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Saccadic selectivity during visual search: The influence of central processing difficulty

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### **Abstract**

The current study examined the relation between the difficulty of central discrimination and the efficiency of peripheral selection in visual search tasks. Participants were asked to search for a target among high-, medium-, and low-similarity distractors. In Experiment 1, while the duration of current fixations increased with increasing target-distractor similarity, there was no evidence that saccadic selectivity was influenced by the target-distractor similarity of the previously fixated item or by the duration of the previous fixation. In addition, we manipulated the difficulty of the central discrimination by introducing a concurrent visual task (Experiment 2) and by presenting a gaze-contingent moving mask (Experiment 3). Although both manipulations substantially degraded the overall visual search performance, the magnitude of peripheral selection was not affected. Results from the current study suggest that peripheral selection is a robust process, largely independent of the central processing difficulty.

## Introduction

Visual search is one of the dominant paradigms used for investigating visual attention. In a typical visual search task, participants have to decide whether a search display contains a designated target among distractors (nontarget elements). In most studies, response times (RTs) and error rates are analyzed as a function of the number of items in the display (display size). Based on such data, several theories of visual search have been suggested (e.g., Duncan & Humphreys, 1989, 1992; Treisman & Gelade, 1980; Treisman & Sato, 1990; Treisman, Sykes, & Gelade, 1977; Wolfe 1994; Wolfe, Cave, & Franzel, 1989). By monitoring participants' eye movements during the search process, fine-grained temporal and spatial measures (such as fixation duration, initial latency to move, saccadic amplitude, saccadic error, etc) could be provided to supplement global performance indicators such as RT and error rate (Bertera & Rayner, 2000; Binello, Mannan, & Ruddock 1995; Gould, 1967; Jacobs, 1986; Motter & Belky, 1998a; Rayner & Fisher, 1987; Viviani & Swensson, 1982; D. E. Williams, Reingold, Moscovitch, & Behrmann, 1997; Zelinsky & Sheinberg, 1997; see Rayner, 1998 for a review).

The current paper illustrates one important way in which the eye movement data could provide unique insights into the search process by quantifying the extent of saccadic selectivity - the bias in the spatial distribution of saccadic endpoints towards or away from certain distractor types. Accordingly, a brief review of several visual search theories and their predictions concerning saccadic selectivity are provided, followed by a review of empirical studies on saccadic selectivity. Then, we report three experiments investigating the relation between the difficulty of the central discrimination and the magnitude of saccadic selectivity,

showing that the guidance of eye movements is robust and largely independent of central processing difficulty.

### **Theories of visual search and predictions concerning saccadic selectivity**

In a complex search display containing several types of distractors with different levels of target-distractor similarity, participants will typically have to make a few saccades before a decision on target presence can be made. During this process, will they exhibit saccadic selectivity by preferentially directing their eye movements towards one type of distractors over others? Different predictions could be derived from current theoretical frameworks on visual search.

An early theory of visual search is the original feature integration theory by Treisman and her colleagues (Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977). This theory proposes the existence of preattentive feature maps, one for each stimulus dimension (such as color, shape, orientation, etc). Information from parallel preattentive processes could only mediate performance in a visual search task if the target was defined by the presence of a unique feature (i.e., feature search), such as searching for a green *X* among red and blue *X*s. However, if the target is defined by a specific combination of features (i.e., conjunction search), such as searching for a green *X* among red *X*s and green *O*s, attention is necessary to locally combine the information from the corresponding feature maps. As a result, participants have to inspect the search display in a serial item-by-item fashion until target detection or exhaustive search. Given the nature of serial item-by-item processing, this theory predicts that in a conjunction search task that allows free eye movements, each type of distractors has an equal probability of being fixated for inspection and therefore there will be no selectivity in the distribution of saccades.

The original feature integration theory was inconsistent with the findings from many subsequent studies. For example, parallel or highly efficient performance has been found in a variety of conjunction search tasks (e.g., McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986; Theeuwes & Kooi, 1994; Wolfe et al, 1989; Zohary & Hochstein, 1989). This is inconsistent with the notion of serial item-by-item search proposed by that theory. Furthermore, some feature search tasks were found to induce serial or inefficient performance (e.g., Nagy & Sanchez, 1990; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). This indicates that search efficiency in both feature and conjunction search tasks may vary along a continuum (see Wolfe, 1998, for review).

Several other theories have been proposed to explain variations in search efficiency. For example, the guided search model by Wolfe and his colleagues (e.g., Cave & Wolfe, 1990; Wolfe 1994; Wolfe et al., 1989) argues that in a visual search task participants selectively use peripheral information to guide the search process. In an initial processing stage, a parallel analysis is carried out across all locations of a search display; preattentive information is extracted to segment the search display and to create an "activation map". The overall activation at each stimulus location consists of a top-down component, reflecting the similarity to the target, and a bottom-up component, quantifying the similarity to the other distractors. The activation map is then used to guide shifts of attention in a subsequent stage of serial search (the focus of attention is directed serially to the locations with the highest activation until the target is found or the criterion to make a negative response is reached. One prediction based on this model is that those distractors that are more similar to the target item would be more likely to be fixated than would the less similar ones and therefore there would be a bias in the distribution of saccadic endpoints (i.e., saccadic selectivity).

A similar prediction of search efficiency and saccadic selectivity can be derived from the attentional engagement theory proposed by Duncan and Humphreys (1989, 1992). These researchers argue that in a search task, display inputs must be entered into visual short-term memory before accessing awareness and becoming the focus of current behavior. Due to the limited capacity of the visual short-term memory system, information is admitted competitively following a process of selection on the basis of both target-distractor similarity and distractor-distractor similarity. As a result, selective processing of visual information will likely occur in a complex search task. Similarly, the revised feature integration theory (feature-inhibition hypothesis: Treisman & Sato, 1990) also predicts selective processing of distractors by proposing that individual feature maps can inhibit nontarget features. If the features are sufficiently distinct and separable, such a mechanism might eliminate the activity generated in the master map by distractor items, allowing the target to pop out. However, if the inhibition is incomplete, a serial scan is necessary through the master map, in which the locations differ only in their levels of activation. Given the mechanism of distractor inhibition, those locations containing items that are more similar to the target or share feature(s) with the search target will be more likely to "survive" the inhibition for further inspection.

### **Empirical studies on saccadic selectivity**

During the past few decades, the guidance of eye movements have been examined in several visual search studies. In one of the earliest studies, L. G. Williams (1967) employed search arrays of 100 simple geometric forms, which were defined by unique combinations of color, shape, and size. In the center of each display item, there was a two-digit number and participants were instructed to search for a particular number. In most of the trials, additional information concerning one or more attributes (color, shape, or size) of the search target was

prespecified. Williams found that providing participants with prior color information greatly shortened the search time. Participants could effectively restrict their search within the color dimension, directing most of the saccades towards those items sharing the target color. This was true regardless whether the target color was specified alone or together with additional shape and/or size information. Providing participants with size information, however, was much less effective whereas specifying the shape of the target yielded little evidence of saccadic selectivity. In a subsequent study, Luria and Strauss (1975) asked participants to look for the only dial in an array of 16 that had not been rotated from the starting position. They examined the efficiency of coding dials by color, shape, and a combination of the two. They similarly found that, when provided with color information, participants showed a marked tendency to direct saccades towards target-color items. Unlike Williams (1967), they found that participants could use the shape information to guide search, although to a lesser extent compared to the color information. When provided with both the color and shape information, participants' saccadic endpoints were guided by both dimensions.

