it moves (see, e.g., Tsal, 1983; Yantis, 1988). To avoid an interpretation of our compatibility effect in terms of the processing of green distractors due to attention moving over them, in the next experiment we used a task in which visual attention moved directly to the position of the target letter. In this task, there was only one red letter, the target, which was accompanied by a variable number of green letters (the distractors). The distractors could again be compatible or incompatible with the response. We also added a control condition in which the distractors were not associated with a response, to allow the assessment of possible separate facilitation and inhibition effects as compared with this control condition. The resulting color-singleton search task is a variant of the feature search task, because the location of the target can be found on the basis of a single basic feature, color. Again, two-stage theories of visual attention predict that no compatibility effects should be obtained in such an experiment.

Experiment 2

Method

Participants. Ten students from the Vrije Universiteit took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. Participants were paid about $5 for their cooperation.

Materials. The displays had the same properties as in Experiment 1. The target letter was either a capital *N* or a capital *T*, displayed in red. Green distractors were *N*s, *T*s, and *C*s. In the compatible condition, the green distractors were the same as the target letter; in the incompatible condition, they were associated with a different response. In addition, in the control condition, the green distractors consisted of *C*s that were not associated with a response.

There were 2, 4, 6, 8, 10, or 12 green distractors present in the displays. The experiment was preceded by a practice series in which the green distractors from the experimental displays were replaced with green letters that were *K*s, *U*s, or *A*s so that none of these distractors were compatible or incompatible with the response.

Apparatus. The apparatus was the same as in the previous experiment.

Procedure. The procedure was almost the same as in the previous experiment. Participants were told that they would see one red letter and several green letters, but they were only to respond to the red letter. Participants had to press the *Z* key when they saw a red *N* and the *slash* key when they saw a red *T*, one of which would be present in each display.

The session again started with the presentation of a practice series that consisted of 2 (targets) × 6 (number of green distractors) × 3 (number of green letters) × 2 (repetitions), to equal 72 trials. Three experimental series then followed. Each series consisted of 2 (targets) × 6 (number of green distractors) × 3 (conditions) × 9 (repetitions), to equal 324 trials.

Results

Correct responses that took longer than 1,100 ms were treated as errors. This accounted for 0.07% of the trials. All remaining RTs for correct responses were used for the calculation of the means for the compatible, incompatible, and control conditions for each of the six display sizes. Figure 2 shows these means and the corresponding mean numbers of errors.

Mean RTs were analyzed by a 6 × 3 ANOVA, with the number of green elements and compatibility as within-participant variables. The effect of compatibility was significant, $F(2, 18) = 252.5$, $p < .01$, $MSE = 185$. In general, participants responded slower in the incompatible condition than in the compatible condition, with RTs in the control condition in between. The effect of the number of green distractors was also significant, $F(5, 45) = 18.0$, $p < .01$, $MSE = 110$. Participants' RTs increased as the number of green elements increased. Finally, the interaction of these two variables proved significant, $F(10, 90) = 7.3$, $p < .01$, $MSE = 118$. Inspection of Figure 2 shows that this interaction was mainly caused by an increase in RTs for the incompatible condi-

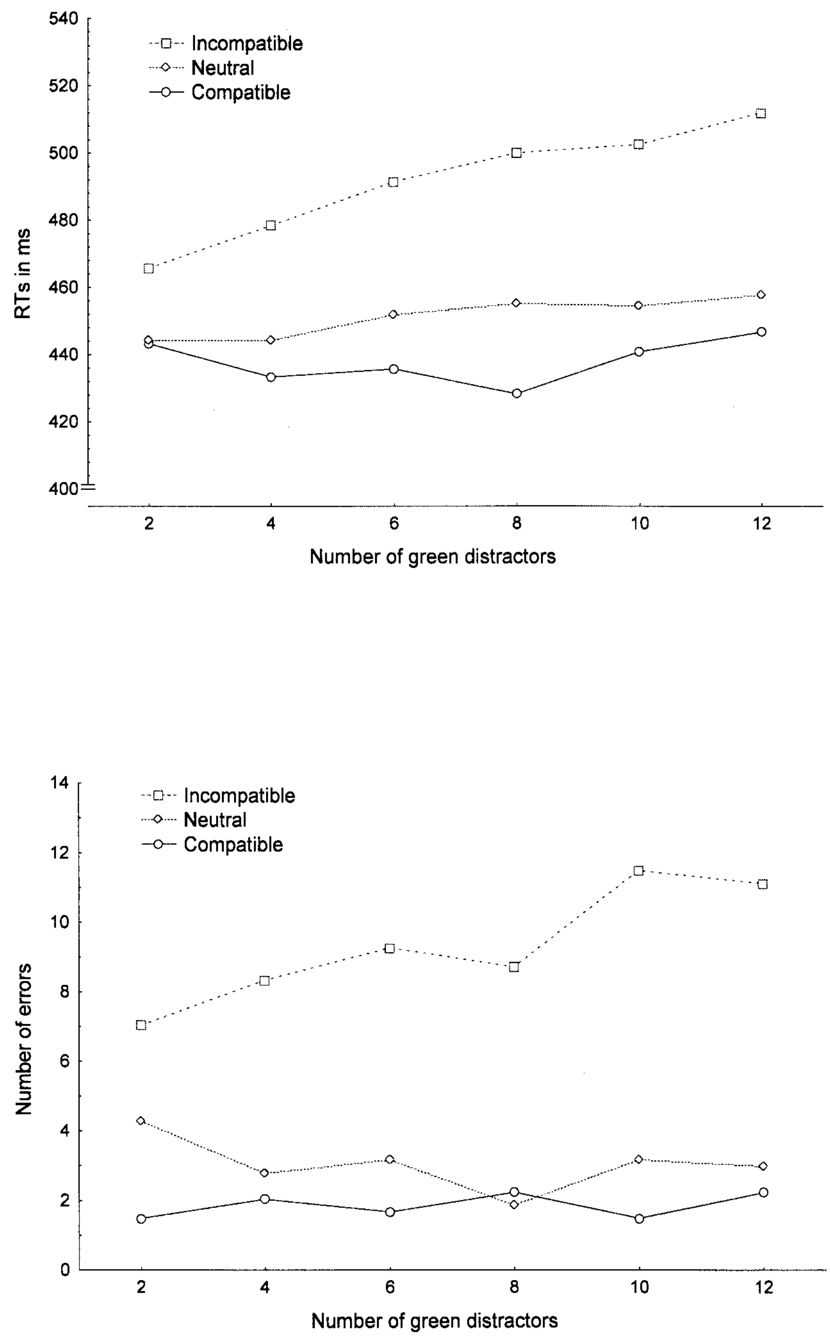


Figure 2. Mean reaction times (RTs) and mean numbers of errors for the incompatible, neutral, and compatible conditions of Experiment 2 for each number of green distractors.

tion with increasing number of green distractors. The mean slope of the linear fits for the search functions for this condition was nevertheless very small, only 4.46 ms.

The mean numbers of errors were analyzed using the same 6 × 3 ANOVA. Only the effect of compatibility proved significant, $F(2, 18) = 28.4$, $p < .01$, $MSE = 34$. Newman–Keuls post hoc tests showed that more errors were made in the incompatible condition than in the other two conditions.

Discussion

The results of this experiment were obtained in a task that showed very efficient search among the green elements (cf. Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Enns & Rensink, 1990; Treisman & Gormican, 1988), indicating that visual attention was directly deployed to the location of the target. However, as in Experiment 1, clear compatibility effects of the green distractors were obtained: Distractors associated with an incompatible response caused longer RTs than distractors not associated with a response or distractors associated with the correct response. Therefore, the results of Experiment 2 present corroborating evidence for the conclusions drawn from the results of Experiment 1. Again, predictions of two-stage models of visual search were disproved.

In the General Discussion section, we elaborate on these results. For now, we mention that a possible explanation of the present results might be derived from the fact that the green distractors and the red targets were identical except for their color. Therefore, it could be hypothesized that if the attentional system had used form-based templates to find the targets, the distractors would also have matched these templates. To prevent an interpretation of our results in terms of form-based templates, in the next two experiments we replicated both Experiments 1 and 2 using the same capital letter targets, but with green distractors that were either small *a*s and *r*s (Experiment 3) or small *n*s and *t*s (Experiment 4). In Experiment 3, participants searched among a color-defined subset of the display elements, as they did in Experiment 1.

Experiment 3

Method

Participants. Eight students from the Vrije Universiteit took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. Participants were paid about $5 for their cooperation.

Materials. Same as in Experiment 1, except that the green distractors consisted of small letters instead of capital letters. The MEL FR-25 font was chosen to depict the letters because in this font, the small letters differ considerably from the corresponding capital letters. Note that both the red distractor elements and the target were capital letters.

Apparatus. The apparatus was the same as in Experiment 1.

Procedure. The procedure was the same as in Experiment 1.

Results

The data were treated the same way as in Experiment 1. The removal of the RTs for correct trials that took longer than 1,100 ms accounted for 0.6% of the trials. Figure 3 shows the means for the compatible and incompatible conditions for each number of red elements (within a graph) and for each number of green elements (between graphs) as well as the corresponding mean numbers of errors.

A 3 × 3 × 2 ANOVA was performed, with the number of red elements, the number of green elements, and compatibility as within-participant variables. The effect of compatibility was significant, $F(1, 7) = 32.2$, $p < .01$, $MSE = 847$. Participants responded more slowly in the incompatible condition than in the compatible condition. The effect of the number of red elements was also significant, $F(2, 14) = 44.4$, $p < .01$, $MSE = 1{,}635$. Finally, the effect of the number of green distractors was significant, $F(2, 14) = 34.1$, $p < .01$, $MSE = 230$. Most important, as in Experiment 1, neither the second-order interactions nor the third-order interaction was significant (all ps $> .40$).

