What influences visual search efficiency? Disentangling contributions of preattentive and postattentive processes

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The present experiments introduce a new search technique for disentangling contributions of preattentive guidance and postattentive template matching to search efficiency. Participants performed searches (for negative or positive faces in Experiment 1; pop-out search in Experiment 2; conjunction search in Experiment 3) under either standard viewing conditions or a new restricted viewing condition in which items were occluded by black placeholders and revealed only when a participant moved the mouse pointer over the black square. Under full viewing conditions, search performance can be aided by both preattentive and postattentive mechanisms, whereas the mouse-contingent search relies solely on postattentive template-matching processes. Results demonstrate the utility of this new methodology for distinguishing contributions of preattentive guidance and postattentive template-matching processes in ambiguous search situations. Furthermore, application of the new restricting viewing method to search for emotionally expressive faces suggested that emotional information is processed preattentively and influences the allocation of focal attention.

Visual search is a common, everyday activity. Indeed, the act of searching only becomes salient to us when search is difficult, thus requiring effort and time for us to find the object of our search. Other times, we do not even notice that we have searched, because the object we are looking for just “pops out” of its surroundings. Understanding the basic mechanisms that underlie visual search has been a focus of considerable research (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe, 1994). Perhaps the most dominant view that has emerged from laboratory studies is that the efficiency of visual search depends on two distinct yet interrelated processes—namely, (1) *preattentive processing*, which is the processing of objects prior to attentional selection (i.e., unattended objects), and (2) *postattentive processing*, which is the processing of objects within the focus of attention (i.e., attended objects). Search performance is typically thought to be determined by some combination of these two processes and, as such, in many search situations, it has proven difficult to isolate the distinct contributions of the two processes.

In the present article, we develop a new methodology designed to separate the contribution of preattentive and postattentive processes during search. This procedure extends the moving-window technique developed in studies of reading (McConkie & Rayner, 1975; Rayner, 1995, 1998) and visual search (Gilchrist, North, & Hood, 2001; Thomas et al., 2006; van Diepen & d’Ydewalle, 2003). Specifically, we compared performance in a standard visual search task in which target and distractors were presented simultaneously in full view, with performance in a modified visual-search task, in which the search items were occluded by black squares and participants had to move the mouse pointer over the black square to reveal the object underneath. To illustrate the utility of this methodology, we applied the procedure in a context in which the relative contributions of preattentive guidance and postattentive processing have been contentious—namely, search for faces expressing positive and negative emotions. To further explore the boundary conditions of the novel methodology, we also applied it to a simple feature search, as well as an inefficient conjunction search.

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Measuring the Mechanisms Underlying Visual Search

In the laboratory, the mechanisms underlying visual search have been examined using a variety of different search tasks. In a typical search task, participants are shown displays consisting of a target item embedded among a varying number of distractor items. Their task is to find the target as fast and as accurately as possible. By varying the number of distractors in the display (i.e., set size), it is possible to plot a search function relating the time to detect a target to the number of items in the display.

The slopes of search functions have played a central role in theories of visual search. In the context of *feature integration theory* (Treisman, 1988, 1991; Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977), the slopes of search functions were used as direct indices of whether search was done preattentively or whether it required attention. Preattentive search was characterized by near flat search functions, whereas search requiring attention was characterized by steeper search slopes with response times (RTs) increasing as set size increased. A critical prediction from this framework is that, across many studies, a frequency distribution should be bimodal with a high frequency of slopes near 0 msec/item, reflecting preattentive search, and a high frequency of steep search slopes reflecting attentive search (see Wolfe, 1998). However, extensive analysis revealed that search slopes are continuous from flat to steep, with no evidence for a strict dichotomy (Wolfe, 1998). This finding suggests that search slopes are likely determined by both preattentive and postattentive search processes; therefore, absolute search slopes can not be used as direct indices of preattentive and postattentive processes. Clearly, therefore, a method is needed that can separate the contributions of preattentive and postattentive processes in visual search.

A promising approach for separating the contributions of preattentive and postattentive processes comes from studies of reading (McConkie & Rayner, 1975; Rayner, 1995, 1998). McConkie and Rayner developed a *moving-window technique* to evaluate the roles of attended and unattended information on reading. These studies involved a comparison of reading performance across two conditions. In one condition, participants were required to read printed text presented in full view. In the second condition, participants again read text, but were only able to see the words in a predetermined window spanning a few characters on either side of fixation. Any letters outside of this window were replaced with placeholders (e.g., the letter "x"). The movement of the window was contingent on the participant's fixation on the text. Eliminating information outside of the moving window effectively removes the influence of peripheral (i.e., unattended) information on performance. By comparing reading in the full-view and moving-window conditions, it was possible to evaluate the specific contribution of peripheral information on performance. In the case of reading, eliminating information on either side of a fixated word reduces reading speed, and eliminating information on the right of a fixated word seems to affect reading much more than remov-

ing information on the left side of fixation (see Findlay & Gilchrist, 2003; Rayner, 1995, for reviews).

Variants of the moving-window technique have also been applied to studies of visual search to evaluate various processes that underlie search (Gilchrist et al., 2001; Thomas et al., 2006; van Diepen & d'Ydewalle, 2003). For instance, van Diepen and d'Ydewalle had participants search visual scenes while presenting either a foveal or a peripheral mask that was contingent on eye fixations. The results showed that peripheral masking influenced search by increasing the number of fixations on a given trial and reduced the amplitudes of eye saccades. Thomas et al. had participants search for fruit that was occluded by leaves in a virtual reality setting. Participants were required to point a virtual wand at the leaves to reveal what was behind them. Thomas et al. used this methodology to demonstrate that inhibition of return (IOR; Posner, Rafal, Choate, & Vaughan, 1985) facilitates search in such virtual foraging tasks. In a more real-world variant of the moving-window technique, Gilchrist et al. had participants move through a room to check a varying number of film canisters for one containing a marble. Consistent with previous studies of serial search on computer displays, the results showed that search times increased linearly with set size and that the slope of the search function for target-absent trials was twice that of the search function for target-present trials.