More recent studies on saccadic selectivity have yielded conflicting results. Zelinsky (1996) had participants search through displays containing two subsets of distractors. A subset of "similar" distractors was chosen to share either color or orientation with the search target whereas another subset of "dissimilar" distractors did not share color or orientation with the target item. Zelinsky reasoned that if the search process were guided (e.g., Wolfe, 1994), participants should make more saccades towards the similar distractors than towards the dissimilar ones. He examined the distribution of saccadic endpoints, only to find very weak evidence for guidance. Of all valid saccades, 55% were directed to the similar distractors and 45% were directed to the dissimilar ones. Instead of biasing saccadic endpoints towards one specific type of distractors, Zelinsky argued that participants adopted an oculomotor strategy to

aid the search process in a multi-element display. The oculomotor strategy involves programming a series of fixations in an orderly fashion such that every display element has an equal chance of being recognized correctly. In accordance with this argument, he found that the endpoints of the first saccades were systematically biased towards the top-left quadrant of the display.

However, subsequent studies have shown strong evidence of selectivity in the distribution of saccadic endpoints in visual search tasks (e.g., Bichot & Schall, 1998; Findlay, 1997; Findlay, Brown, & Gilchrist, 2001; Findlay & Gilchrist, 1998; Hooge & Erkelens, 1999; Motter & Belky, 1998b; Pomplun, Reingold, & Shen, 2001a, submitted; Pomplun, Reingold, Shen, & D. E. Williams, 2000; Scialfa & Joffe, 1998; Shen & Reingold, 1999; Shen, Reingold, & Pomplun, 2000; D. E. Williams & Reingold, 2001). Stimulus dimensions such as color, shape, contrast polarity, and size have been shown to guide the search process. In light of these findings, the failure to demonstrate saccadic selectivity by Zelinsky (1996) seems to be anomalous. This discrepancy across studies might be attributable to several factors. First, although the differences observed in the experiment by Zelinsky were relatively small and sometimes nonsignificant, saccades were still more likely to be directed towards "similar" distractors than towards "dissimilar" distractors (55% vs. 45%). Thus, Zelinsky's findings do provide weak evidence for selectivity, as he acknowledges. Second, to examine guidance, Zelinsky compared "similar" and "dissimilar" distractors, with "similar" distractors consisting of two types (target-color vs. target-orientation). When calculating the proportion of saccades directed towards "similar" distractors, he did not distinguish between saccades directed towards target-color distractors and those directed towards target-shape distractors. Given that participants heavily rely on color information to guide visual search but make little use of orientation information (e.g., Motter & Belky, 1998b; D. E. Williams & Reingold, 2001),



lumping these two types of distractors together may have led to an underestimation of the strength of guidance in his study.

### **Effect of central processing difficulty on peripheral selection**

Most of the above-mentioned studies employed multi-fixation search tasks. In such tasks, during each fixation information may be extracted from foveal, parafoveal, and peripheral regions of the visual field (Findlay, 1997; Hooge & Erkelens, 1999; Lévy-Schoen, 1981, Rayner & Fisher, 1987). Such information subserves both the discrimination of the foveated object from the search target (henceforth the central discrimination task) as well as the selection of the next object to be foveated (henceforth the peripheral selection task). The main goal of the current study was to investigate whether the difficulty of the central discrimination task affects the efficiency of the peripheral selection task (i.e., saccadic selectivity). This issue has been recently studied by Hooge and Erkelens (1999). These investigators examined saccadic selectivity in a search task by manipulating the difficulty of the central discrimination and peripheral selection tasks separately. They found that the difficulty of the central discrimination task influenced the peripheral analysis and saccadic selectivity indirectly via fixation duration. Specifically, they demonstrated that saccadic selectivity was more pronounced when the difficulty of the central discrimination task was increased. They argued that increasing the difficulty of the central discrimination task led to longer fixation duration, which in turn permitted more time for peripheral analysis, consequently leading to a better selection of the next saccadic target.

Hooge and Erkelens's (1999) interpretation can be illustrated by a variant of the waiting-room metaphor proposed by Navon and Pearl (1985; henceforth the "waiting-room" model). Let us imagine the central discrimination of the foveated stimulus as the doctor examining one

patient while at the same time, peripheral selection is likened to a nurse screening other patients in the waiting room, attempting to select the next patient to be examined by the doctor based on the severity of the symptoms. The amount of information the nurse can gather and consequently the quality of the selection depends on the availability of the doctor - the longer the doctor is preoccupied by the previous patient, the more information the nurse can gather from other patients. Note that in this metaphor the waiting time is solely determined by the availability of the doctor rather than the complexity of the procedures carried out by the nurse (such as retrieving the patients' files, taking temperature, interviewing patients, etc). This parallels the findings by Hooge and Erkelens that fixation duration in a multi-fixation search task was influenced by the difficulty of the foveal discrimination task but not by the difficulty of the peripheral selection task (see also Findlay, 1997; Gould, 1967; Jacobs, 1986; Nazir & Jacobs, 1991).

### **Experiment 1**

The goal of Experiment 1 was to evaluate the waiting-room model concerning the relation between the difficulty of the central discrimination and peripheral selection. The manipulation of central discrimination difficulty was accomplished by adopting a set of stimuli with varying degrees of target-distractor similarity (high, medium, or low similarity). We examined the proportions of fixations on the high-, medium-, and low-similarity distractors as a function of the target-distractor similarity of the previously fixated display item and of the duration of the previous fixation.

*Method.*

*Participants.* Eight participants were tested individually in a single one-hour session. All participants had normal or corrected-to-normal visual acuity. They were naïve with respect to the purpose of the experiment and received course credits for their participation.

*Apparatus.* The eyetracker employed in the current study was the SR Research Ltd. EyeLink system. This system has a sampling rate of 250 Hz (4 ms temporal resolution) and an average error of less than  $0.5^\circ$  of visual angle in the computation of gaze position. The EyeLink headband has three cameras, allowing simultaneous tracking of both eyes and of head position for head-motion compensation. By default, only the participant's dominant eye was tracked. In the present investigation, the configurable acceleration and velocity thresholds were set to detect saccades of  $0.5^\circ$  or greater. Stimulus displays were presented on two monitors, one for the participant (a 17-inch ViewSonic 17PS) and the other for the experimenter. The experimenter monitor was used to give feedback in real-time about the participant's computed gaze position.

*Stimuli.* As illustrated in Figure 1, four types of display items – search target, high-, medium-, and low-similarity distractors – were created based on Hooge and Erkelens (1999). Each individual item had a diameter of  $1.37^\circ$ . The target was a circle with a line width of  $0.17^\circ$  and the distractors were Cs with a gap of  $0.1^\circ$ . The high-, medium-, and low-similarity distractors had a line width of  $0.17^\circ$ ,  $0.26^\circ$ , and  $0.34^\circ$ , respectively. The orientation of the gap of individual Cs was chosen randomly from facing up, left, down, and right.

*Design.* Search displays were created by using an imaginary matrix of  $6 \times 6$  cells, which subtended  $13.2^\circ \times 13.2^\circ$  at a viewing distance of 60 cm. For all trials, the total number of items presented in a display (display size) was held constant at 18. Participants were asked to search for the target item in displays containing all three types of distractors (high-, medium-, and low-similarity distractors). In a target-absent display, there were six distractors of each type.