As in Experiment 1, we calculated the slopes for the participants' search functions for search among the red elements and the green elements. The mean slope of the linear fits for search among the red elements was 19.4 ms per item. The mean slope of the linear fits for search among the green elements was only 6.3 ms per item.

The same ANOVA performed on the RT data was performed on the number of errors. Only the effect of the number of red elements was significant, $F(2, 14) = 16.0$, $p < .01$, $MSE = 23$. The effect of compatibility approached significance, $F(1, 7) = 5.2$, $p = .06$, $MSE = 17$. Also, the interaction of number of red elements and compatibility approached significance, $F(2, 14) = 2.8$, $p = .10$, $MSE = 19$, the effect of compatibility tended to be larger for displays that contained two red elements than for displays that contained more than two red elements.

Discussion

The results nicely replicated the results of Experiment 1, but using green distractors that consisted of small letters instead of capital letters. Again, we obtained evidence that participants were able to restrict their search to the red elements, because the slope of the search function among the green elements was well below 10 ms (e.g., Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Enns & Rensink, 1990; Treisman & Gormican, 1988). More important, we again obtained clear compatibility effects from the green distractors.

The results showed that an explanation of the obtained compatibility effects cannot be framed in terms of form templates used by the attentional system. To further generalize this finding, in the next experiment we tried to replicate the results of Experiment 2, again using distractors that were small letters. Recall that this experiment was a variant of a feature search task because in this task, the target was a color singleton.

Experiment 4

Method

Participants. Eight students from the Vrije Universiteit took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. Participants were paid about $5 for their cooperation.

Materials. The materials were the same as those in Experiment 2, except that the green distractors consisted of small letters instead of capital letters.

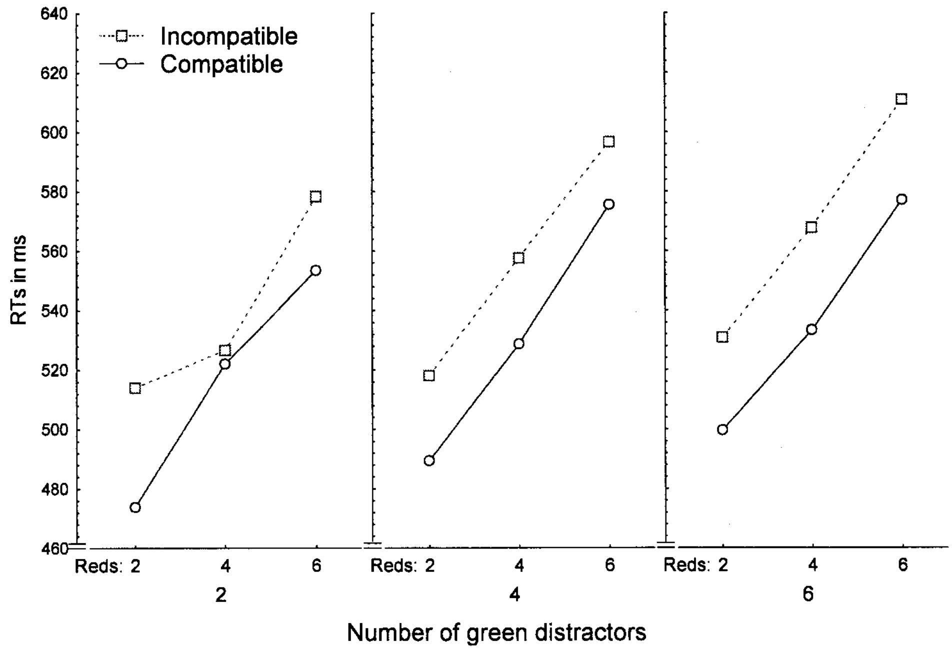
Apparatus. The apparatus was the same as in Experiment 2.

Procedure. The procedure was the same as in Experiment 2.

Results

The data were treated the same way as in Experiment 2. The removal of the RTs for correct trials that took longer than 1,100 ms accounted for 0.09% of the trials. Figure 4 shows the means for the compatible, incompatible, and control conditions for each number of green elements and the corresponding mean numbers of errors.

A 6 × 3 ANOVA was performed, with the number of green elements and compatibility as within-participant variables. The effect of compatibility was significant, $F(2, 14) = 43.5$, $p < .01$, $MSE = 637$. As in Experiment 2, in general, participants responded slower in the incompatible condition than in the compatible condition, with RTs in the control condition in between. The effect of the number of green distractors was also significant, $F(5, 35) = 5.4$, $p < .01$, $MSE = 124$. Participants' RTs increased as the number of green elements increased. Finally, the interaction of these two variables proved significant, $F(10, 70) = 6.7$, $p < .01$, $MSE = 97$. Inspection of Figure 4 shows that this interaction was



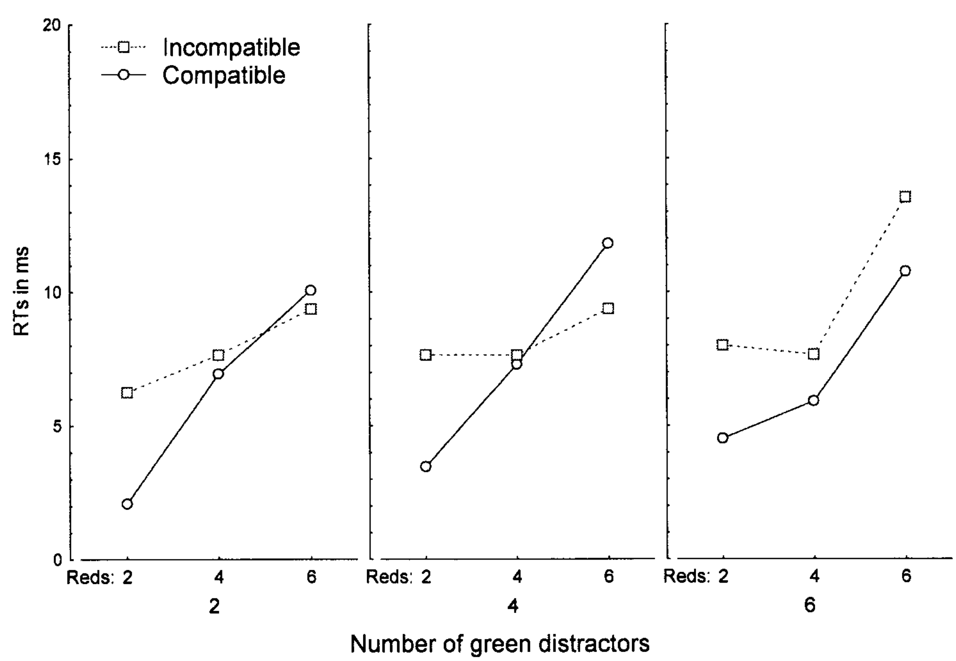
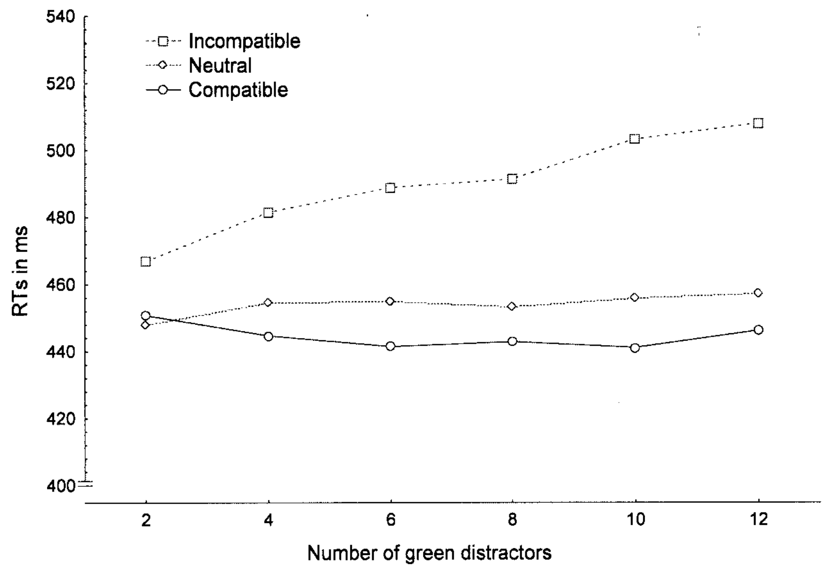


Figure 3. Mean reaction times (RTs) and mean numbers of errors for the incompatible and compatible conditions of Experiment 3 for each number of red elements (within a graph) and for each number of green elements (between graphs).



