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Guidance of Eye Movements during Conjunctive Visual Search: The Distractor-Ratio Effect

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Abstract

The distractor-ratio effect refers to the finding that search performance in a conjunctive visual search task depends on the relative frequency of two types of distractors if the total number of items in a display is fixed. The current study examined the mechanisms underlying the distractor-ratio effect by monitoring participants' eye movements during the search process. Experiment 1 examined the influences of stimulus discriminability on the distractor-ratio effect. A quadratic change in response time, number of fixations per trial, and initial saccadic latency as a function of distractor ratio and a tendency to flexibly search through a smaller subset of distractors was observed when the shape dimension was highly discriminable but was largely eliminated when less-discriminable shapes were employed. Experiment 2 extended the distractor-ratio effect to a color × color within-dimension conjunction search task by demonstrating that saccades were consistently biased towards the smaller subset of distractors. Implications of the current findings for visual search theories are discussed.

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 the past two decades, several models of visual search have been proposed to explain search efficiency across a variety of search tasks. The first major theory is the original feature-integration theory by Treisman and her colleagues (Treisman & Gelade, 1980; Treisman, 1988). This theory proposes a dichotomy between a preattentive mode and an attentive mode of visual information processing. More specifically, this model argues that searching for a target defined by the presence of a unique feature (feature search), such as searching for a green *X* among red and blue *X*s, could be carried out preattentively. Response time in such a task is not influenced by display size. 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, focal attention is required. Participants have to inspect the search display in a serial item-by-item fashion until target detection or exhaustive search.

The original feature-integration theory, however, 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., Egeth, Virzi, & Garbart, 1984; McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986; Theeuwes & Kooi, 1994; Wolfe et al., 1989; Zohary & Hochstein, 1989). This is inconsistent with the notion of a 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 (e.g., the attentional-engagement theory by Duncan & Humphreys, 1989; the guided-search model by Wolfe, 1994; see also the revised feature-integration theory by Treisman & Sato, 1990). For example, the guided-search model by Wolfe and his colleagues (e.g., Cave & Wolfe, 1990; Wolfe 1994; Wolfe et al., 1989; Wolfe & Gancarz, 1996) 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 of that item to the target, and a bottom-up component, quantifying the similarity of that item 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 highest activation until the target is found or the criterion to make a negative response is reached (Cave & Wolfe, 1990; Chun & Wolfe, 1996).

The original feature-integration theory and the guided-search model also have different predictions concerning patterns of eye movements during the search process. Imagine a complex conjunctive search task involving several types of distractors with different levels of target-distractor similarity. In such a task, participants will typically have to make a few saccades before a decision on target presence can be made. Given the nature of serial item-by-item processing, the feature-integration theory predicts that 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. In contrast, the guided-search model predicts that those distractors that are more similar to the target item have higher activation values and thus will be more likely to be fixated than will the less similar ones. As a result, there will be a bias in the distribution of saccadic endpoints (i.e., saccadic selectivity).

During the past few decades, the selectivity in the spatial distribution of eye movements have been examined in several visual search studies. Consistent with the guided-search model, stimulus dimensions such as color, shape, contrast polarity, and size have been shown to bias the distribution of saccadic endpoints in conjunctive search tasks (e.g., Findlay, 1997; Findlay & Gilchrist, 1998; Hooge & Erkelens, 1999; Luria & Strauss, 1975; Motter & Belky, 1998b; Pomplun, Reingold, Shen, 2001; Scialfa & Joffe, 1998; Shen, Reingold, & Pomplun, 2000; Shen, Reingold, Pomplun, D. E. Williams, in press; D. E. Williams & Reingold, 2001; L. G. Williams, 1966; but see Zelinsky, 1996).

Distractor-ratio effect

Evidence for a selective processing mechanism in conjunctive search tasks also comes from studies using the *distractor-ratio manipulation*. In a typical conjunction search task, each trial contains an equal number of two types of distractors. The total number of items within a search display (display size) is manipulated and the search efficiency is examined by the change in response time and/or error rate as a function of display size (see Treisman, 1988; Wolfe, 1998 for a review). However, several previous studies have shown that visual search performance is sensitive to the ratio between the two types of distractors, even when the total number of items in a display remains constant (e.g., Bacon & Egeth, 1997; Egeth et al., 1984; Kaptein et al., 1995; Poisson & Wilkinson, 1992; Zohary & Hochstein, 1989).