In target-present trials, a target-absent display was first created and then one of the distractors at 16 possible target locations (four cells at each corner of the grid) was randomly chosen to be replaced by the target item.

### **FIGURE 1 ABOUT HERE**

Each participant performed 480 trials in 5 blocks of 96 trials. An equal number of target-present and target-absent trials were used. The order of stimulus displays was randomized with a restriction that no more than four consecutive displays of a given type would occur. At the beginning of the experiment, participants received 24 practice trials.

*Procedure.* A 9-point calibration procedure was performed at the beginning of the experiment, followed by a 9-point calibration accuracy test. Calibration was repeated if any point was in error by more than 1° or if the average error for all points was greater than 0.5°. Each trial started with a drift correction in the gaze position. Participants were instructed to fixate on a black dot in the center of the computer screen and then press a start button to initiate a trial. They were asked to search for the target item and indicate whether it was in the display or not by pressing an appropriate button as quickly and as accurately as possible. The trial terminated if participants pressed one of the response buttons or if no response was made within 20 seconds. The time between display onset and the participant's response was recorded as the response time. The particular buttons used to indicate target presence were counterbalanced across participants.

### *Results and discussion.*

Trials with a saccade or a blink overlapping the onset of the search display, or with an incorrect response, were excluded from analysis. These exclusions accounted for 2.3% and 3.6% of total trials respectively. Following the convention of visual search literature, for each

participant, an outlier analysis was performed on the target-absent and target-present trials separately to eliminate those trials with response times more than 3.0 standard deviations above or below the mean. This resulted in the removal of 2.6% of trials from further analysis. The average response times were 2456.6 ms for the remaining target-absent trials and 1729.6 ms for the target-present trials.

For each trial, the distance was calculated between the fixation following each saccade and every item in the display. The item closest to the fixation was taken to be the target of that saccade. The number of saccades towards each type of distractor (high-, medium-, and low-similarity distractors) was then summed to assess saccadic selectivity. As pointed out by Zelinsky (1996), results from target-absent trials can be interpreted more clearly than those from target-present trials where the presence of the target item may influence search behavior. Therefore, only target-absent trials were included in the current analysis. Small-amplitude saccades, resulting in no change in the fixated display item, were also excluded from the analysis. Across eight participants, 12, 722 valid saccades were collected.

### **FIGURE 2 ABOUT HERE**

Following Hooge and Erkelens (1999), we examined whether saccadic selectivity was influenced by the type of display item fixated previously. A one-way repeated-measures ANOVA revealed that average duration of fixation on the currently fixated item (see Figure 2, Panel A) varied as a function of target-distractor similarity,  $F(2, 14) = 57.45, p < .001$ . Pairwise t-tests indicated that the duration of fixations on the high-similarity distractors was longer than that on the medium-similarity distractors, which, in turn, was longer than that on the low-similarity distractors, all  $t_s(7) > 6.36, p_s < .001$ . This analysis replicated the finding from previous studies that fixation duration varied with the difficulty in the discrimination of

the currently fixated display item. (e.g., Gould, 1967; Hooge & Erkelens, 1999; Jacobs, 1986; Lévy-Schoen, 1981).

Figure 2 (Panel B) shows the proportion of fixations on the high-, medium-, and low-similarity distractors following a previous fixation on a high-, medium-, or low-similarity distractor. Overall, high-similarity distractors received a larger percentage of fixations compared to both medium- and low-similarity distractors; saccadic frequencies towards the latter two types also differed significantly, all  $F_s(1, 7) > 48.01$ ,  $p_s < .001$ . Thus, this analysis clearly indicates that search process is guided by the overall target-distractor similarity: the more closely the distractors resemble the search target, the more likely they will be fixated during the search process. However, inconsistent with the waiting-room model, saccadic selectivity did not vary as a function of the central discrimination difficulty. Despite a difference of 36.6 ms in fixation duration between the high- and medium-similarity distractors and 15.0 ms between the medium- and low-similarity distractors, the proportion of fixations on the high-, medium-, and low-similarity distractors did not differ as a function of the type of distractor fixated previously, all  $F_s(2, 14) < 3.76$ ,  $p_s > .05$ .

If peripheral analysis benefits from a longer duration of the previous fixation as suggested by the waiting-room model, a more direct way of examining this issue would be to measure saccadic selectivity across the whole range of the fixation duration distribution. Thus, we segmented the distribution of fixation duration into four quarters by using the first quartile, the median, and the third quartile (The average fixation durations for the first, second, third, and last quarters of the distribution were 119.3, 172.8, 214.7, and 306.4 ms respectively). Figure 2 (Panel C) shows that the selectivity of a subsequent saccade became slightly weaker following a longer fixation duration. The percentage of saccades directed towards the high-similarity distractors decreased from 73.2% in the first quarter of the fixation duration distribution to

67.8% in the fourth quarter of the distribution,  $t(7) = 2.81, p < .05$ . This finding is clearly inconsistent with the prediction of the waiting-room model.

Although the current experiment attempted to replicate the findings by Hooge and Erkelens (1999), there are some methodological differences between the two studies that may explain the inconsistency in findings. Specifically, Hooge and Erkelens adopted a blocked design (using different combinations of line width and gap size of Cs in different sessions). In contrast, in the current study a combination of high-, medium-, and low-similarity distractors were presented in each display. In addition, unlike in the present study, Hooge and Erkelens manipulated the difficulty of peripheral selection (line-width of Cs). Accordingly, one could argue that these methodological differences are responsible for the sizeable difference in fixation duration between the high- and low-similarity distractors as well as the effect of central processing difficulty on peripheral selection found in the study by Hooge and Erkelens. One could further argue that a difference of 50 ms in fixation duration observed in the current study might be too small to influence saccadic selection. However, our examination of saccadic selectivity across the whole range of the fixation duration distribution (see Figure 2C) did not provide evidence for this argument.

A recent study by Findlay, Brown, and Gilchrist (2001) may be relevant to the current findings. These investigators examined the relationship between the duration of a previous fixation and the precision of target acquisition in a subsequent saccade. They similarly found that saccades following brief fixations had the same probability of reaching the target as those following longer fixations. Thus, results from the current experiment and Findlay et al. indicate that saccadic selectivity is not strongly influenced by the duration of previous fixation as proposed by the waiting-room model.

## Experiment 2

The underlying assumption of the waiting-room model is that the peripheral analysis is an independent process, which is carried out in parallel to the central discrimination task but does not share resources with the latter. If the central discrimination and peripheral selection share resources, a different prediction can be derived when increasing the difficulty of the central discrimination task. This can be illustrated considering prior research on foveal load (henceforth the "foveal-load" model). Those studies (e.g., Ikeda & Takeuchi, 1975; Mackworth, 1965) typically employed two concurrent visual tasks, one in the center of the display and the other in the periphery. L. J. Williams (1989), for example, had participants perform a central letter discrimination task that either induced a high or low foveal load. In a simultaneous peripheral task, participants named a one-digit number shown in the periphery. It was found that a more difficult central task (i.e., higher foveal load) decreased participants' performance in the peripheral detection task. Similar dependence of peripheral analysis on the difficulty of the central processing has also been found in reading research. Henderson and Ferreira (1990) investigated the influence of foveal task difficulty on the benefit of parafoveal previewing by manipulating the lexical frequency and syntactic difficulty of the foveated word. They found that less parafoveal information was acquired when the foveal processing was difficult, despite the fact that in the difficult condition the parafoveal word was available for a longer amount of time than in the easy condition. In the context of visual search, this model would predict that peripheral analysis is inversely related to the demands of central processing and saccade selection will be less efficient if the central discrimination task becomes more difficult.