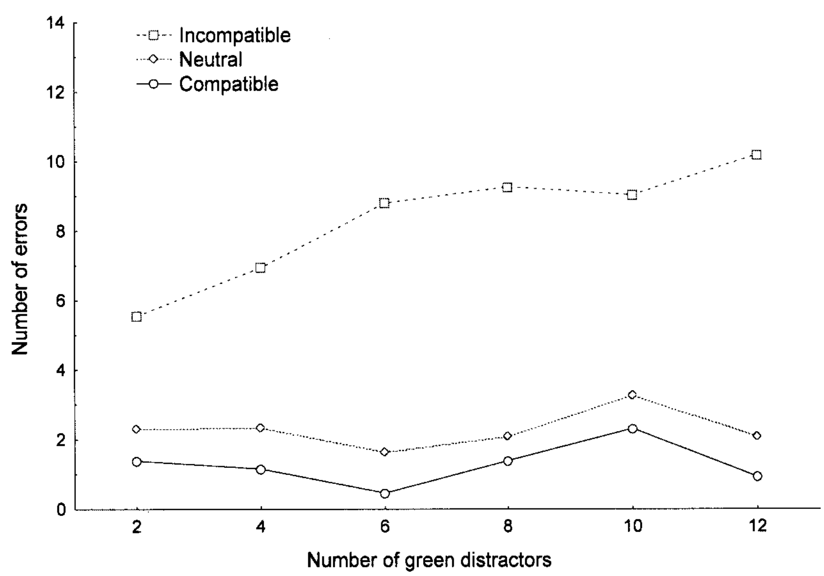


Figure 4. Mean reaction times (RTs) and mean numbers of errors for the incompatible, neutral, and compatible conditions of Experiment 4 for each number of green distractors.

mainly caused by an increase in RTs for the incompatible condition with increasing number of green distractors. The mean slope of the linear fits for the search functions for this condition was nevertheless very small, only 3.9 ms.

The mean number of errors was analyzed using the same 6 × 3 ANOVA. Only the effect of compatibility proved significant, $F(2, 14) = 37.8$, $p < .01$, $MSE = 18$. Newman–Keuls post hoc tests showed that more errors were made in the incompatible condition than in the other two conditions.

Discussion

The results nicely replicated the results of Experiment 2, but using green distractors that consisted of small letters instead of capital letters. Again, clear compatibility effects were obtained in an experiment in which search among the green elements was very efficient (e.g., Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Enns & Rensink, 1990; Treisman & Gormican, 1988). Because targets and distractors differed in form, we conclude that the occurrence of compatibility effects cannot be explained in terms of form-based templates. In terms of two-stage models of visual search, the results showed that no visual attention was deployed to the green elements. Nevertheless, the results showed clear compatibility effects induced by the green distractors. These results were not predicted by two-stage models of visual search, but are in accordance with predictions of parallel models. We elaborate on this issue in the General Discussion section.

Alternative interpretations. Proponents of two-stage models of visual search might come up with alternative interpretations of the results obtained so far. To uphold the core assumptions of any two-stage theory, and at the same time account for the compatibility effects we obtained, three options result. The first two options are similar in that they both assume that, despite the small search slopes over the green elements that we obtained, nevertheless a green distractor was occasionally identified before the target was found. The first of these options is that this might have occurred because in our experiments participants might occasionally have guessed the location of the upcoming target and in anticipation focused their attention on that location. We call this the "guess interpretation." The second interpretation is that participants might always have directed their attention toward the general area of the red element. However, they might occasionally, yet mistakenly, have focused their attention on a distractor element in a location adjacent to the target first. We call this the "mistake interpretation." If a distractor was occasionally identified before the target, this might have caused the obtained compatibility effects.

In our view, these accounts are not very satisfactory. According to these accounts, a distractor was only occasionally attended first. Thus, in the majority of the trials, a distractor was not identified before the target was found. This implies that the compatibility effects induced by the occasionally identified distractors should have been very large in order to show up in the means. However, if a distractor would regularly have been identified before the target was, these interpretations remain feasible, so they deserve further scrutiny.

Both the guess and the mistake interpretation predict an increase in mean RT with increasing display size for the incompatible and control conditions. An increase in mean RT is also predicted for the compatible condition if the reasonable assumption is made that a compatible distractor causes interference as compared with a situation in which the target is presented alone (e.g., B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Schultz, 1979). The reason for these predictions is that according to the guess interpretation, the chance of the occurrence of a distractor at a guessed location increases with increasing display size. According to the mistake interpretation, the chance that an element in the near vicinity of the target was mistakenly selected first also increases because with increasing display size, in our experiments the distance of the nearest distractors to the target decreased so that more distractor elements were present in the vicinity of the target. These predictions can be evaluated by examining our data presented so far. The predictions were clearly not borne out for the control and correct conditions, because for these conditions the predicted increases were not obtained. However, in Experiments 2 and 4, we did obtain such increases in RTs for the incompatible condition. Although these increases were small—and therefore indicative of parallel search among these distractors—we wanted to more thoroughly rule out the alternative interpretations mentioned previously by an investigation into the precise origin of the increase of RTs with increasing set size for the incompatible condition. Experiments 5, 6, and 7 were run to investigate this issue by trying to isolate the variable that caused the small increase and, in doing so, to investigate the relative merits of the guess interpretation and the mistake interpretation.

The third and final interpretation to account for our compatibility effects, and still uphold the core assumptions of any two-stage theory, is to assume that the compatibility effects were caused by identification of one or more distractors after the identification of the target had taken place but before response selection had occurred. Although this posttarget-processing hypothesis is clearly post hoc because a corresponding mechanism is not included in two-stage theories of visual search (e.g., Wolfe, 1994, stated that "a search ends when a target is found," p. 209), it might nicely account for the compatibility effects that we have obtained so far. Therefore, in Experiment 8, we investigated further this interpretation by masking the distractors in order to minimize the chance that distractors received such posttarget processing.

Identification of distractors before identification of the target. In the experiments reported so far, an increase in the number of green distractors was always accompanied by an increase in search set size and, thus, by an increase in display density. In Experiment 5, we evaluated the role of an increase in display density per se. In this experiment, we kept the number and relative location of the compatible/neutral/incompatible distractors (experimental distractors) fixed, but varied the number of display elements by introducing neutral filler elements. Neutral filler elements were located between the target and the experimental distractors (and between the experimental distractors themselves). Note that, on the basis of the results obtained with a location cuing task, Yantis and Johnston (1990) argued that the number of intervening items between the target and the experimental distractors was an important variable governing the size of compatibility effects.

The guess interpretation predicts a clear increase in overall RTs for all conditions, because the chance that a nontarget element occurred at a fixed random location increased with increasing display size. It also predicts that the size of the compatibility effects should remain constant for the various display sizes used, because the chance that an experimental distractor occurred at a fixed random location remained the same with this manipulation. In contrast, the mistake interpretation predicts very small, if any, compatibility effects to begin with, because there were no experimental distractor elements in the near vicinity of the target. In addition, it predicts a clear decrease of the compatibility effects with increasing display size, because with increasing display size more and more neutral filler elements were present near the target location.

Experiment 5

Method

Participants. Ten students from the Vrije Universiteit took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. Participants were paid about $5 for their cooperation.

Materials. The characteristics of the display were the same as in the previous experiments. To build a particular display, a target element (either a red *N* or a red *T*) was placed at a random position on an imaginary circle. Two experimental elements (green *N*s, *T*s, or *C*s) were located in such a way that all distances between neighboring elements were equal. Finally, zero, three, six, or nine filler elements (green *S*s) were added to the display in such a way that an equal number of filler elements were placed between the target and each experimental element and between the two experimental elements. This way, in all displays, the two experimental elements were located at the same relative distance from the target while display size varied from 3 to 12 in steps of three.

The experiment was preceded by a practice series in which the experimental elements from the experimental displays were replaced with green letters that were *K*s, *U*s, or *A*s so that none of these distractors were compatible or incompatible with the response.

Apparatus. The apparatus was the same as in the previous experiments.

Procedure. The procedure was the same as in Experiments 2 and 4. The session again started with the presentation of a practice series that consisted of 2 (targets) × 4 (number of green fillers) × 3 (conditions) × 6 (repetitions), to equal 144 trials. The practice series was presented in three blocks of 48 trials. Three experimental series then followed. Each series consisted of 2 (targets) × 4 (number of green distractors) × 3 (conditions) × 13 (repetitions), to equal 312 trials. Each series was presented in four blocks, with brief pauses in between.

Results

Correct responses that took longer than 1,100 ms were treated as errors. This accounted for 0.16% of the trials. All remaining RTs for correct responses were used for the calculation of the means for the compatible, incompatible, and control conditions for each of the four different display sizes. Figure 5 shows these means and the corresponding mean numbers of errors.

Mean RTs were analyzed by a 4 × 3 ANOVA, with display size and compatibility as within-participant variables. Only the effect of compatibility was significant, $F(2, 18) = 63.3$, $p < .01$, $MSE = 145$. The effect of display size showed a trend toward significance, $F(3, 27) = 2.82$, $p < .10$, $MSE = 99$, but the interaction of these two variables proved far from significant ($p > .40$). Newman–Keuls post hoc tests showed that participants responded slower in the incompatible condition than in the compatible condition, with RTs in the control condition in between (all *p*s $< .05$). The mean slope of the linear fits for the search functions averaged over conditions was negligible (0.75 ms).

The mean number of errors was analyzed using the same 4 × 3 ANOVA. Only the effect of compatibility proved significant, $F(2, 18) = 10.8$, $p < .01$, $MSE = 19$. Newman–Keuls post hoc tests showed that more errors were made in the incompatible condition than in the other two conditions. Therefore, no speed–accuracy trade-offs were apparent in the data.

Discussion

The results clearly showed that the effect of the experimental elements in the display was independent of the total number of elements in the display. In addition, the experiment provided clear evidence that search among the green elements was very efficient. The results rule out the mistake interpretation because clear compatibility effects were found for distractors that were not located in the vicinity of the target. In addition, these compatibility effects did not decrease with increasing display size. The guess interpretation could not be ruled out completely. Whereas the evidence for an increase in overall RTs was only weak, we did obtain equal congruency effects at all display sizes used, as predicted by this interpretation.