In the present article, we applied the moving-window technique in the context of visual search to distinguish between the contributions of attended and unattended information to the efficiency of visual search. To reduce the dependency of the method on eye-tracking technology, we modified the moving-window technique by making the movement of the window contingent on the movement of a computer mouse. Thus, we compared search when all items were in full view with search when all items were occluded, except for the item currently beneath the mouse pointer. To demonstrate the utility of this methodology, we first applied it to a search context in which the contributions of preattentive and postattentive processes are contentious. Specifically, we evaluated the role of attended and unattended information in search for faces expressing positive and negative emotions (Experiments 1A and 1B). We further explored the boundary conditions of the methodology by applying it to both preattentive feature search (Experiments 2A and 2B) and postattentive conjunction search (Experiments 3A and 3B).

Visual Search for Emotionally Expressive Faces

The affective valence of another's facial expression can signal specific social outcomes for the observer. For example, a smiling face might suggest the possibility of a positive encounter, whereas a threatening expression might indicate hostility toward the observer, and therefore potential harm. In order to successfully navigate social situations, an attentional bias for detecting the emotion of facial expressions would be of considerable adaptive value. Consistent with this idea, recent studies have found evidence that the emotional valence of faces can influence the allocation of attention (e.g., Eastwood, Smilek, & Merikle, 2001; Fox et al., 2000; Hansen & Hansen, 1988;

Öhman, Lundqvist, & Esteves, 2001). For example, Eastwood et al. (2001) presented a visual-search display with varying numbers of schematic faces. One of the faces in the display had either a negative¹ or positive expression, whereas the remaining distractor faces had a neutral expression. Participants were required to localize the unique target face as quickly as possible. Eastwood et al. (2001) measured the time that was taken to locate the target as a function of set size so that it was possible to plot the search functions associated with localizing the positive and negative faces. The results of the experiment showed that the slope of the search function for negative faces was shallower than that for positive expressions. On the basis of these findings, Eastwood et al. (2001) concluded that in their particular experimental context, faces with negative expressions were more efficiently located than those with positive faces. This result suggests the more general conclusion that the emotional expression of a target face can influence search efficiency.

What are the cognitive mechanisms that might account for differential search efficiency for positive and negative faces? Common interpretations of visual search would suggest that when the distractor context is held constant (i.e., faces with neutral expressions) and participants do not know whether to expect a positive or negative target face on any given trial, a comparison of the slopes of the search functions for the positive and negative faces can indicate whether positive and negative faces differ in their ability to guide attention (see Wolfe, 1994).² Hence, we have argued (Eastwood et al., 2001) that differential search efficiencies (under the experimental parameters described above) are the result of cognitive mechanisms that operate before the target faces are attended; that is, before they are within the focus of attention. In other words, the differential search efficiency for emotionally expressive faces is the result of preattentive guidance of attention.

However, the difference in search efficiency for detecting positive and negative faces could also be explained in terms of postattentive mechanisms. That is, the difference in search slopes could be due to a differential bias in responding to positive and negative faces once the faces have been attended and are within the focus of attention. Once an item in the display is within the focus of attention, the observer must compare it with a search template in order to determine whether the display item is a target. Because there are two possible targets (positive face or negative face) in the present context, observers have to maintain two templates in visual short-term memory and must compare the attended display item against each of the two templates. It is possible that observers first search the whole display for a match to the negative target template and then search the whole display for a match to the positive target template. If this were indeed the case, the negative target face would be located more efficiently than the positive target face (i.e., shallower search slopes would be obtained for the negative target face than for the positive target face) without positive and negative faces differentially guiding attention.

Another possible explanation in terms of postattentive mechanisms is that observers sometimes miss identify-

ing a unique positive and negative face as a target when comparing it with its associated templates or search images, and then continue to sample items from the display until returning to the unique target face. If observers were more likely to miss identifying the positive rather than the negative target face, then once again, such a process would result in differential search efficiency for positive and negative target faces, which was not the result of differential guidance of attention.³

The Present Experiments

In Experiment 1, we applied a new methodology to disentangle the possible accounts of the differential search efficiencies for positive and negative targets—namely, an account based on the preattentive process of attentional guidance versus the two accounts based on the postattentive process of template matching. Specifically, we sought to empirically test the assumption that more efficient search for negative faces results from the guidance of attention by unattended information, as proposed by Eastwood et al. (2001), or whether it reflects a process that occurs after the target faces are attended. To adjudicate between these two views, we compared search for affective faces in a standard visual-search task, in which the target and distractor faces were presented simultaneously in full view (Experiment 1A) with search for the affective faces in a modified visual-search task, in which the search items were occluded by black squares and participants had to move the mouse pointer over the black square to reveal the face underneath (Experiment 1B). By occluding all search items except for the one underneath the mouse pointer, we could be certain that no information in the unattended parts of the display was guiding attention.

We reasoned that if negative faces are processed while they are still outside the focus of attention and subsequently guide focal attention to themselves, then a difference in the search slopes for identifying positive and negative faces should be present when the entire display is in full view (Experiment 1A), but not when unattended information is unavailable (Experiment 1B). On the other hand, if more efficient search for negative faces is not the result of the faces' being processed while unattended, then eliminating unattended information from the search display should not affect the difference in search efficiency between positive and negative target faces. On this alternative, a difference in search slopes for detecting positive and negative faces should be present in both Experiments 1A and 1B. More generally, Experiments 1A and 1B will demonstrate that it is possible to apply the new search methodology to separate the contributions of preattentive guidance mechanisms from postattentive comparison processes. In Experiments 2 and 3, we further explore and validate the approach by applying it to both feature and conjunction searches.

EXPERIMENTS 1A AND 1B

In Experiments 1A and 1B, participants were required to identify a unique target face that was presented among neutral distractor faces as being either positive or nega-

tive. In Experiment 1A, the target and distractor faces were in full view. In Experiment 1B, the search items were occluded by placeholders (i.e., black squares), and a search item was only revealed when the mouse pointer was moved over a given placeholder. In this way, only one of the faces could be exposed or visible at any given moment. Examples of the stimulus displays used in Experiments 1A and 1B are shown in Figure 1.