In Experiment 2, we further examined whether participants' performance of peripheral selection is influenced by the difficulty of the central discrimination with a dual-task



manipulation. In a dual-task condition, the central processing was rendered more difficult with the introduction of a concurrent visual task – besides detecting the presence of the search target, participants also had to find and memorize the largest number presented within a gaze-contingent moving window (see Figure 3 for an example). Gaze-contingent techniques have been widely used in reading, scene perception, and recently in visual search studies (e.g., Bertera & Rayner, 2000; Murphy & Foley-Fisher, 1988; Pomplun, Reingold, & Shen, 2001a, b; Rayner & Fisher, 1987; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Reingold, Charness, Pomplun, & Stampe, 2001; van Diepen, De Graef, & d'Ydewalle, 1995; see Rayner, 1998 for a review). In a single-task condition, participants were asked to concentrate on the visual search task only while ignoring the numbers presented. We examined whether saccadic selectivity differ across the two conditions – the foveal-load model predicts a decrease in saccadic selectivity in the dual-task condition whereas the waiting-room model makes an opposite prediction.

### *Method.*

*Participants.* Eight participants were tested in a single one-hour session. None of them had participated in the previous experiments. All participants had normal or corrected-to-normal vision and were paid \$10 for their participation. They were not aware of the purpose of the experiment.

*Stimuli and design.* Four types of display items – search target, high-, medium-, and low-similarity distractors – were constructed by using a matrix of  $4 \times 4$  squares, with eight of them filled with black and the rest remaining white (see von Grünau, Dubé, & Galera, 1994, Experiment 5). The high-, medium-, and low-similarity distractors had a physical difference of

1, 3, and 6 with respect to the target item. The physical difference was defined as the number of black squares that had to be moved from one location in the  $4 \times 4$  matrix to another in order to change the target into the respective distractor. This construct of similarity by physical difference was verified by a subjective rating of stimulus similarity as well as search efficiency data (von Grünau et al., 1994). Each individual element subtended  $1.0^\circ \times 1.0^\circ$  on a white background of  $15.2^\circ \times 15.2^\circ$ .

### **FIGURE 3 ABOUT HERE**

The current experiment examined whether participants' performance of peripheral selection is influenced by the difficulty of the central discrimination with a dual-task manipulation. This was achieved by introducing a gaze-contingent moving window and by instructing participants to attend, or not to attend, to information presented within the window across conditions. In each trial, a circular gaze-contingent moving window of  $4.8^\circ$  in diameter was presented (see Figure 3 for an example). The moving window, constantly centered on the participants' fixation point, unveiled one 2-digit number from 10 to 99 during each fixation. The numbers were placed at a distance of  $1.8^\circ$  from any neighboring display item. Each individual number extended  $0.4^\circ$  horizontally and  $0.3^\circ$  vertically. Display items falling outside the window were clearly visible to the participants. In the single-task condition, participants were asked to make a decision regarding the presence of the search target as quickly and as accurately as possible. They were instructed to ignore any number presented within the window. In the dual-task condition, once participants made response regarding the presence of the search target, they also had to report the largest number they had seen in that trial.

The current experiment included eight blocks of 36 test trials, with half of the trials in the single-task load condition and the other half in the dual-task condition. This amounted to 72 trials in each cell of the design (target presence by task manipulation). Single-task and dual-

task conditions were tested in alternating blocks with the order of conditions counterbalanced across participants. At the beginning of the experiment, participants received 48 practice trials.

### *Results and discussion.*

Trials with a saccade or a blink overlapping the onset of a search display, with an incorrect response, or with an excessively long or short response time (3.0 standard deviations above or below the mean) were excluded from further analysis. These exclusions accounted for 2.6%, 7.2%, and 2.3% of total trials respectively. Although the primary focus of the current experiment was the examination of saccadic selectivity during the search process, response time (RT), error rate, number of fixations per trial, and fixation duration were also analyzed (see Table 1). These search performance measures were included to validate the effectiveness of the dual-task manipulation.

### **TABLE 1 ABOUT HERE**

*Search performance.* Response time, error rate, number of fixations, and fixation duration were subject to separate  $2$  (target presence: present vs. absent)  $\times$   $2$  (task manipulation: single vs. dual) repeated-measures ANOVAs. Overall, target-absent trials yielded longer search time,  $F(1, 7) = 45.88, p < .001$ , more fixations,  $F(1, 7) = 68.08, p < .001$ , and fewer errors,  $F(1, 7) = 13.92, p < .01$ , than did target-present trials. It is also clear from Table 1 that the dual-task condition yielded longer RT,  $F(1, 7) = 10.33, p < .05$ , more fixations,  $F(1, 7) = 12.83, p < .01$ , and longer fixation duration,  $F(1, 7) = 26.64, p < .001$ , than did the single-task condition.

*Saccadic selectivity.* The preceding search performance analyses suggest that the dual task manipulation influenced search performance. It is important to determine whether saccadic selectivity was similarly affected. For each individual participant, the proportions of saccades

directed to each type of distractor were determined in both the single-task condition and the dual-task condition (see Figure 4).

#### **FIGURE 4 ABOUT HERE**

As can be seen from Figure 4, saccadic frequency towards high-similarity distractors was higher than that towards low-similarity distractors, which, in turn, was higher than that towards the low-similarity distractors, all  $F_s(1, 7) > 143.78, p_s < .001$ . More importantly, although the dual-task manipulation decreased search efficiency, it had very little influence on the pattern of saccadic selectivity. Proportions of saccades directed towards the high-, medium-, and low-similarity distractors did not differ across the single-task and dual-task conditions, all  $F_s < 1$ . This pattern of saccadic selectivity did not provide support for either the waiting-room model or the foveal-load model.

#### **Experiments 3A and 3B**

Experiment 3 was designed to further investigate the relation between the difficulty of the central discrimination and peripheral selection by employing a more powerful manipulation of the central discrimination difficulty. We adopted a gaze-contingent moving-mask paradigm, in which a mask was presented centered on the point of gaze at a certain delay following the beginning of a fixation. With this manipulation, we selectively masked information required for the central discrimination while leaving information vital for the peripheral selection relatively intact. If the central discrimination and peripheral selection are independent processes, interference with the central discrimination should have no effect on peripheral selection. We should predict that saccadic selectivity remains constant even if the information supporting the central discrimination is severely degraded. However, if the two processes are

interdependent as suggested by the foveal-load model, a decrease in saccadic selectivity is predicted when the central discrimination becomes more difficult.

Two versions of mask manipulation were adopted. In Experiment 3A, we manipulated the delay between fixation onset and mask onset: a no-mask condition, and two masking conditions (50-ms mask delay and 117-ms mask delay) were included. Based on previous studies (e.g., Rayner et al., 1981), it was expected that a shorter mask delay (50 ms) would lead to a greater degradation of foveal processing and add to the difficulty of the discrimination task. In Experiment 3B, we manipulated the mask frequency by including three conditions: a no-mask condition, in which none of the fixations was masked, a sparse-masking condition, in which a quarter of the fixations were masked, and a dense-masking condition, in which half of the fixations were masked. In masked fixations, the delay between the beginning of the fixation and the onset of the mask was 50 ms. The mask frequency manipulation allowed us to compare search performance and saccadic selectivity across the dense-masking, sparse-masking and no-mask conditions. It also allowed us to examine the selectivity of saccades following a masked fixation and following an unmasked fixation within the same trial.