Note that because there was no trace of an interaction between the variables' display size and compatibility, the results strongly corroborate the conclusions drawn in the discussions of Experiments 2 and 4: Even when search among display elements was very efficient, and even if only a proportion of those elements was related to the responses in the experiment, the experimental elements clearly caused compatibility effects. Therefore, this experiment provided additional evidence that, irrespective of the total number of display elements, identity information was extracted from the experimental distractors, contrary to what two-stage models of visual search predict.

Experiment 6

For now, we continue our search for the cause of the increases of the congruency effect and the interference effect with increasing set size as obtained in Experiments 2 and 4. Because the results of Experiment 5 showed that display size per se is most probably not related to the size of these compatibility effects, we examined in Experiment 6 whether these effect sizes were influenced by the distance between targets and experimental distractors. This variable is known to influence the size of compatibility effects in standard flanker tasks (see, e.g., B. A. Eriksen & Eriksen, 1974; Miller, 1991). In Experiments 2 and 4, the distances between the target and the distractors were smaller when larger display sizes were used than when smaller display sizes were used, as a result of our presentation technique in which all neighboring elements were presented equidistant from each other on an imaginary circle. In Experiment 6, we used a constant display size and again both experimental distractors and neutral filler elements. We kept the number of experimental distractors fixed at two and varied their distance to the target. This manipulation allowed us to obtain a clearer view of the role of the distance variable in this type of task.

The guess interpretation again predicts that the size of the compatibility effects should remain constant for the various distances used because the chance that an experimental distractor occurs at a fixed random location remains the same with this manipulation. In contrast, the mistake interpretation predicts decreasing compatibility effects with increasing distances. In addition, to uphold the core assumption of this interpretation (i.e., that attention was directed to the *general area* of the target), it predicts that at some not-too-far-away distance from the target the compatibility effects should vanish.

Method

Participants. Nine students from the Vrije Universiteit took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. Participants were paid about $5 for their cooperation.

Materials. The characteristics of the display were the same as in the previous experiments. However, display size was always nine. To build a

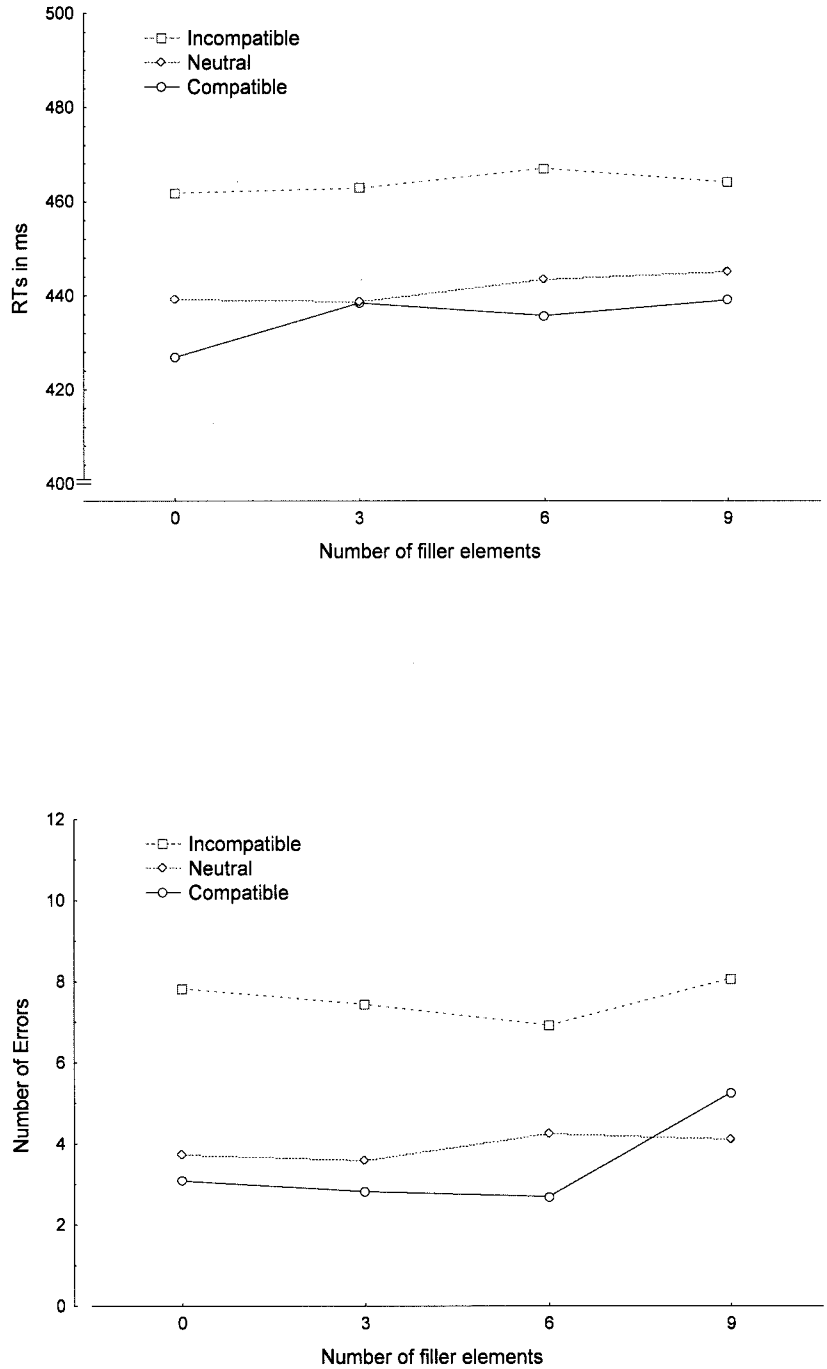


Figure 5. Mean reaction times (RTs) and mean numbers of errors for the incompatible, neutral, and compatible conditions of Experiment 5 for each number of filler elements.

particular display, a target element (either a red *N* or a red *T*) was placed at a random position on an imaginary circle. Eight filler elements (green *S*s) were located in such a way that the distances between neighboring elements were equal. Finally, two experimental elements (green *N*s, *T*s, or *C*s) replaced two filler elements, separated from the target by zero, one, two, or three filler elements. This way, in all displays, two experimental elements were present, but they varied in their location relative to the target.

The experiment was preceded by a practice series in which the experimental elements from the experimental displays were replaced with green letters that were *K*s, *U*s, or *A*s so that none of these distractors were compatible or incompatible with the response.

Apparatus. The apparatus was the same as in the previous experiments.

Procedure. The procedure was the same as in Experiments 2, 4, and 5. The session again started with the presentation of a practice series that consisted of 2 (targets) × 4 (distance of experimental green distractors) × 3 (conditions) × 6 (repetitions), equal to 144 trials. The practice series was presented in two blocks. Then three experimental series followed. Each series consisted of 2 (targets) × 4 (distance of experimental green distractors) × 3 (conditions) × 13 (repetitions), equal to 312 trials. Each series was presented in four blocks, with brief pauses in between.

Results

Correct responses that took longer than 1,100 ms were treated as errors. This accounted for 0.05% of the trials. All remaining RTs for correct responses were used for the calculation of the means for the compatible, incompatible, and control conditions for each of the four different relative distances of the experimental distractor elements to the target. Figure 6 shows these means and the corresponding mean numbers of errors.

Mean RTs were analyzed by a 4 × 3 ANOVA, with the relative distance of the experimental green elements and compatibility as within-participant variables.

The effect of compatibility was significant, $F(2, 16) = 116.2$, $p < .01$, $MSE = 100$. Participants responded slower in the incompatible condition than in the compatible condition, with RTs in the control condition in between. The effect of relative distance was also significant, $F(3, 24) = 4.6$, $p < .05$, $MSE = 86$. Finally, the interaction of these two variables proved significant, $F(6, 48) = 4.8$, $p < .01$, $MSE = 91$. Inspection of Figure 6 shows that this interaction was due to a decrease in RTs for the incompatible condition with increasing relative distance. An analysis of simple effects at the largest relative distance revealed that the effect of compatibility was still significant at this distance, $F(2, 16) = 11.7$, $p < .01$, $MSE = 99$. Newman–Keuls post hoc tests revealed that even at this relative distance, all conditions differed from each other.

In an additional analysis, we examined only the compatible and the control conditions, to evaluate whether the facilitation effect differed for different relative distances. A 4 × 2 ANOVA was performed on the means for these conditions, with the relative distance of the experimental green elements and compatibility as within-participant variables. Only the effect of compatibility was significant, $F(1, 8) = 68.1$, $p < .01$, $MSE = 31$. A clear facilitation effect (mean of 11 ms) was obtained for all relative distances used.

The mean number of errors was analyzed using the same 4 × 3 ANOVA. The effect of compatibility was significant, $F(2, 16) = 50.5$, $p < .01$, $MSE = 10$. The effect of relative distance was also significant, $F(3, 24) = 7.2$, $p < .01$, $MSE = 4$. Finally, the interaction of these two variables proved significant, $F(6, 48) = 3.1$, $p < .05$, $MSE = 8$. Inspection of Figure 6 shows that the error pattern closely resembles the RT pattern. Therefore, no speed–accuracy trade-offs were apparent in the data.

Discussion

The results clearly showed that with an increase in distance to the target, the RTs of the incompatible conditions decreased. These results rule out the guess interpretation because the congruency effects did not remain constant with increasing distance. In addition, the results are also incompatible with the mistake interpretation. Although the interference effect decreased with increasing distance, as predicted, the facilitation effect did not decline. In addition, there remained clear congruency effects for the larger distances, which were not predicted.