According to the experimental logic outlined above, if the emotional valence of unattended faces is processed and guides attention, then a difference in the search slopes for identifying positive and negative faces should be present in Experiment 1A, when the entire display is in full view, but not in Experiment 1B, when unattended information is unavailable. In contrast, if the difference in search slopes for identifying affective faces is due to postattentive template-matching processes, occluding the unattended information should have no influence on the difference between the search slopes, which should be present in both Experiments 1A and 1B.

Method

Participants. Twenty-six University of Waterloo undergraduate students participated in each experiment. A single session lasted 30 min, and participants were paid \$4.00 for their participation. All participants reported normal or corrected-to-normal vision.

Stimulus displays. Examples of the stimulus displays for each experiment are shown in Figure 1. Each display contained one target face and 6, 10, 14, or 18 distractor faces. The target was a schematic face expressing either a positive (upward curved mouth) or negative (downward curved mouth) emotion. The distractor faces had a neutral expression (straight mouth line). Each of those stimuli occupied one of 36 possible locations on an imaginary 6×6 matrix. Stimulus location, target emotion (positive or negative), and set size (7, 11, 15, or 19) were selected randomly for each trial, with the constraint that each condition (emotion/set size) was tested 30 times across 240 experimental trials.

The displays were presented on a ViewSonic PF775 17-in. monitor, which was controlled by a 1.4 GHz Pentium processor using E-Prime Version 1.1 (Psychology Software Tools, Inc., Pittsburgh, PA). The imaginary 6×6 matrix subtended a visual angle of approximately 14.9° in both directions at the prescribed viewing distance of 60 cm. Each schematic face measured 13 mm in diameter, subtending 1.2° of visual angle, and was presented in white on a dark background.

In Experiment 1A, the schematic faces in each display were presented simultaneously in full view (see top panels of Figure 1). In Experiment 1B, however, each of the schematic faces in a given display was occluded by a solid black square (i.e., placeholder) that indicated the location of the schematic faces on the screen (see bottom panels of Figure 1). Each side of the black square was 23 mm in length, subtending 2.2° visual angle. Participants were able to view the schematic faces underneath the black squares by moving the mouse pointer over the black squares. When the mouse pointer was over the black square, the schematic face underneath the black

Figure 1. Examples of the stimulus displays used in Experiments 1A and 1B. Panels A and B show examples of displays from Experiment 1A that contain a positive and a negative target, respectively. Panel C shows the display as it appeared at the beginning of a trial with all faces occluded by placeholders (Experiment 1B), and Panel D shows how a face was “uncovered” when the mouse pointer was moved over a placeholder.

square appeared in white in front of the black square. When the mouse was moved off the black square, the corresponding schematic face disappeared. Thus, only one schematic face could be viewed at any given time. The black squares (i.e., placeholders) were presented against a white background.

Procedure. In both Experiments 1A and 1B, participants were instructed to quickly identify whether the unique image in each display was a positive or negative face, while maintaining high accuracy. Participants were not told which target they would be searching for on any given trial. They initiated each trial by clicking the left mouse button to proceed to the search display. The displays remained on the screen until participants had indicated the emotion of the unique target face once it was found by pressing the “z” or “x” keys on a QWERTY keyboard. The correspondence between the keys (“z” or “x”), and the emotion of the target face (positive or negative) was counterbalanced across participants. Following a 500-msec interval, visual feedback regarding accuracy was given for 1,000 msec on correct trials and 3,000 msec on incorrect trials; then, a cue for the next trial was presented. Participants first completed 12 practice trials and then the 240 experimental trials.

In Experiment 1B only, participants were told that the schematic faces were occluded by black squares that functioned as place holders indicating the location of each of the faces in the display. Participants were instructed to use the mouse to “flip over” the black square to reveal the face underneath the placeholder. A face only remained visible as long as the cursor was over the placeholder. Once participants found the target face, they identified it as being either positive or negative in the same manner as that in Experiment 1A. In all other respects, Experiments 1A and 1B were identical.

Results and Discussion

RT. We began by analyzing the RT data from Experiments 1A and 1B separately. The correct RT data from Experiment 1A were trimmed using a recursive procedure (van Selst & Jolicoeur, 1994); the same trimming procedure was applied to the data of all other experiments reported here. As a result, 1.34% of the trials were removed. The resulting data were evaluated by a repeated measures ANOVA to assess the impact of target type (positive face vs. negative face) and set size (7, 11, 15, and 19).

The mean RTs and search slopes for each condition in Experiment 1A are shown in Table 1. As can be seen in Table 1, negative faces were identified faster than were positive faces [$F(1,25) = 51.70$, $MS_e = 43,261.45$, $p < .001$], and search became more difficult with increasing set size [$F(1,25) = 67.76$, $MS_e = 41,331.42$, $p < .001$]. Importantly, the search slope for negative faces (slope = 19 msec/item) was shallower than that for positive faces (slope = 33 msec/item) [$F(1,25) = 22.52$, $MS_e = 8,888.56$, $p < .001$].⁴ Thus, the results of Experiment 1A replicated those of Eastwood et al. (2001). When target and distractor faces were visible at the same time—and, thus, unattended information was available—search for negative faces was much more efficient than that for positive faces.

The present results also extend the findings of Eastwood et al. (2001) by using an identification task rather than a localization task. When participants are required to merely localize the target regardless of its emotional valence, it is possible that this can be accomplished without conscious awareness of the emotional valence. However, the present results suggest that Eastwood et al.’s (2001) findings are clearly not unique to localization tasks. Even when participants are required to identify the target with

high accuracy, which arguably requires awareness of its emotional valence, participants still find negative faces more efficiently than positive faces. Therefore, the findings further corroborate Eastwood et al.’s (2005) claim that the difference in search slopes for detecting positive and negative faces reflects a difference in the efficiency with which the faces are brought into awareness.