#### *Method.*

*Participants.* Sixteen participants (half in Experiment 3A and half in Experiment 3B) were tested in a single one-hour session. None of them had participated in the previous experiments. All participants had normal or corrected-to-normal vision and were paid \$10 for their participation. They were not aware of the purpose of the experiment.

*Stimuli and design.* The same set of display items as in the previous experiment was used. Each individual item subtended  $1.37^\circ$  both horizontally and vertically. One major change implemented in the current experiment was the introduction of a circular gaze-contingent

moving mask in some trials. The mask, 4° of visual angle in diameter, was displayed 50 ms (50-ms mask delay condition in Experiment 3A and all mask conditions in Experiment 3B) or 117 ms (117-ms mask delay condition in Experiment 3A) following the onset of a fixation, and remained centered on the gaze position. The mask, composed of random black-and-white patches, replaced display items or fragments of display items that were within 2.0° radius from the gaze position. The pattern of the moving mask varied from trial to trial (see Figure 5 for an example). In other trials, no mask was displayed (no-mask condition).

### **FIGURE 5 ABOUT HERE**

In Experiment 3A, participants were tested in six blocks of 48 trials, with half of the trials in the no-mask condition and the remaining trials divided evenly between the 50-ms and 117-ms mask delay conditions. In Experiment 3B, participants received 288 test trials, with 48 trials in each cell of the design (mask condition by target presence). In both experiments, participants also received 48 practice trials at the beginning of the experiment.

#### *Results and discussion.*

Trials with a saccade or a blink overlapping the onset of a search display, with an incorrect response, with an excessively long or short response time, or with no response (timed-out) were excluded from further analysis. These exclusions accounted for 1.5%, 4.8%, 0.6%, and 2.7% of total trials respectively for Experiment 3A and 2.0%, 4.8%, 1.4%, 0% respectively for Experiment 3B.

*Search performance.* In order to validate the effectiveness of the mask manipulation, response time, error rate, and number of fixations per trial were analyzed by separate 2 (target presence: present vs. absent)  $\times$  3 (mask condition: no mask, 50-ms mask delay, or 117-ms mask delay in Experiment 3A; no mask, dense masking, or sparse masking in Experiment 3B)

repeated-measures ANOVAs. Tables 2 and 3 summarize the results of these analyses. As can be seen in Table 2, in Experiment 3A response times were longest in the 50-ms mask delay condition, and shortest in the no-mask condition. This difference was more pronounced in target-absent trials than in target-present trials, as indicated by a significant interaction between target presence and mask condition,  $F(2, 14) = 8.19, p < .01$ . This pattern was similarly exhibited in the fixation-number data,  $F(2, 14) = 5.36, p < .01$ . In addition, the error-rate data suggest that the presence of a foveal mask was detrimental to the search performance, as the 50-ms mask delay condition was more error-prone than were the other two conditions,  $F(2, 14) = 5.24, p < .01$ .

Similarly, as can be seen in Table 3, search performance in Experiment 3B varied as a function of mask condition. Response times were longest in the dense-masking condition and shortest in the no-mask condition. This difference was more pronounced in target-absent trials than in target-present trials, as indicated by a significant interaction between target presence and mask condition,  $F(2, 14) = 4.29, p < .05$ . The dense-masking condition also produced more fixations than did the sparse-masking condition, which in turn produced more fixations than did the no-mask condition,  $F(2, 14) = 26.63, p < .001$ . Thus, in both Experiments 3A and 3B, masking substantially degraded search efficiency. These changes in search performance induced by a foveal mask are consistent with findings from previous studies (e.g., Bertera, 1988; Bertera & Rayner, 2000; Murphy & Foley-Fisher, 1988; Rayner et al., 1981).

#### **TABLES 2 AND 3 ABOUT HERE**

*Saccadic selectivity.* As can be seen in Panel A of Figure 6, in Experiment 3A, although the presence of a foveal mask affected search performance substantially, it had very little effect on the performance of peripheral selection. Proportions of saccades directed towards the high-

medium- and low-similarity distractors did not differ across the no-mask, 50-ms mask delay, and 117-ms mask delay conditions, all  $F$ s (2, 14) < 1.99,  $p$ s > .05.

In Experiment 3B, we first categorized five types saccades (saccade type): those in the no-mask condition, those following a masked fixation in the dense-masking condition, those following an unmasked fixation in the dense-masking condition, those following a masked fixation in the sparse-masking condition, and those following an unmasked fixation in the sparse-masking condition. For each individual participant, the proportions of fixations on the high-, medium-, and low-similarity distractors were calculated (see Figure 6, Panel B). Despite the fact that the central discrimination was made more difficult by the presence of a gaze-contingent moving mask, saccadic selectivity was not influenced by the mask manipulation. The proportion of saccades directed towards high-similarity distractors remained the same across the five types of saccades,  $F(4, 28) = 1.36, p = 0.274$ .

### **FIGURE 6 ABOUT HERE**

#### **Summary**

The current paper examined the robustness of guidance of eye movements during visual search. Consistent with major visual search theories (e.g., Duncan & Humphreys, 1989; Treisman & Sato, 1990; Wolfe, 1994; Wolfe et al., 1989; but see Treisman & Gelade, 1980; Treisman et al., 1977), the present experiments demonstrated that participants direct their saccades selectively during the search process, revealing a strong correspondence between target-distractor similarity and saccadic frequency towards the respective distractors. This adds to a growing literature on the guidance of eye movements in visual search tasks (e.g., Bichot & Schall, 1998; Findlay, 1997; Findlay et al., 2001; Findlay & Gilchrist, 1998; Hooge & Erkelens, 1999; Luria & Strauss, 1975; Motter & Belky, 1998b; Pomplun, Reingold, & Shen,



2001a, submitted; Pomplun, Reingold, Shen, & Williams, 2000; Scialfa & Joffe, 1998; Shen & Reingold, 1999; Shen, Reingold, & Pomplun, 2000; D. E. Williams & Reingold, 2001; L. G. Williams, 1967)

We studied the robustness of visual guidance by examining whether the magnitude of saccadic selectivity is influenced by the difficulty of the central discrimination task. In Experiment 1, while the duration of current fixations increased with increasing target-distractor similarity, there was no evidence that saccadic selectivity was influenced by the target-distractor similarity of the previously fixated display item or by the duration of the previous fixation (see also Findlay et al., 2001). These findings are inconsistent with the predictions by the waiting-room model (Hooge & Erkelens, 1999). In addition, we manipulated the difficulty of the central discrimination by introducing a concurrent visual task (Experiment 2) and by presenting a gaze-contingent moving foveal mask (Experiments 3A and 3B). Although both manipulations substantially degraded the overall visual search performance, the magnitude of peripheral selection was not affected. This is not consistent with the notion that the central discrimination and the peripheral analysis share the same pool of attentional resources as suggested by the foveal load model. Thus, the current series of experiments provide convergent evidence that peripheral selection is a robust process, largely independent of the central processing difficulty.