Note that because the RTs in both the control condition and the compatible condition remained more or less stable at all relative distances used, the relative distance to the target seems to affect the interference of incompatible elements in a different way than the facilitation of compatible elements. It may also be the case that there was a floor effect on the RTs of the compatible condition that constrained the size of the facilitation effect.

As mentioned earlier, in Experiments 2 and 4 we obtained an increase in RTs for the incompatible condition with an increasing number of green distractors. In those experiments, an increase in the number of green distractors was always accompanied by a decrease in relative distance between the target and the distractors. The results of Experiment 6 showed that the distance variable is clearly related to the size of the compatibility effect.

Experiment 7

In Experiment 5 we varied the number of filler elements and obtained results that ruled out the mistake interpretation. In Experiment 6 we varied the distance of the experimental distractors to the target and obtained results that ruled out the guess interpretation. In the next experiment, we varied the number of experimental distractors, but again used a fixed display size. This allowed us to obtain a clearer view of the role of the number of experimental distractors. Because Experiment 6 showed that the relative distance of the experimental elements to the target is an important variable governing the size of the incompatibility effect, we always presented two experimental elements neighboring the target. We varied the number of compatible and incompatible distractors, by replacing filler elements with various numbers of experimental elements. The guess interpretation predicts that the size of the compatibility effects should increase with increasing number of experimental distractors, because the chance that an experimental distractor occurs at a fixed random location increases with this manipulation. In contrast, the mistake interpretation now predicts equal compatibility effects with an increasing number of experimental distractors because there are always two experimental distractors in the vicinity of the target.

Method

Participants. Nine students from the Vrije Universiteit took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. Participants were paid about $5 for their cooperation.

Materials. The characteristics of the display were the same as in the previous experiments. However, display size was always 13. To build a particular display, a target element (either a red *N* or a red *T*) was placed at a random position on an imaginary circle. Twelve filler elements (green *S*s) were located in such a way that the distances between neighboring elements were equal. Finally, 2, 4, 6, 8, 10, or 12 experimental elements (green *N*s, *T*s, or *C*s) replaced a corresponding number of filler elements, in such a way that the first two were neighbors of the target, the next two were neighbors of the first two, and so on. This way, in all displays, two experimental elements were located at neighboring locations of the target.

The experiment was preceded by a practice series in which the experimental elements from the experimental displays were replaced with green letters that were *K*s, *U*s, or *A*s so that none of these distractors were compatible or incompatible with the response.

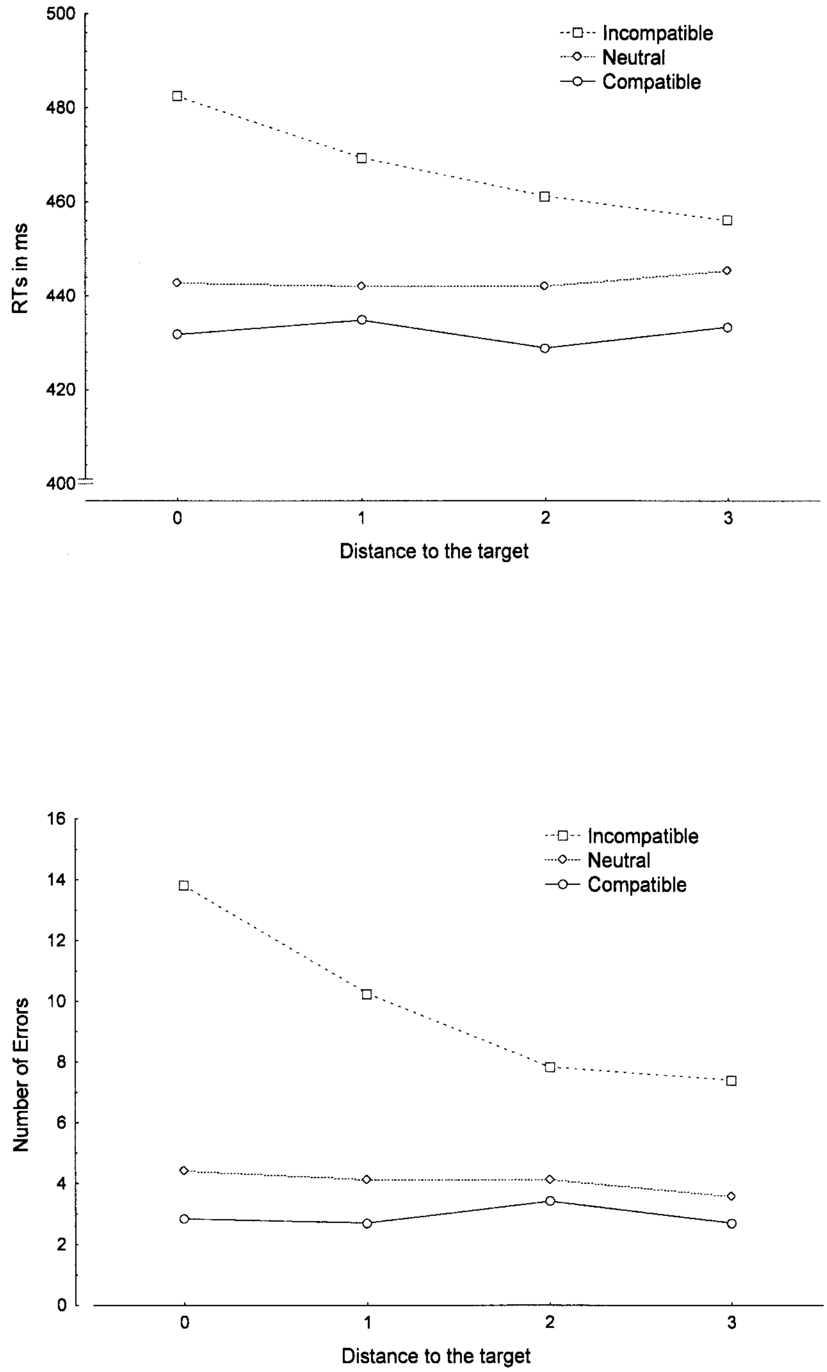


Figure 6. Mean reaction times (RTs) and mean numbers of errors for the incompatible, neutral, and compatible conditions of Experiment 6 for several distances of the experimental distractors to the target. Distance is expressed in number of intervening filler elements.

Apparatus. The apparatus was the same as in the previous experiments.

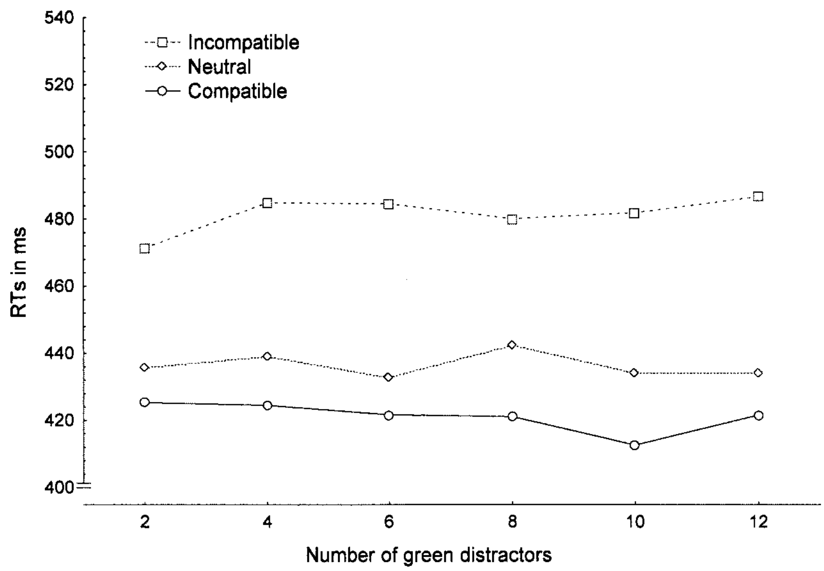
Procedure. The procedure was the same as in Experiments 2, 4, 5, and 6. The session again started with the presentation of a practice series that consisted of 2 (targets) × 6 (number of experimental green distractors) × 3 (conditions) × 4 (repetitions), to equal 144 trials. The practice series was presented in two blocks. Three experimental series then followed. Each series consisted of 2 (targets) × 6 (number of experimental green distractors) × 3 (conditions) × 9 (repetitions), to equal 324 trials. Each series was presented in four blocks, with brief pauses in between.

Results

Correct responses that took longer than 1,100 ms were treated as errors. This accounted for 0.19% of the trials. All remaining RTs for correct responses were used for the calculation of the means for the compatible, incompatible, and control conditions for each of the six different numbers of experimental distractor elements. Figure 7 shows these means and the corresponding mean numbers of errors.

Mean RTs were analyzed by a 6 × 3 ANOVA, with the number of experimental green elements and compatibility as within-participant variables. Only the effect of compatibility was significant, $F(2, 14) = 155.6$, $p < .01$, $MSE = 305$. Newman–Keuls post hoc tests showed that all conditions differed from each other; participants responded slower in the incompatible condition than in the compatible condition, with RTs in the control condition in between (all $ps < .01$).