Trimming of the correct RT data for Experiment 1B resulted in the removal of 0.38% of the trials. The resulting means for each condition are also displayed in Table 1. A repeated measures ANOVA revealed that positive faces were identified marginally faster than negative faces [$F(1,25) = 2.85$, $MS_e = 136,146.11$, $p = .10$] and that search became more difficult with increasing set size [$F(1,25) = 563.48$, $MS_e = 209,225.54$, $p < .001$]. Strikingly, a comparison of the slopes of the search functions revealed that the slope of the search function for identifying the negative face (slope = 168 msec/item) did not differ from that for identifying the positive face (slope = 168 msec/item) ($F < 1$). That is, unlike in Experiment 1A, the search slopes for positive and negative faces in Experiment 1B were virtually identical. Clearly, occluding the unattended schematic faces completely eliminated any difference in search efficiency for identifying positive and negative faces. Thus, these findings are consistent with the notion that the difference in search efficiency for emotional faces found in Experiment 1A resulted from the guidance of attention by unattended target faces.

Furthermore, the results of Experiment 1B are inconsistent with the first postattentive account that we discussed earlier—namely, that participants search the display for a negative target before they search the display for a positive target. If the difference in search slopes that was observed in Experiment 1A was due to faster or more accurate template matching for negative faces, one would expect faster identification of negative faces than positive ones. However, if anything, participants took longer to identify negative faces than positive ones. This finding is consistent with the general observation that positive facial expressions are identified more quickly and accurately than negative facial expressions when faces are presented within focal attention (Kirouac & Doré, 1983, 1984; Mandal & Palchoudhury, 1985; McAndrew, 1986; Stalans & Wedding, 1985).

Table 1
Mean Response Times (in Milliseconds) and Search Slopes (Milliseconds/Item) for the Positive and Negative Search Conditions in Experiments 1A and 1B

Search Condition	Set Size				Slope
	7	11	15	19	
Full View (Experiment 1A)					
Positive face	1,157	1,347	1,472	1,554	33
Negative face	1,048	1,159	1,209	1,285	19
Difference					14
Contingent View (Experiment 1B)					
Positive face	2,356	2,990	3,761	4,346	168
Negative face	2,426	3,123	3,811	4,439	168
Difference					0

The results are also inconsistent with the other postattentive explanation, which argues that negative faces are found more efficiently than positive faces under full viewing conditions, because observers are more likely to miss the positive rather than the negative target faces. If observers were more likely to miss identifying the positive target face than the negative target face, then—assuming that the template matching process does not differ across search methods—one would expect that such missing would also occur when participants search the display with a mouse-contingent window. Accordingly, this alternative would predict a slope difference between positive and negative faces in Experiment 1B. The lack of a slope difference between positive and negative target face conditions in Experiment 1B is clearly inconsistent with this prediction.

z-Transformed RTs. In order to directly compare whether the difference between the search slopes observed in Experiment 1A is qualitatively different from the lack of such an interaction observed in Experiment 1B, we rescaled the data from each experiment by transforming each participant's RT data into z-scores. This step was necessary because with untransformed RTs, the distribution of search slope differences between positive and negative faces in Experiment 1B (range = -187 to 105 , $SD = 70$) encompasses the distribution of search slope differences observed in Experiment 1A (range = -0.38 to 15 , $SD = 14$). Furthermore, it placed both experiments on the same scale. The resulting data are shown in Figure 2, with the transformed data from Experiment 1A shown on the left and the transformed data from Experiment 1B shown on the right.

An ANOVA was performed on the z-transformed RT data, with target type (positive vs. negative) and set size (7, 11, 15, and 19) as within-participants factors and experiment (1A vs. 1B) as a between-participants factor. Critically, the difference in search slopes for identifying

positive in comparison with negative targets was significantly larger in Experiment 1A than in Experiment 1B [$F(1,50) = 11.90$, $MS_e = 0.228$, $p < .001$]. Thus, a direct comparison of Experiments 1A and 1B confirms that the results of the experiments were very different from each other. When the schematic faces were all in full view and unattended information was available (Experiment 1A), search for negative faces was much more efficient than that for positive faces. In contrast, when the unattended faces were occluded (Experiment 1B), the difference in the search efficiency between positive and negative face was eliminated.

This analysis further supports the general conclusion that the difference in search slopes between positive and negative faces that is found when items are in full view is due to preattentive guidance mechanisms. Critically, the findings illustrate that it is possible to separate the contributions of preattentive guidance mechanisms from postattentive comparison processes by comparing search when items are in full view with search using the new mouse-contingent viewing methodology.

Errors. The mean percentage errors for each condition of Experiment 1A and 1B are shown in Table 2. All error rates were less than 5%, and separate ANOVAs for each experiment revealed no significant effects (all F s < 2.87 ; all p s $> .10$). Thus, the interpretation of the RT data does not appear to have been compromised by speed-accuracy trade-offs.

EXPERIMENTS 2A AND 2B

Although the results of the previous experiments demonstrate the utility of our method for disentangling preattentive and postattentive accounts of ambiguous search situations, our current interpretation of the data may be limited by a potential floor effect that is due to

Figure 2. Mean z-transformed reaction times for identifying the positive and negative faces in Experiments 1A (panel A) and 1B (panel B).

Table 2
Mean Percent Errors and Search Slopes (%/Item)
for the Positive and Negative Search Conditions in
Experiments 1A and 1B

Search Condition	Set Size				Slope
	7	11	15	19	
Full View (Experiment 1A)					
Positive face	2.4	2.9	3.6	3.5	0.09
Negative face	3.2	2.8	4.1	3.5	0.05
Difference					0.04
Contingent View (Experiment 1B)					
Positive face	1.3	1.7	2.7	2.8	0.14
Negative face	1.8	2.8	1.8	2.3	0.01
Difference					0.13

the unique motor component associated with moving the mouse across the placeholders in Experiment 1B. In other words, it is possible that there is no difference between search slopes in Experiment 1B, because participants cannot search the display at a faster rate than the observed 168 msec/item. Although it is likely that search performance in this task is ultimately limited by how quickly the mouse can be moved from one potential target to the next, it is unclear whether this would be slow enough to attribute the null effect of emotion in Experiment 1B to a floor effect. Thus, the purpose of Experiments 2A and 2B was to evaluate whether the relatively steeper search slopes observed in Experiment 1B (in comparison with the shallower search slopes that were found in Experiment 1A) represent a lower bound on search performance.