The dissociations between the strong effects of the present manipulations on the central processing difficulty and the lack of impact on saccadic selectivity suggest that different processes may underlie the performance of the central discrimination and peripheral selection tasks. Specifically, peripheral selection may be supported by a preattentive process, which is carried out in a spatially parallel manner. Although the preattentive processing successfully supports and biases the selection of the next display item to be fixated, it does not enable the

observer to determine the exact form of the item or to bind the individual features into a complete object (see Rayner & Fisher, 1987; Treisman, 1996; Wolfe, 1998; Wolfe & Bennett, 1997). In contrast, the post-selection central discrimination requires focal attention and involves extracting critical feature of the fixated item or integrating individual features into a complete object (e.g., Navon & Pearl, 1985; Rayner & Fisher, 1987; Treisman, 1988; Wolfe, 1998; Wolfe & Bennett, 1997). Thus, the present study provides important convergent evidence that saccadic selectivity in visual search is a form of preattentive guidance.

During the past two decades, several studies have investigated the relation between foveal processing and peripheral analysis in reading research, and different theoretical models (e.g., Henderson, 1992; Henderson & Ferreira, 1990, 1993; Morrison, 1984) have been proposed to explain the interplays between the two processes in reading tasks. The current study, along with Hooze and Erkelens (1999) and Findlay et al. (2001), began to provide similar data in the context of visual search. The picture emerging from these recent studies is complex and suggests that the components of visual processing are multi-determined by variables such as task context, stimulus materials, and attentional factors. The present investigation highlights the need for further explorations of the relation between foveal processing and peripheral analysis in complex visual tasks and provides a theoretical and methodological framework for this line of research.

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Table 1.

*Search performance as a function of target presence and task manipulation in Experiment 2*

	Single Task		Dual Task	
	Absent	Present	Absent	Present
Response Time (ms)	2157.7 (182.4)	1289.2 (84.7)	2788.2 (331.8)	1665.6 (204.3)
Error Rate (%)	1.7 (0.6)	13.4 (3.3)	2.7 (0.5)	10.8 (1.6)
Number of Fixations per trial	8.7 (0.7)	4.3 (0.2)	10.4 (1.1)	5.5 (0.5)
Fixation Duration (ms)	203.8 (7.6)	193.8 (8.7)	221.6 (6.5)	232.6 (9.0)

Note. Values in parentheses represent standard errors.

Table 2.

*Search performance as a function of target presence and mask condition in Experiment 3A*

	No Mask		117-ms Mask Delay		50-ms Mask Delay	
	Absent	Present	Absent	Present	Absent	Present
Response Time (ms)	3036.2 (363.2)	1467.0 (167.5)	5191.3 (811.9)	2609.9 (467.3)	7711.9 (1012.1)	3894.7 (619.6)
Error Rate (%)	1.0 (0.3)	3.8 (1.2)	1.7 (1.0)	7.6 (1.6)	6.6 (2.8)	12.5 (2.9)
Number of Fixations/trial	12.4 (1.4)	5.8 (0.8)	19.5 (3.2)	9.3 (1.9)	27.2 (3.6)	13.3 (2.7)
Fixation Duration (ms)	194.7 (7.5)	194.2 (8.2)	225.1 (9.1)	234.7 (12.6)	241.2 (13.2)	251.3 (20.4)

Note. Values in parentheses represent standard errors.





Table 3.

*Search performance as a function of target presence and mask condition in Experiment 3B*





	No Mask		Sparse Masking		Dense Masking	
	Absent	Present	Absent	Present	Absent	Present
Response Time (ms)	2529.4 (301.5)	1359.1 (163.1)	3081.3 (392.5)	1675.0 (237.5)	3655.7 (374.7)	2161.5 (298.1)
Error Rate (%)	0.5 (0.3)	6.5 (2.4)	2.1 (0.7)	6.8 (2.2)	2.9 (2.0)	10.2 (2.7)
Number of Fixations/trial	10.8 (1.2)	5.0 (0.5)	12.7 (1.5)	6.2 (0.7)	14.3 (1.4)	7.6 (1.0)
Fixation Duration (ms)	203.54 (9.0)	195.3 (11.9)	218.1 (9.7)	222.8 (10.5)	227.2 (9.6)	236.4 (12.1)

Note. Values in parentheses represent standard errors.

## Figure Captions

*Figure 1.* Sample search displays used in Experiment 1. The target was a filled circle  and the distractors were open circles with different target-distractor similarity (High: ; Medium: ; Low: .

*Figure 2.* Panel A: Average duration of fixations as a function of target-distractor similarity of the currently fixated stimulus. Panel B: Frequency of saccades towards the high-, medium-, and low-similarity distractors as a function of the type of distractor (high-, medium-, or low-similarity) fixated previously. Panel C: Frequency of saccades directed towards the high-, medium-, and low-similarity distractors as a function of the previous fixation duration. The distribution of the previous fixation duration was segmented into four quarters by using the first quartile, the median, and the third quartile.

*Figure 3.* Sample search displays overlaid with a gaze-contingent moving window (Experiment 2). Target was  and distractors had different levels of target-distractor similarity (High: ; Medium: ; Low: ). The window center was aligned with the current gaze position.

*Figure 4.* Frequency of saccades directed to the high-, medium-, and low-similarity distractors in the single-task and dual-task conditions.

*Figure 5.* Sample search displays used in Experiments 3A and 3B. The gaze-contingent moving mask was centered on the participant's current gaze position.

*Figure 6.* Panel A: Frequency of saccades directed to the high-, medium-, and low-similarity distractors in the no-mask, 50-ms mask delay, and 117-ms mask delay conditions in Experiment 3A. Panel B: Frequency of saccades directed to the high-, medium-, and low-similarity distractors in Experiment 3B. Note: No Mask = saccades in the no-mask condition; Sparse Masking, No Mask = saccades following an unmasked fixation in the sparse-masking condition; Sparse Masking, Mask = saccades following a masked fixation in the sparse-masking condition; Dense Masking, No Mask = saccades following an unmasked fixation in the dense-masking condition; Dense Masking, Mask = saccades following a masked fixation in the dense-masking condition.