The mean number of errors was analyzed using the same 6 × 3 ANOVA. Only the effect of compatibility proved significant, $F(2, 14) = 21.5$, $p < .01$, $MSE = 55$. Newman–Keuls post hoc tests



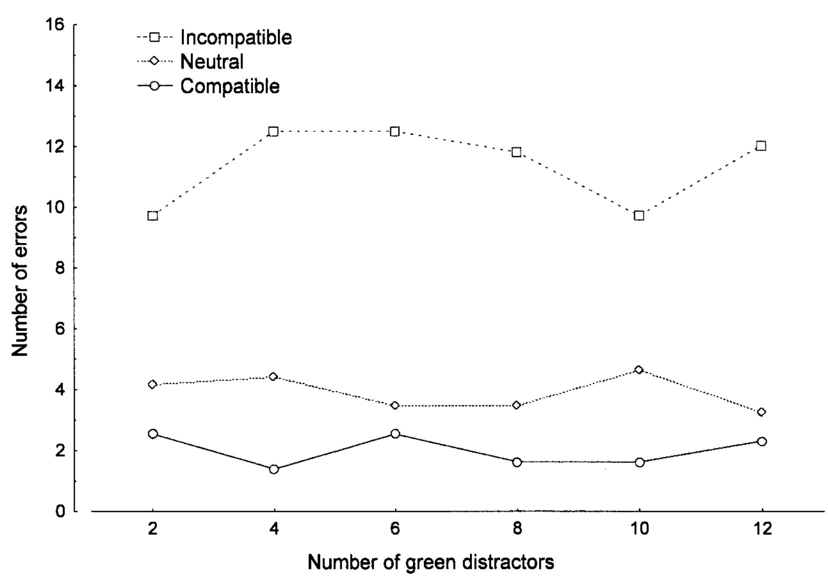


Figure 7. Mean reaction times (RTs) and mean numbers of errors for the incompatible, neutral, and compatible conditions of Experiment 7 for several numbers of experimental distractors.

showed that more errors were made in the incompatible condition than in the other two conditions.

Discussion

The results clearly showed that the effect of the number of experimental distractors in the display did not influence the size of the compatibility effects when there were always two experimental distractors neighboring the target. This is again strong evidence against the guess hypothesis. The mistake hypothesis is compatible with these results but was already discarded earlier.

The results of Experiments 5, 6, and 7 taken together allow us to conclude that the increases in RTs of the incompatible condition with increasing numbers of distractors obtained in Experiments 2 and 4 were not caused by the occasional identification of a distractor element before the target was found. The increase must most likely be attributed to the fact that in these experiments the distance of the closest distractor to the target decreased with increasing set size. In addition, the results of these experiments showed that the obtained compatibility effects could not be accounted for by either the guess interpretation or the mistake interpretation.

Identification of distractors after identification of the target. According to the posttarget-processing interpretation, a distractor might influence the RT to the target when it is identified after the identification of the target has taken place but before response selection has finished. This interpretation might account for all compatibility effects obtained while it still adheres to the principles of two-stage theories of visual search (i.e., only one item is identified at a time). Although such an interpretation was not part of the original two-stage theories of visual search (e.g., Treisman & Gelade, 1980; Wolfe, 1994), a similar idea was recently put forward by Wolfe et al. (2000). These authors presented an assembly line analogy to visual processing. They proposed that during visual processing one selected item could enter a visual processing assembly line, say, every 50 ms. In that way, although items entered the assembly line one by one, several items could be worked on by various visual processes at the same time. The amount of 50 ms was taken to reflect the time it took visual attention to select an item for further processing. According to this proposal, search slopes indicate the rates that items can move through the system, or, put in other words, the rate at which the line can be fed with new items. This assembly line analogy thus illustrates how a distractor element might be processed after the target has been selected. The idea that a distractor element might have entered the assembly line after the target was tested in the next experiment, simply by preventing the distractors from entering the line.

To prevent the distractors from entering the assembly line after the target has entered it, we presented the distractors for a very short time and then masked them. Pilot work showed that if distractors were presented for only 33 ms, they were able to cause clear compatibility effects in a feature-search paradigm (see Experiment 2). Such a feature-search task, however, has the disadvantage of not knowing exactly how much time it took for the target element to enter the assembly line. If this took, for example, 50 ms,[2] then distractors should not have been able to enter the assembly line after the target, and clear evidence against this idea would have been found. However, if the target entered the assembly line in say 20 ms, then another 13 ms would have been left for a distractor element to enter the line. Therefore these results, although indicative, were not conclusive. To be sure that distractors did not enter the line, we needed accurate estimates of the mean time it took until the target element had entered the assembly line. Fortunately, these estimates can be obtained by using the conjunction-search paradigm of Experiment 1, in which participants had to search for a target in a specified color among a subset of elements from the same color. For each target-color subset, the estimate is simply the slope for the search function among the target-colored elements multiplied by the number of elements in the subset.

Experiment 8

In the present experiment, the paradigm used was a variant of the one used in Experiment 3. We again presented the target-color subset for the full 200 ms, but now presented the different-color experimental distractors that were compatible, incompatible, or neutral for only 33 ms. The different-color experimental distractors were then masked to block access to their representations in iconic memory. As stated previously, this paradigm allowed us to estimate the mean target search time. Prediction of the posttarget-processing interpretation is clear: With increasing mean target search time, the experimental distractors are less and less likely to have entered the assembly line after the target, so compatibility effects should decrease quickly. In contrast, if all elements in the display are processed in parallel, masking them should not make much of a difference (although a certain minimum exposure duration to identify the elements is, of course, necessary). To make sure that the specific color in which the target-color subset was presented did not cause the results, half of the participants searched a red subset, and the other half searched a green subset.

Method

Participants. Eight participants from the Vrije Universiteit took part in the experiment. All had normal or corrected-to-normal vision and no reported color blindness. They were unaware of the purpose of the experiment. They were paid about $5 for their cooperation.

Materials and apparatus. The apparatus was the same as in Experiment 1. The displays had the same properties as in Experiment 3, with the following changes.

The target letter was either a capital *N* or a capital *T*. There were two types of distractors: target-color elements (i.e., distractors with the same color as the target) and different-color distractors (i.e., distractors with a different color as the target). The target-color elements were randomly chosen from the set *A, B, E, G, H, K, R, S, U, Z,* and the number of these elements was 1, 2, 4, or 6. The different-color distractors could be compatible, incompatible, or neutral with respect to the target. They could be

[2] An estimate of 50 ms seems reasonable, given the fact that in Experiments 1 and 3 we obtained search slopes for search among the target-color subsets of about 25 ms per item. Thus, when two elements are added to the display, mean RT to find the target increases by twice the slope (i.e., 50 ms). However, on average, only one of these two elements needs to be searched in order to find the target because, on average, the target is found after considering half of the items of the target-color subset. It follows that the processing time necessary to select a single element equals twice the slope of the search function.

small letter *t*s, *n*s, or *c*s, and the number of these distractors was 2, 4, or 6. Numbers of target-color elements and different-color distractors were factorially combined to yield 12 different display constitutions ranging from 4 display elements (2 different-color distractors, 1 target-color element and 1 target) to 13 display elements (6 different-color distractors, 6 target-color elements, and 1 target). Half of the participants were presented with a red target-color subset (and green different-color distractors), whereas the other half were presented with a green target-color subset (and red different-color distractors).

Procedure. Participants began each trial by fixating on a central fixation dot. After 700 ms, the search display was presented on a black background. After 33 ms, only the different-color distractors were replaced by a mask of the same color (a # sign). The resulting display remained on the screen for another 167 ms.

Half of the participants pressed the *Z* key when the target was an *N* and the *slash* key when the target was a *T*. For the other half of the participants, the response mapping was reversed. Each participant received 144 practice trials, followed by 20 experimental blocks. Each block comprised 72 trials. There was a total of 1,440 experimental trials consisting of 2 (targets) $\times$ 4 (same-color elements) $\times$ 3 (different-color distractors) $\times$ 3 (conditions) $\times$ 20 (repetitions).

Results

RTs from incorrect response trials and correct responses longer than 1,100 ms were excluded from the analysis. This accounted for 7.3% and 1.0% of the data, respectively. Figure 8 shows the means for the compatible and incompatible conditions for each number of target-color elements (within a graph) and for each number of different-color distractors (between graphs) as well as the corresponding mean numbers of errors.

A 3 $\times$ 4 $\times$ 3 ANOVA was performed, with the number of different-color distractors, the number of target-color elements, and compatibility as within-participant variables. The effect of the number of target-color elements was significant, $F(3, 21) = 106.7$, $p < .01$, $MSE = 1{,}393$. The effect of the number of different-color distractors was also significant, $F(2, 14) = 8.3$, $p < .05$, $MSE =$ 474. The effect of compatibility was significant, $F(2, 14) = 20.6$, $p < .01$, $MSE = 375$. The mean size of the congruency effect was 17.3 ms. Newman–Keuls post hoc analyses showed that participants responded slower in the incompatible condition than in both the compatible condition and the control condition (both *p*s $< .01$). The compatible and control conditions did not differ from each other. Finally, the interaction between the number of different-color distractors and compatibility approached significance, $F(4, 28) = 2.4$, $p < .10$, $MSE = 363$.

As in Experiment 1, we calculated the slopes for the participants' search functions for search among the target-color elements and the different-color distractors. For the target-color elements, the average slope of the linear fits was 20.4 ms per item. For the different-color distractors, the average slope of the linear fits was 3.0 ms per item. The average slope of the linear fits for only the incompatible condition for these different-color distractors was 6.0 ms.

The same ANOVA as was performed on the RT data was performed on the number of errors. There was only an effect of the number of target-color elements, $F(3, 21) = 13.1$, $p < .01$, $MSE =$ 114.8. Therefore, no speed–accuracy trade-offs were apparent in the data.