In order to assess what the lower bound might be, we examined search performance under conditions that are known to produce pop-out search. In Experiment 2A, participants searched for either an “x” or “+” that was presented among “o” distractors, with all of the stimuli presented simultaneously. In Experiment 2B, the display was occluded, and participants performed search using the mouse as they had in Experiment 1B. Typically, when participants are required to search for a target that is defined by a single basic feature (such as finding a “+” shape among “o” shapes) in a standard visual-search task, search for the target is essentially unaffected by the number of distractors in the display, yielding search slopes near 0 msec/item (see, e.g., Treisman & Gelade, 1980). Thus, if search performance for the face targets in Experi-

ment 1B had been limited by the unique motor demands, we would expect very similar search slopes of around 168 msec/item when search items are occluded in a pop-out search task (in Experiment 2B). However, if the slopes of 168 msec/item that were observed in Experiment 1B do not reflect a lower bound of the mouse-contingent viewing technique, we might obtain much shallower slopes when searching for pop-out targets using this technique.

Method

Participants. Eighteen University of Waterloo undergraduate students participated in each experiment. A single session lasted approximately 20 min, and participants were paid \$4.00 for their participation. All participants reported normal or corrected-to-normal vision.

Stimulus displays. The structures of the stimulus displays were identical to those used in Experiments 1A and 1B. The only difference was that the target was either an “x” or “+” among “o” distractors. In Experiment 2A, the stimuli were presented simultaneously in full view, as were those in Experiment 1A. In Experiment 2B, however, each stimulus was occluded by a solid black square, as were those in Experiment 1B.

Procedure. The procedure was identical to that of Experiments 1A and 1B, with two minor exceptions. First, the number of trials was reduced to 160 experimental trials. Second, participants were required to press the “z” key if the target was a “+” and the “x” key if the target was an “x.”

Results and Discussion

RT. We began by analyzing the RT data from Experiments 2A and 2B separately. The correct RT data from Experiments 2A and 2B were trimmed, resulting in the removal of 0.6% and 2.2% of the trials, respectively. The resulting data are shown in Table 3. A repeated measures ANOVA assessing set size (7, 11, 15, and 19) in Experiment 2A revealed that there was no linear effect of set size [$F(1,17) < 1$, $MS_e = 1,630$, $p > .20$] (slope = 1 msec/item). In contrast, an analysis of Experiment 2B revealed that RT increased substantially with set size [$F(1,17) = 127.5$, $MS_e = 179,020$, $p < .001$] (slope = 89 msec/item).

Thus, Experiment 2B yielded shallower search slopes than did Experiment 1B, even though the same mouse-contingent search technique was used in both experiments. In order to confirm this difference statistically, a mixed ANOVA was conducted on the data of Experiments 1B and 2B, with set size (7, 11, 15, and 19) as a within-participants factor and experiment (Experiment 1B vs. Experiment 2B)

Table 3
Mean Response Times (in Milliseconds) and Search Slopes
(Milliseconds/Item) for Each Experiment Averaged
Across the Targets in Each Experiment

Search Experiment	Set Size				Slope
	7	11	15	19	
Full View Technique					
Affective faces (Experiment 1A)	1,102	1,253	1,341	1,419	26
Pop-out (Experiment 2A)	659	656	661	668	1
Conjunction (Experiment 3A)	2,650	3,838	5,028	6,595	326
Mouse-Contingent Technique					
Affective faces (Experiment 1B)	2,391	3,056	3,786	4,392	168
Pop-out (Experiment 2B)	2,004	2,484	2,794	3,087	89
Conjunction (Experiment 3B)	3,064	4,198	5,473	6,392	281

as a between-participants factor. Search performance in each experiment was averaged across the different targets in each experiment. Search slopes were indeed significantly shallower in Experiment 2B than those in Experiment 1B [$F(1,42) = 54.4$, $MS_e = 197,000$, $p < .05$]. This result clearly shows that the 168-msec/item slope obtained with the mouse-contingent search for faces in Experiment 1B is not a lower bound on search when this technique is used. In fact, the search slopes in Experiment 2B were about 80 msec/item shallower than those in Experiment 1B, suggesting that the slopes in Experiment 1B were quite far from the lower bound on search caused by the motor component of the task associated with moving the mouse. Thus, the null difference between positive and negative conditions in Experiment 1B is likely not due to a floor effect.

Nevertheless, it is possible that the mouse-contingent search technique is not sensitive enough to reveal small differences in search performance, such as the 14-msec slope difference between searches for negative and positive face targets in Experiment 1A. More specifically, one could argue that the mouse-contingent search technique simply adds so much variability that any slope differences observed under free viewing conditions will be obscured by the “noise” introduced by the contingent-viewing methodology.

One possible way to address this concern is to demonstrate that under certain conditions, small differences in search slopes under full viewing conditions can be magnified using the mouse-contingent viewing method. As we have noted earlier, when distractors are matched across search conditions and the targets are varied unpredictably from trial to trial, differences in search slopes are thought to reflect differences in preattentive guidance. In such search situations, template matching is likely constant across search conditions because templates of each of the targets are matched to each of the distractors, which are the same across conditions. But a different situation arises when a comparison of search conditions is made across experiments with different target and distractor combinations. If the search conditions being compared across experiments differ with regard to the difficulty of matching the target templates to the distractors, then small differences between search slopes under full viewing conditions might actually be magnified when postattentive template-matching processes are isolated with the mouse-contingent method. Regardless of the theoretical

rationale, showing that a small difference in search slopes between two conditions under full view is magnified by the mouse contingent method would demonstrate that the mouse-contingent method is a sensitive measure.