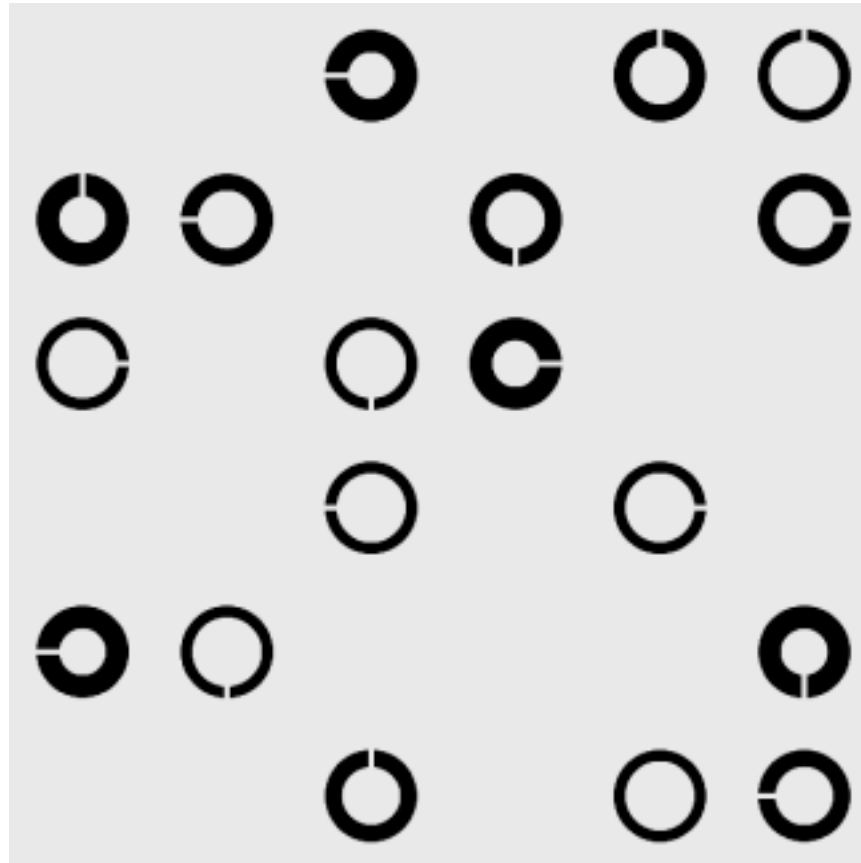


Figure 1

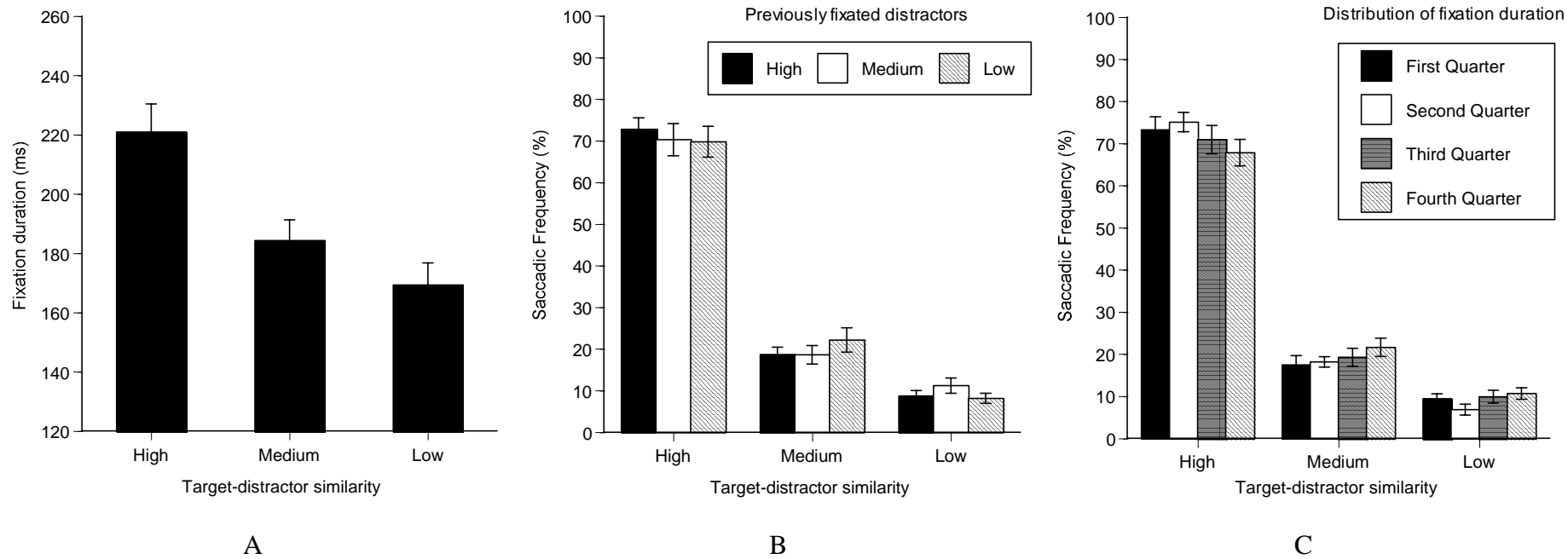


Figure 2

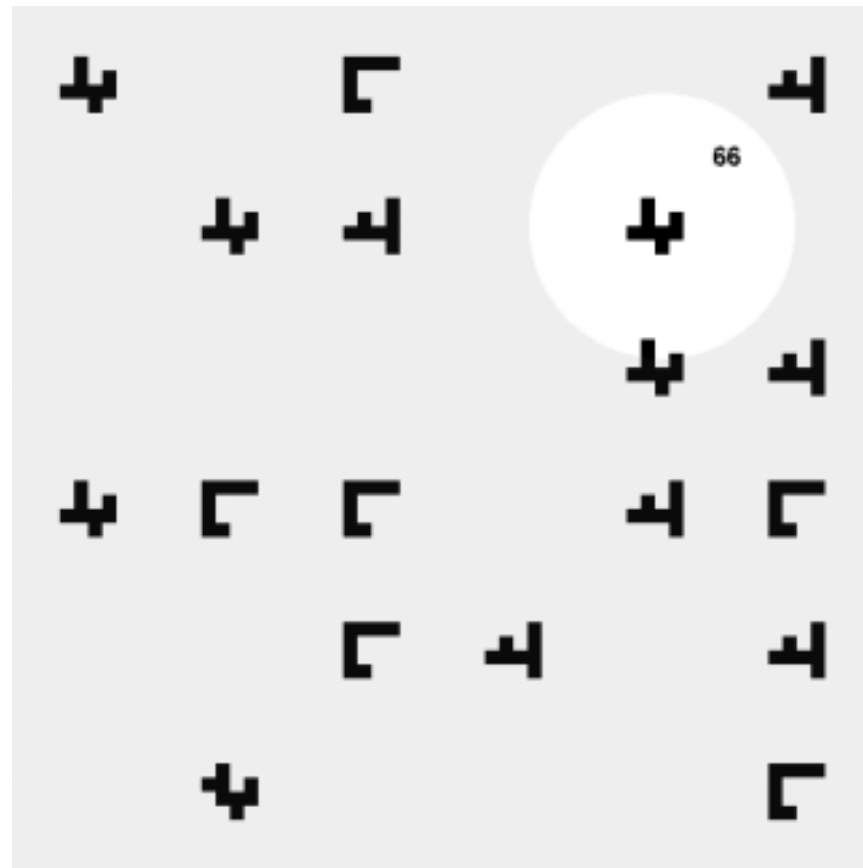


Figure 3



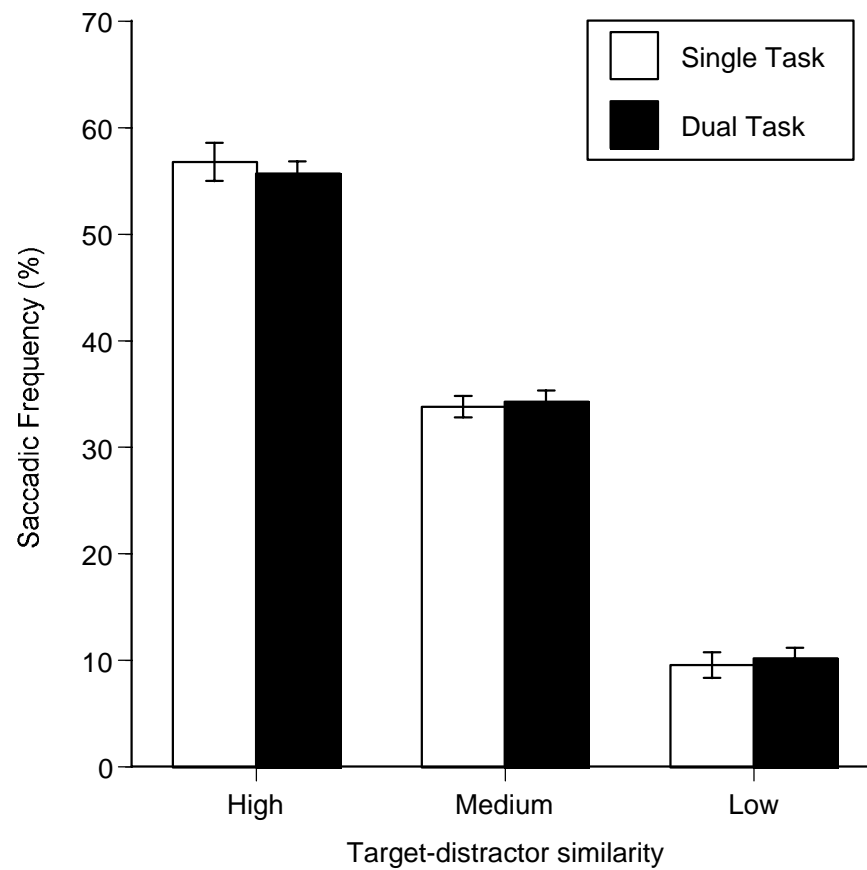