Discussion

The results of the present experiment replicated those of Experiment 3. The mean slope of the search function for the number of different-color distractors was only 3.0 ms. This small number is generally taken to reflect that the corresponding elements were only processed preattentively (e.g., Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Enns & Rensink, 1990; Treisman & Gormican, 1988). Also, the slope for the search function among the target-color elements was 20.4 ms. This finding is generally interpreted as showing inefficient serial search (e.g., Horowitz & Wolfe, 1998). In addition, clear compatibility effects were obtained in all relevant cells of the design.

The most important findings of the experiment were that (a) the compatibility effects were obtained with an exposure duration of the different-color distractors of only 33 ms and (b) the size of the compatibility effect did not differ for the various levels of the target-color set sizes, as was apparent from the nonsignificant interaction between the number of target-color elements and compatibility. Because the search slope for the subset of target-color elements was 20.4 ms per item, it can be estimated that, for example, the mean time to find a target in a search set of seven would have been about 143 ms. At that point in time, the green distractors were long replaced by masks, so it would be impossible for them to enter the visual processing assembly line. Therefore, the posttarget-processing interpretation can be ruled out to explain the obtained compatibility effects. In contrast, the results are fully compatible with the assumption that all elements of the display were processed in parallel.

General Discussion

In the first four experiments, we showed that increases in the number of green distractor elements caused negligible increases in RTs to find the target. Nevertheless, these distractors caused clear compatibility effects: When the green elements had the same identity as the target letter, responses were faster than when the green elements had the identity of the other potential target. In Experiment 1, we used a variant of the classic conjunction search task. In this variant, participants looked for a red target among red and green distractors. In the experiment, participants were able to successfully limit their searches to the target-color subset. Still, we obtained a clear effect of the compatibility of the green elements. In Experiment 2, we showed that in a variant of a feature search task, participants were able to find one red target among green distractors quickly and efficiently. Again, the identities of the green distractors caused clear compatibility effects.

In Experiments 1 and 2, the red target and the green distractors were identical in form (all were capital letters). If in these experiments selection of the target element was in any way guided by form-based templates, then the green distractors might have influenced target processing because they also matched these templates. However, Experiments 3, 4, and 8 replicated the findings of Experiments 1 and 2 using the same red capital letter targets but green distractors that consisted of small letters. These results dismiss an explanation of the obtained compatibility effects in terms of form-based templates.

Experiments 4 to 6 showed that an interpretation in which it is assumed that occasionally a distractor item was identified before

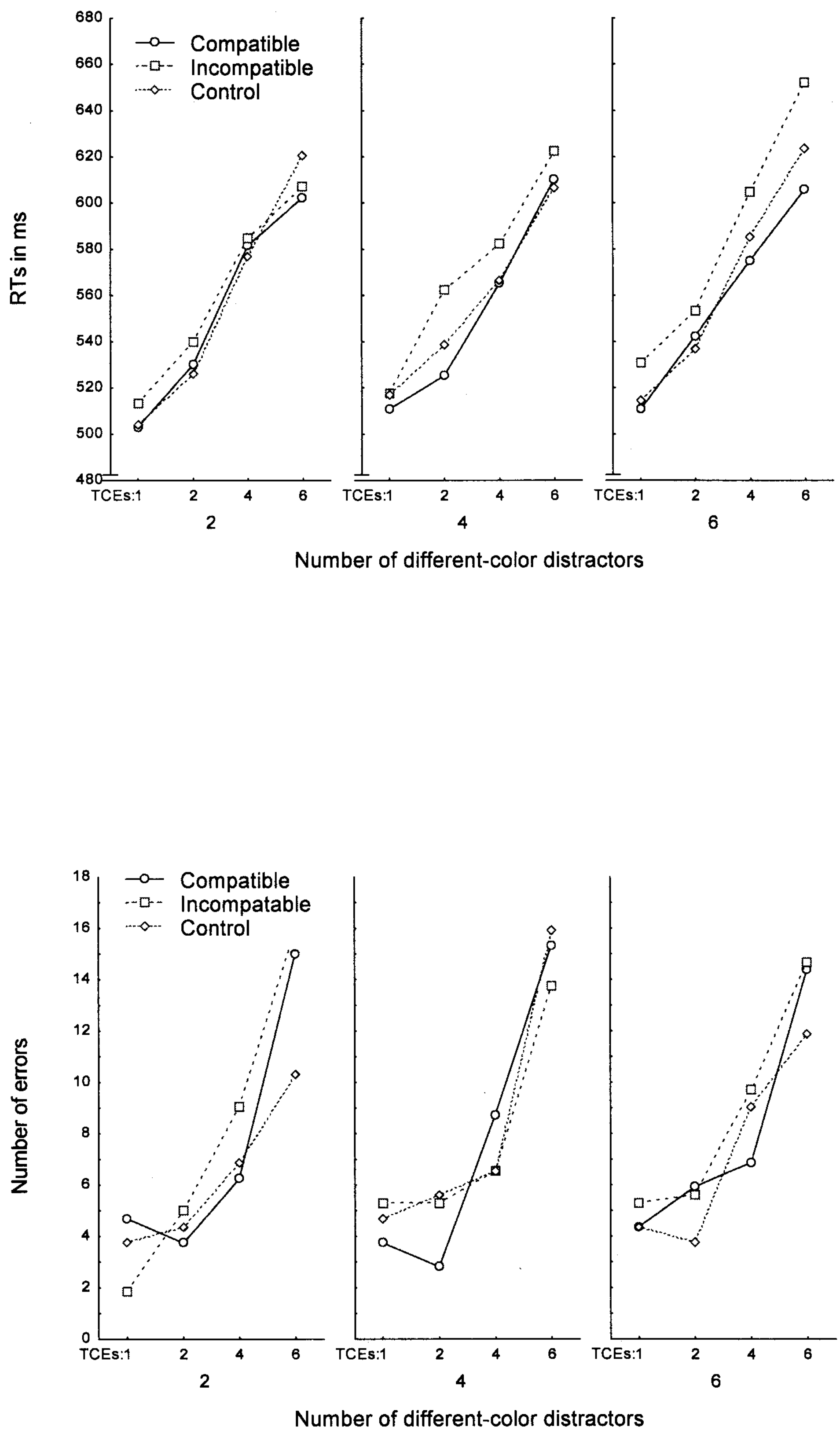


Figure 8. Mean reaction times (RTs) and mean numbers of errors for the incompatible, neutral, and compatible conditions of Experiment 8 for each number of target-color elements (TCEs; within a graph) and for each number of different-color distractors (between graphs).

the identification of the target cannot account for the results. In these experiments, we also showed that in the visual search experiments used here, the relative distance of the experimental distractor elements to the target is of crucial importance in determining the size of the compatibility effect, not their number. Finally, Experiment 8 showed that a very brief presentation duration of the experimental distractors (33 ms) still sufficed to produce reliable compatibility effects.

Compatibility Effects and Models of Visual Search

Can two-stage theories (feature integration theory: Treisman & Gelade, 1980; revised feature integration theory: Treisman, 1999; Treisman & Sato, 1990; and guided search: Wolfe, 1994; Wolfe et al., 1989) explain the compatibility effects induced by our experimental distractors? In the introduction we argued that according to two-stage models of visual search, visual attention is necessary in order to compute the identity of a display element when this identity is based on a conjunction of basic features (like colors, curvatures, and orientations). Treisman (1999), for example, argued that "attention is needed to bind features together, and that without attention, the only information recorded is the presence of separate parts and properties" (pp. 107–108). As a logical necessity, the occurrence of compatibility effects implies that the identity of the distractors was computed. Therefore, two-stage models of visual search make the strong prediction that without visual attention being deployed to them, distractors cannot cause compatibility effects.

The question then becomes whether in our present experiments attention was deployed to the distractors. Generally, search slopes smaller than 10 ms per display element are interpreted as indicative of parallel search among those elements; that is, it is assumed that visual attention was not deployed to these elements (e.g., Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Enns & Rensink, 1990; Treisman & Gormican, 1988; Wolfe et al., 1989). In our experiments, the search slopes for the green distractors were all well below 10 ms. For example, in Experiment 1, the mean search slope for search among the green distractors was 5.6 ms. In addition, the largest slopes obtained in Experiments 2 and 4, for the incompatible condition, were still very small (4.5 and 3.9 ms, respectively). Furthermore, the results of Experiments 5, 6, and 7 indicate that these latter slopes should not be attributed to the variable set size, but to the variable target–distractor distance. Finally, we obtained essentially flat search functions in the control and compatible conditions of our experiments. Therefore, in terms of two-stage models of visual attention, the present results strongly suggest that in none of our experiments was visual attention deployed to the green elements.

In addition, we examined two alternative interpretations of our results in terms of the processing of a distractor element before the target item was processed. According to the mistake interpretation, occasionally a distractor element in the general area of the target might mistakenly have been attended before the target was attended. Experiment 5 showed that when filler items were added to the display, and these items were located in a region near the target, there was no decrease in the obtained compatibility effects, as would be expected according to this hypothesis. In addition, Experiment 6 showed that when experimental distractor elements were located far away from the general area of the target, clear congruency effects for these large distances remained. These results cannot be explained by this interpretation.

According to the guess interpretation, participants sometimes guessed the upcoming location of the target and had already focused their attention on that location. If it happened that a distractor element was presented at that location, it would be identified and cause the obtained compatibility effects. Experiment 6 provided clear evidence against this view. With only two experimental distractors present in a display that was filled with one target and a constant number of filler elements, every location in the visual field has the same chance of containing an experimental distractor element. Therefore, the guess interpretation clearly predicts no effect of the distance of the experimental distractors to the target on the size of the compatibility effect, whereas we obtained a clear interaction of these variables. In addition, Experiment 7 showed that an increase in the number of experimental distractors did not lead to a predicted increase in the size of the compatibility effect. Taken together, both the mistake interpretation and the guess interpretation can be ruled out by the results of these experiments.