Consistent with this line of reasoning, we compared search for negative faces (in Experiment 1) with search for the target “+” (in Experiment 2) to evaluate whether the contingent-viewing method is indeed able to detect small search slope differences that are evident under full viewing conditions. Under full viewing conditions, search for negative faces (in Experiment 1A) and search for the target “+” (in Experiment 2A) differ by 18 msec/item (see Table 4). In contrast, when using the mouse-contingent viewing method, the difference in slopes between negative face condition (in Experiment 1B) and the “+” condition (in Experiment 2B) is substantially increased to 86 msec/item. This observation was confirmed by an ANOVA with viewing method (full view vs. mouse contingent) and set size (7, 11, 15, and 19) as within-participants factors and search stimuli (negative face among neutral faces vs. “+” among “o”) as a between-participants factor. This analysis revealed a significant three-way interaction between search stimuli, viewing method, and set size [$F(1,84) = 13.6$, $MS_e = 93,303$, $p < .05$]. Thus, the small difference between these two conditions when items are in full view is actually magnified when items are viewed using the mouse-contingent method. Clearly, therefore, small differences in search slopes obtained under full viewing conditions can be effectively detected using the mouse-contingent viewing method. Therefore, the results demonstrate that the lack of difference between the positive and negative face conditions found under mouse-contingent viewing is not due to a general insensitivity of the contingent viewing method.

Why is the small slope difference between positive and negative faces in the full viewing condition eliminated under mouse-contingent viewing conditions, whereas the small slope difference between the negative face condition and the “+” condition under full viewing is substantially magnified when using the mouse-contingent viewing method? In keeping with the rationale described above, we suggest that the two slope differences are caused by very distinct underlying search processes. Specifically, the findings are consistent with the notion that the difference in search slopes between positive and negative face

Table 4
Mean Response Times (in Milliseconds) and Search Slopes (Milliseconds/Item) for Searching for Negative Faces (Experiments 1A and 1B) and for Searching for “+” Among “o” (Experiments 2A and 2B) in Both Full Viewing and Mouse-Contingent Viewing Conditions

Search Condition	Set Size				Slope
	7	11	15	19	
Full View					
Negative face (Experiment 1A)	1,048	1,159	1,209	1,285	19
“+” among “o” (Experiment 2A)	696	685	682	705	1
Difference					18
Contingent View					
Negative face (Experiment 1B)	2,426	3,123	3,811	4,439	168
“+” among “o” (Experiment 2B)	2,018	2,532	2,850	3,013	83
Difference					86

conditions (under full viewing) are due to differential guidance by those target faces. When any possibility of guidance is eliminated by the mouse-contingent method, the slope differences are completely eliminated. In contrast, the difference between the negative face condition and the “+” condition under full viewing conditions could involve both a difference in guidance between search targets as well as a difference in the difficulty with which the search items are matched to the templates of the targets in those conditions. That is, when searching for faces, it might be relatively difficult to reject selected distractors (neutral faces), because they are visually similar to the target templates (positive and negative faces). When searching for pop-out targets, however, rejecting selected distractors (“o”) might be much easier, because they are visually quite different from the target templates (“+” and “x”). The impact of template matching between the face and pop-out search conditions is likely magnified under mouse-contingent viewing, because this method eliminates the possibility of guidance, and differences in search efficiency are now primarily determined by differences in template matching between conditions.

To summarize, these results demonstrate that the null effect of emotion that was observed in Experiment 1B was neither attributable to a floor effect that was due to the motor component of the mouse search, nor was it the result of a general insensitivity of the new search method. Thus, it seems reasonable for one to conclude that the difference in search slopes for detecting positive and negative faces is due to a difference in preattentive guidance across conditions rather than postattentive template-matching processes. As such, the findings demonstrate the usefulness of the new search method for disentangling the contributions of preattentive and postattentive process in visual search.

Errors. The mean percent errors for each condition of Experiments 2A and 2B are shown in Table 5. All error rates were less than 10%, and separate ANOVAs for each experiment revealed no significant effects (all F s < 1.5). Furthermore, there was no interaction between experiments (F s < 1.5). The percent errors for the comparison between the negative face condition (Experiment 1) and the search for “+” among “o”s (Experiment 2) were all below 10%. There were no significant differences in search slopes between viewing conditions (F < 1). Thus, interpretation of the RT data does not appear to have been compromised by speed–accuracy trade-offs.

EXPERIMENTS 3A AND 3B

The purpose of Experiments 3A and 3B was two-fold. First, we sought further validation of the mouse-contingent search method by exploring the upper bound of the range of search efficiencies associated with this method. Second, we sought to further evaluate the extent to which the mouse-contingent method is informative with regard to the differential role of guidance and template matching in visual search.

To address these objectives, we observed search in which the possibility of guidance was reduced as much as possible by defining the target by a conjunction of features and mak-

ing the targets very similar to the distractors. Specifically, participants searched for either a “T” tilted to the right or a “T” tilted to the left among distractors that were like “T”s, except that the vertical lines of the “T”s were shifted slightly, so that they were not connected to the center of the horizontal line of the “T”s. In Experiment 3A, all of the stimuli were presented simultaneously and in full view. In Experiment 3B, the display was occluded, and participants performed search using the mouse as they had in Experiment 1B.

With regard to the first objective, we expected that search in Experiments 3A and 3B would be much less efficient than those studied in the previous experiments. Specifically, we expected that, even with the mouse-contingent method, search for conjunction targets that are extremely similar to distractors (Experiment 3B) would be much less efficient (i.e., search slopes would be much steeper) than search for emotional faces (Experiment 1B). Such a finding would indicate that the 168-msec/item search slope that was found when searching for affective faces using the mouse-contingent method is not at the upper bound of search performance using this method. This result would imply that the lack of difference between the slopes of the search functions of detecting positive and negative faces when using the mouse-contingent method is not due to the fact that people will not search at a slower rate than 168 msec/item when this method is used (i.e., a ceiling effect).

We also further evaluated our claim that the mouse-contingent method is informative with regard to the differential role of guidance and template matching in visual search. We chose easily confusable targets and distractors in Experiments 3A and 3B that will likely lead to very little preattentive guidance, and we predicted that template matching would be the main contributor to search performance under both full view and mouse-contingent view conditions. Accordingly, we expected that the efficiency of search for the conjunction search targets should be more similar across the full view and mouse-contingent view conditions than we have observed in previous experiments.

Method

Participants. Twenty-two University of Waterloo undergraduate students participated in each experiment. A single session lasted approximately 30 min, and participants were paid \$6.00 for their participation. All participants reported normal or corrected-to-normal vision.