Figure 4

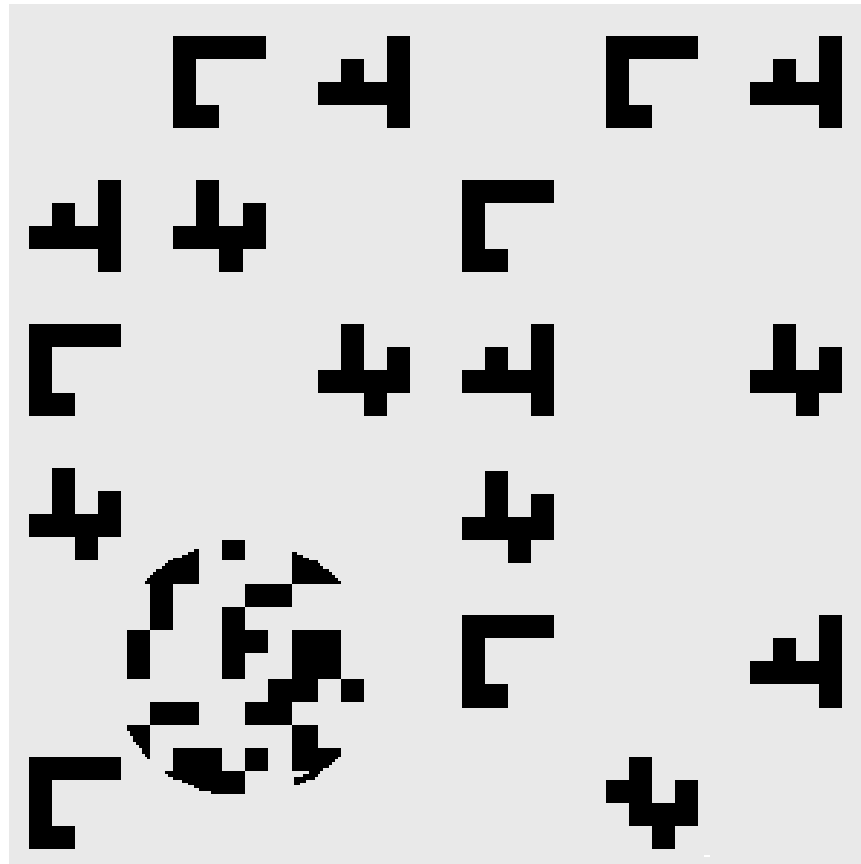
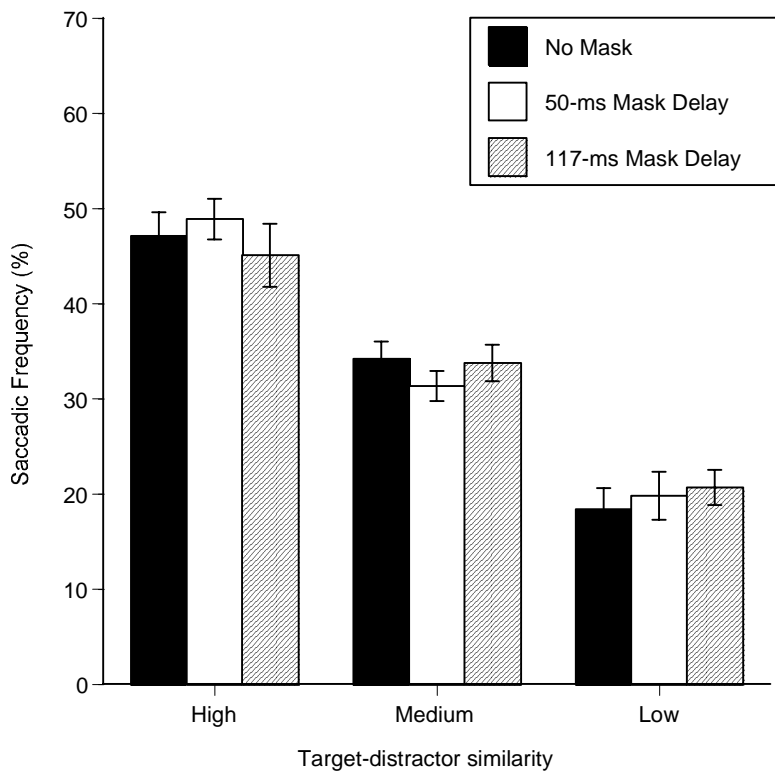
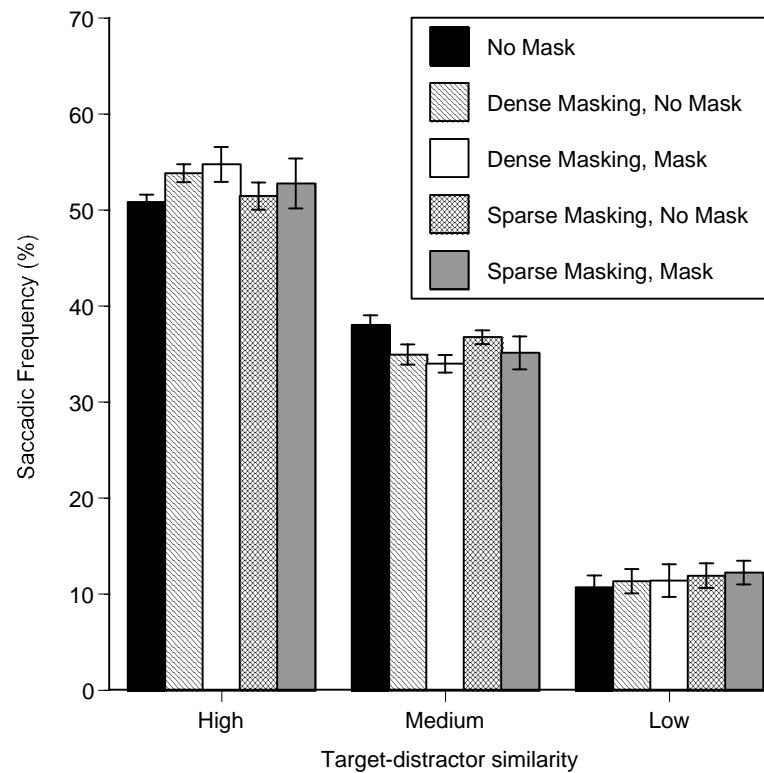


Figure 5



A



B

Figure 6