Finally, we examined an alternative interpretation of our results in terms of the processing of a distractor element after the target item has been found. According to the posttarget-processing hypothesis, a distractor element might be processed after identification of the target had started but before response selection had occurred (see, e.g., Wolfe et al., 2000). In Experiment 8, we showed that this view could be rejected because we obtained clear compatibility effects in an experiment in which the experimental distractors were presented very briefly, and, therefore, their ability to be processed after the processing of the target element was essentially prohibited.

As a result of these analyses, we conclude that two-stage models of visual search cannot account for the compatibility effects we obtained. However, if these models are modified to allow that in the second stage attention is not only deployed to the target but also spills over to elements surrounding it, these models can accommodate for most of the present results because in that case the identity of the distractors could be computed (for similar proposals, see, e.g., Chastain, Cheal, & Lyon, 1996; Johnston & Dark, 1986; Schmidt & Dark, 1998). It should be noted though that in order to explain the occurrence of a congruency effect in Experiment 6 at the largest distance used (the target at one side of the circle, two experimental distractors at the opposite side), the spilling over of attention has to include the complete stimulus as we presented it. This essentially renders a type of parallel model.

Can parallel models explain our present results? Limited-capacity parallel models assume that all elements in the visual field are compared with a target representation concurrently (e.g., McElree & Carrasco, 1999; Murdock, 1971; Rumelhart, 1970; Shaw & Shaw, 1977; Townsend & Ashby, 1983; see also Miller, 1987; Shiffrin, Diller, & Cohen, 1996). This means that (partial) information about the identity of the distractors is available in these models. To explain the effects of compatibility as found in this study, these models have to assume that the results of the comparison processes are able to further influence the response production processes. Confusability models (e.g., Kinchla, 1974; Palmer et al., 1993) may account for the present results in a similar vein. Finally, also, the neural network model of Humphreys and Müller (1993) computes the identity of the distractors. Although, at present, the model does not specify what happens with these identities once they have been computed, it is plausible that the model might be extended to produce compatibility effects based on the already computed identities.

However, to explain the distance effects obtained in our experiments, parallel models also have to make the additional assumption that although all elements of the display are processed (in order to explain the occurrence of a congruency effect in Experiment 6 at the largest distance used), a preferential treatment is given to the processing of elements in a region around the target, with the amount of preference decreasing with increasing distance to the target. Note that the resulting parallel visual search model is very similar to the modified two-stage model that we derived earlier in which attention spills over to the complete stimulus. Also note that distance effects have been reported for the standard flanker task (e.g., B. A. Eriksen & Eriksen, 1974; Goolkasian & Tarantino, 1999; Miller 1991). In that domain, several types of space-based theories of visual attention have been proposed to explain these effects along the lines sketched previously (e.g., C. W. Eriksen & St. James, 1986; Jonides, 1983; LaBerge, 1983). Similar theories have also been developed based on the results of cuing studies (e.g., Downing, 1988; Downing & Pinker, 1985; Henderson & Macquistan, 1993), dual-task studies (LaBerge & Brown, 1989), and event-related potential studies (e.g., Mangun & Hillyard, 1988).

Finally, the present results allow a general conclusion with respect to the interpretation of flat search slopes in visual search. In Experiments 2, 4, and 5 (see Figures 2, 4, and 5), our set-size manipulation produced essentially flat search slopes, especially for the neutral and compatible conditions. However, because we also obtained clear facilitation effects (compatible vs. neutral) and congruency effects (compatible vs. incompatible), we conclude that although flat search slopes are indicative of efficient search (this is merely a theory free description of the data; see, e.g., Wolfe, 1998), such slopes need not be indicative of the successful preclusion of identity information extraction from distracting elements.

An Explanation of Compatibility Effects in Visual Search

Many researchers share the idea that response selection processes are responsible for the bulk of the compatibility effect in the standard flanker task (e.g., Cohen & Magen, 1999; Cohen & Shoup, 1997; B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Schultz, 1979; Grice & Gwynne, 1985; Miller, 1991). In addition, psychophysiological measures obtained with standard flanker tasks even indicate the activation of the motor cortex associated with the response based on the identity of the flankers (e.g., Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; C. W. Eriksen, Coles, Morris, & O'Hara, 1985; Gratton, Coles, & Donchin, 1992; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Smid, Mulder, & Mulder, 1990).

This idea can easily be generalized to explain our compatibility effects obtained in visual search tasks. The effects may have come about as follows: All elements in the visual field were processed up to a level in which they were able to activate their associated response. When these elements were incompatible, they activated an incorrect response. As a result, response competition arose between the response activated by the target and the response activated by the distractors. The resolution of the response competition caused the increase in RT for the incompatible distractors relative to the compatible and control distractors. Neutral distractors did not activate a response, so no response competition arose in the neutral condition. Finally, compatible distractors provided additional activation of the correct response to the target, facilitating responding as compared with the neutral distractors.

Note that in order to activate their associated response, the identities of the distractors should have been computed.[3] Also note that the classic feature search and conjunction search results that inspired the development of two-stage theories of visual search are not in conflict with this view. The classic results were obtained in situations in which neutral distractors were used, so response competition was most probably minimal in these experiments.

Finally, we discuss the role of the variable perceptual load on the size of the obtained compatibility effects.

Compatibility Effects and Perceptual Load

Using a variant of the classic Stroop task (Stroop, 1935), Kahneman and Chajczyk (1983) showed that with increasing perceptual load, the effect of color words on naming the color of a color patch decreased. Lavie (1995) addressed this issue with respect to the flanker task and argued that compatibility effects should decrease with increasing perceptual load. She argued that compatibility effects arise whenever the visual processing load necessary to detect a target did not deplete attentional resources. In such cases, leftover resources spill over to the processing of irrelevant display elements, whose processing might then produce compatibility effects in flankerlike tasks. However, in situations characterized by a high visual processing load, no compatibility effects should be obtained. Lavie reported results that were compatible with this view. However, in the experiments reported by Lavie, the manipulations used to increase perceptual load also increased the mean RT to the targets. It could well be that because of this increase in target processing time, the possible interfering influence of a distractor element had already ceased to exist by the time the response to the target element was selected (see also Miller, 1991). The results of the present Experiments 2, 4, and 5 showed that increase of perceptual load did not affect RT much. Therefore, the present results seem to provide a fairer test of Lavie's claims.

In Experiments 2 and 4, perceptual load increased from processing 3 elements to processing 13 elements. This increase in perceptual load did not lead to a decrease in the congruency effects obtained. In contrast, the congruency effects increased by increasing perceptual load. As argued previously, this increase was most

[3] We think it is highly unlikely that the obtained compatibility effects were directly based upon featural information. If this were the case, then the effects obtained with small-letter distractors should have been much smaller than the effects obtained with capital-letter distractors because of the very small featural overlap of the small letters with the corresponding capital letters. However, our results showed that the congruency effects obtained with small letters and capital letters were the same size (mean congruency effects were 29 ms in Experiment 3 and 29 ms in Experiment 1, respectively; 45 ms in Experiment 4 and 44 ms in Experiment 2, respectively).

probably due to a decrease of distance between the target and the distractors with increasing display size. The results of Experiment 5 do not suffer from this confound. As in Experiments 2 and 4, in Experiment 5 we increased the perceptual load from processing 3 display elements to processing 13 elements. However, in this experiment the increase in display size was accomplished by adding filler elements not associated to a response. The increase in perceptual load caused by the adding of the filler elements produced no corresponding increases of the RTs to detect a target. The results further showed no effect of the increase of perceptual load on the size of the compatibility effects, as was apparent from the lack of an interaction between the variables' display size and compatibility. These results do not seem compatible with Lavie's (1995) reasoning.

In addition, in Experiments 1, 3, and 8 we increased the display size by increasing both the number of possible target elements (the target-color elements) and the number of different-color elements. Increasing the number of target-color elements had the additional consequence of increasing the difficulty of the task. The resulting increase in perceptual load produced marked increases of the RTs to detect the target (about 100 ms, 80 ms, and 103 ms from smallest display sizes to largest display sizes in Experiments 1, 3, and 8, respectively). However, also in these experiments, increasing perceptual load failed to influence the size of the obtained compatibility effects, as was apparent from the lack of second-order interactions between the variables' number of target-color elements and compatibility and the variables' number of different-color elements and compatibility, as well as the lack of a third-order interaction between the variables' number of target-color elements, number of different-color elements, and compatibility. Again, these results are not compatible with Lavie's (1995) results.

What might have caused these differences in results? One characteristic of Lavie's (1995) and Lavie and Cox's (1997) experiments was that distractors appeared at locations at which targets were never displayed. However, in the present experiments, distractors were displayed at locations at which targets could also be displayed. This variable might play a crucial role, and further research is needed to explore it.

Conclusions

In conclusion, the present experiments showed that flat search slopes obtained in visual search experiments need not be indicative of a visual attention mechanism that is able to selectively exclude processing of irrelevant elements in the display. In contrast, the results showed that during straightforward visual search tasks, irrelevant distractor elements among which search was efficient clearly influenced the response selection process. These results are incompatible with two-stage theories of visual search (e.g., Treisman, 1999; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994; Wolfe et al., 1989; see also Wolfe et al., 2000).

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