Stimulus displays. The structures of the stimulus displays were identical to those used in Experiments 2A and 2B. The only differ-

Table 5
Mean Percent Errors and Search Slopes (%/Item) for Each Experiment Averaged Across the Targets in Each Experiment

Search Experiment	Set Size				Slope
	7	11	15	19	
Full View					
Affective faces (Experiment 1A)	2.8	2.9	3.8	3.5	0.07
Pop-out (Experiment 2A)	8.3	6.1	5.6	6.1	−0.18
Conjunction (Experiment 3A)	2.8	5.6	5.3	7.8	0.37
Contingent View					
Affective faces (Experiment 1B)	1.5	2.2	2.2	2.6	0.08
Pop-out (Experiment 2B)	6.7	5.6	4.4	6.7	−0.03
Conjunction (Experiment 3B)	4.2	3.9	6.4	7.3	0.30

ence was that the target was either a “T” tilted to the right or a “T” tilted to the left. The distractors were similar to the “T”s, except that in the distractors, the vertical line of the “T” was offset slightly, so that it was not connected to the center of the horizontal line. The distractor “T”s were presented in different orientations to increase the difficulty of search. In Experiment 3A, the stimuli were presented simultaneously in full view. In Experiment 3B, each stimulus was occluded by a solid black square, and participants searched for the target using the mouse-contingent viewing method.

Procedure. The procedure was identical to that of Experiments 2A and 2B, except that participants pressed the “x” key on the keyboard if the target was a “T” tilted to the right and the “z” key if the target was a “T” tilted to the left.

Results and Discussion

RT. As in the previous experiments, the RT data from Experiments 3A and 3B were analyzed separately. The correct RT data were trimmed, removing 2.55% (Experiment 3A) and 2.02% (Experiment 3B) of the trials. The resulting data, displayed in Table 3, were evaluated by repeated measures ANOVAs to assess the impact of set size (7, 11, 15, and 19). RTs increased substantially with increases in set size in both Experiment 3A (slope = 326 msec/item) [$F(1,17) = 91.7$, $MS_e = 3,329,615$, $p < .001$] and Experiment 3B (slope = 281 msec/item) [$F(1,17) = 185.6$, $MS_e = 1,229,753$, $p < .001$]. This result indicates that, overall, search was extremely inefficient under both full viewing and mouse-contingent search conditions.

We believe that the findings of Experiments 3A and 3B are intriguing for two reasons. First, the conjunction search using the mouse-contingent search technique (Experiment 3B) yielded a very steep search slope (281 msec/item), which is much steeper than that of the search function for searching for faces using the same technique as in Experiment 1B (168 msec/item). A mixed ANOVA assessing the within-participants factor of set size (7, 11, 15, and 19) and the between-participants factor of experiment (Experiment 1B vs. Experiment 3B) confirmed that search slopes in Experiment 3B and Experiment 1B differed significantly [$F(1,42) = 35.0$, $MS_e = 311,148$, $p < .001$]. This result indicates that the 168-msec/item slope obtained with the mouse-contingent search for faces in Experiment 1B is not an upper bound on search using this technique. Therefore, the lack of a difference between the positive and negative conditions in Experiment 1B is likely not due to a ceiling effect. Together, the results of Experiments 2 and 3 indicate that the search efficiency (i.e., search slopes) when identifying positive and negative faces using the mouse-contingent method is roughly in the middle of the range of possible search efficiencies for the mouse-contingent method.

Second, these results are consistent with our suggestion that the mouse-contingent viewing method distinguishes between the contributions of preattentive guidance and postattentive template-matching processes in search. On this view, search under full viewing conditions depends on both preattentive guidance and postattentive template-matching processes, whereas search under mouse-contingent viewing conditions depends only on template-matching processes, because occlusion of unattended items does not allow for guidance. On the basis of this view, we predicted that search slopes for detecting conjunction targets, which are rela-

tively poor at guiding attention, should be similar across the full view (Experiment 3A) and mouse-contingent view (Experiment 3B) methods. This prediction was supported by a mixed ANOVA with the within-participants factor of set size (7, 11, 15, and 19) and the between-participants factor of experiment (Experiment 3A vs. Experiment 3B), which showed a nonsignificant main effect of experiment ($F = 1$) and a nonsignificant interaction between set-size and experiment ($F < 1$).

Inspection of the results of Experiments 3A and 3B in Table 3 suggests that, if anything, the slope is somewhat shallower for the mouse-contingent search than for the standard search. Given that the motor demands of moving the mouse pointer across the display would increase search time as the number of items in the display is raised, subtracting this time from the mouse-contingent RTs would actually yield a substantially shallower slope for this condition in comparison with the full viewing condition. Thus, when the target item is perceptually similar to distractor items, grouping of the stimuli may in fact camouflage the target and make its detection difficult. In our new search method, however, such interference from surrounding stimuli is eliminated, making search for the target easier. The mouse-contingent search method may therefore also be a useful tool for investigating perceptual grouping and interference between distractors and targets during visual search.

Errors. The percentage errors in each condition averaged across participants in Experiments 3A and 3B are shown in Table 5. The error data were analyzed using the same set of analyses used on the RT data. Analysis of the errors in Experiment 3A revealed a marginal effect of set size [$F(1,17) = 5.4$, $MS_e = 35.9$, $p < .05$]. Similarly, in Experiment 3B, there was a marginal effect of set size [$F(1,17) = 4.0$, $MS_e = 32.1$, $p = .06$]. A comparison of errors across Experiments 3A and 3B revealed no significant effects (all F s < 1.5 ; all p s $> .22$). Thus, the patterns in the error data do not compromise the main conclusions that we have drawn from the RT data.

GENERAL DISCUSSION

In the present article, we evaluated the role of unattended and attended information by comparing performance when unattended information was available to the visual system with a situation in which unattended information was occluded and only the currently attended object was visible (see also Gilchrist et al., 2001; McConkie & Rayner, 1975; Rayner, 1995, 1998; Thomas et al., 2006; van Diepen & d’Ydewalle, 2003). In the latter situation, participants were required to move the mouse to “uncover” the search items behind the placeholders (the mouse-contingent viewing technique). In Experiment 1, we demonstrated the utility of this method in the context of search for faces expressing positive and negative emotions. We found that negative face search was more efficient than positive face search under full viewing conditions. In sharp contrast, this performance difference did not emerge under mouse-contingent search conditions. These results are consistent with the proposal that differential search efficiency for emotional face targets among

neutral distractor faces is due to preattentive guidance. Furthermore, these findings are not in line with the alternative postattentive explanation that search for negative faces is more efficient because of enhanced template-matching processes once a search item is within the focus of attention.

Once the utility of the mouse-contingent method had been established, Experiments 2 and 3 explored the lower and upper bounds of the method by having participants complete an easy pop-out search (Experiment 2) and a hard conjunction search (Experiment 3). The results of Experiment 3 were particularly interesting, showing that, for difficult conjunction searches involving very little or no preattentive guidance, there is no apparent difference in search efficiencies between full viewing and mouse-contingent viewing conditions. If anything, for the hard conjunction search, the mouse-contingent viewing method led to slightly shallower slopes than did the free viewing method, which suggests that the mouse-contingent search method may be useful for exploring not only the conditions under which grouping of targets and distractors helps search, but also the conditions under which preattentive grouping hurts performance (i.e., camouflage).

What Processes Underlie Search for Positive and Negative Faces?

In addition to demonstrating the utility of the mouse-contingent search method, the present studies also address the processes that underlie search for positive and negative faces. The findings suggest that the difference in search slopes for positive and negative faces is likely due to differences in preattentive guidance across conditions, rather than to postattentive template matching processes.

One conclusion that can be drawn from the findings is that it is the emotional valence of the target faces that is perceived preattentively, and that, in this context, negative faces guide attention to themselves more strongly, thereby making search for negative faces more efficient. Such a conclusion would be consistent with other studies showing that global representation of faces (Suzuki & Cavanagh, 1995), highly overlearned faces (Tong & Nakayama, 1999), and the direction of eye gaze (von Grönau & Anston, 1995) are all capable of influencing the efficiency of visual search. An alternative explanation of the present search findings is that they are the result of featural differences between the positive and negative faces, not emotional valence (see Wolfe & Horowitz, 2004).

In our present investigation, our primary focus was to develop a new search methodology; therefore, we do not attempt to conclusively determine whether the findings of Experiment 1 hinge on features or on emotional valence. Nonetheless, we note that there are a number of findings that are inconsistent with the feature-based explanation. First, schematic faces were used to reduce featural differences between the positive and negative faces. Second, in two previous studies (Eastwood et al., 2001), using exactly the same stimuli, the difference in search slopes for detecting upright positive and negative faces was eliminated when the faces were inverted. Inverting the faces does not affect local features, but disrupts holistic face perception.

Therefore, the elimination of the search-slope difference associated with positive and negative faces when the faces were inverted strongly suggests that the slope difference found with upright faces was the result of facial affect and not simply visual features. Third, the slope difference between positive and negative faces has been shown to be larger in people with anxiety disorders (i.e., social phobia) than in normal age-matched controls (see Eastwood et al., 2005). For these reasons, the feature-based explanation seems less tenable than an emotion-based explanation.

It is also important to highlight that visual search for negative faces might not always be more efficient than search for positive faces. Visual-search performance is a highly contextualized process that depends on the similarity of the targets and distractors. Therefore, it makes little sense, on the basis of visual search data, to make absolute conclusions about the attention-attracting ability of any given facial expression. For instance, search for negative faces might actually be less efficient than that for positive faces if the distractor faces were more affectively similar to the negative target face than to the positive target face. Although it is perhaps less fruitful to make strong conclusions with regard to whether negative faces will always guide attention more effectively than positive faces, it is possible to make the more general conclusion that the emotion of unattended faces is processed and differentially biases attention during search. Furthermore, the general claim that the emotional valence of faces can guide attention does not presuppose that this is always the case.

Visual Scanning Versus Searching With a Computer Mouse

We believe that the mouse-contingent viewing method will be useful for separating the impact of preattentive and postattentive processes across a wide variety of search contexts. However, note that there are important differences between visual scanning and searching for objects using a computer mouse. For instance, eye movements are ballistic, whereas hand movements are typically much slower. This may lead to differences in search strategies, with the mouse-contingent method imposing a more systematic search strategy that is more characteristic of foraging (see Gilchrist et al., 2001; Thomas et al., 2006). Future research will need to examine if and how search using the mouse-contingent method differs from eye-gaze-contingent viewing.

We should also be clear about a critical assumption that underlies our use of the mouse-contingent method as a tool for separating pre- and postattentive processes. Namely, our application of the procedure assumes that the template-matching process does not differ across the mouse-contingent method and free viewing. At present, we have no way of verifying this assumption. As such, there is the possibility that the slower hand movements associated with the mouse-contingent method may change the process involved in inspecting an item once it is attended. Future studies comparing the mouse-contingent method with an eye-gaze-contingent method may resolve this issue also.

We believe that the mouse-contingent method offers considerable promise and that it is important to further

develop this method as a tool for studying the processes that underlie visual search. The obvious and important advantage of the mouse-contingent method is that it does not require eye-monitoring technology. As such, we believe that the mouse-contingent method can be applied in a much wider variety of settings.

AUTHOR NOTE

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NOTES

1. Eastwood et al. (2001; Eastwood et al., 2005) referred to the faces with the downward curving arc for a mouth as "negative" faces. Following Eastwood et al., we do not specify what specific negative emotion (e.g., "sadness" or "anger") this face depicts. We believe that any claims about the specific nature of the emotion expressed by the negative faces used in the present study, such as Williams, Moss, Bradshaw, and Mattingley's (2005) claim that the faces express "sadness" as opposed to "anger" are not warranted.
2. Although it is consistent with common interpretation of visual search findings, note that the logic described here is predicated on several critical innovations. Namely, we are not making inferences from "search asymmetries" and we are not making absolute statements about the ability of a "feature" to guide attention or "pop-out." Rather, by holding constant the distractor context and top-down expectancies of the observers across the positive and negative target face conditions, we are able to determine the relative attention-guiding ability of positive and negative faces.
3. We thank Jeremy Wolfe and Todd Horowitz for this suggestion.
4. When reporting main effects and interactions involving the set-size factor, we report the linear component of the interaction.