For example, Zohary and Hochstein (1989) adopted a color × orientation conjunction search task and asked participants to decide whether a red horizontal bar was present among an array of red vertical (same-color distractors) and green horizontal (same-orientation distractors) bars. The search display was presented very briefly (50 ms) and then, after a variable interval (stimulus onset asynchrony, SOA), masked. One critical manipulation in this study was the ratio between the two types of distractors (same-color vs. same-orientation) presented in a given array. Zohary and Hochstein found that the SOA required to reach a 70% correct response rate was a quadratic function of the number of distractors sharing color with the search target. Specifically, detection was relatively easy for displays with extreme distractor ratios (i.e., either the same-color or same-orientation distractors were rare) but relatively difficult for displays in which the two types of distractors were equally represented. The finding that visual-search efficiency in a conjunctive search task depends on the relative frequency of the two types of distractors has been referred to as the *distractor-ratio effect* (Bacon & Egeth, 1997).

Different interpretations have been proposed to explain the distractor-ratio effect. Zohary and Hochstein (1989) interpreted their findings as reflecting participants' ability to scan a smaller subset of distractors and to switch between different subsets from trial to trial (henceforth subset-switching account). According to this account, upon the presentation of a search display, an a priori decision is made concerning the approximate ratio of the number of items in one subset (as defined by a specific feature shared with the target item) relative to the number of items in the other subset. Such information is then used to segment the search display and determine which feature subset will be scanned. In contrast, Poisson and Wilkinson (1992) suggested that in a search task with distractor-ratio manipulation participants do not switch feature subsets from trial to trial. Instead, participants restrict their search to items belonging to the dominant feature subset (i.e., color in their study). An item-by-item search through a single feature set would produce response times that increase linearly with increasing number of items in the selected subset. However, when most of the items in the display belong to one feature set, response times begin to decrease rather than continue to increase with increasing number of items in that subset. Poisson and Wilkinson argued that this decrease in response time is due to the operation of strong distractor grouping because those search displays contain large clusters of homogeneous distractors, which may enable participants to reject them as a group (henceforth distractor-grouping account).

To test between the subset-switching account and the distractor-grouping account for the distractor-ratio effect, Shen, Reingold, and Pomplun (2000) examined participants' patterns of eye movements during the search process. They employed a color × shape conjunction search task and systematically manipulated the ratio between the same-color and same-shape distractors in a display. They found a quadratic change in search performance measures such as manual response time, number of fixations per trial, and initial saccadic latency as a function of distractor ratio. Search performance was worse when the ratio between the same-color and same-shape distractors approximated 1:1 and gradually improved as the ratio deviated from 1:1, with performance being best at extreme distractor ratios (i.e., very few distractors of one type). More importantly, Shen et al. demonstrated that when there were very few same-color distractors, participants' saccadic endpoints were biased towards the color dimension whereas when there were very few same-shape distractors, saccades were biased towards the shape dimension. Results from that study suggest that in a distractor-ratio paradigm, participants take advantage of the display information and flexibly switch between different subsets of distractors on a trial-by-trial basis (see Zohary & Hochstein, 1989). This rules out distractor grouping (e.g., Poisson & Wilkinson, 1992) as a viable explanation for the distractor-ratio effect.

Current study

The current study provides two extensions to Shen, Reingold, and Pomplun (2000) by examining the generality of the flexibility in the distractor ratio effect. One finding from Shen et al. (see also Zohary & Hochstein, 1989; Possion & Wilkinson, 1992) is that almost all of the search measures examined (manual response time, fixation number, saccadic latency, and saccadic bias) were asymmetrical, suggesting that the distractor-ratio effect is influenced by the greater saliency or discriminability of the color dimension than the shape dimension. The importance of stimulus discriminability is well established in the visual search literature and has been incorporated into major theoretical frameworks of visual search (e.g., Duncan & Humphreys, 1989; Palmer, Verghese, & Pavel, 2000; Treisman, 1991; Wolfe, Cave, & Franzel, 1989; Wolfe, 1994). Numerous previous studies have demonstrated that detecting a search target becomes more difficult with increased similarity (i.e., lower discriminability) between the target item and the distractors (e.g., Nagy & Sanchez, 1990; Neisser, 1967; Pashler, 1987; Rayner & Fisher, 1987).

In conjunction search tasks, several previous studies have reported that changing the stimulus discriminability along one dimension may alter the overall search performance drastically. For example, Driver and McLeod (1992) demonstrated a reversal of search asymmetry (e.g., Treisman & Souther, 1985; Treisman & Gormican, 1988; Shen & Reingold, 2001) in a movement × orientation conjunction search task by changing the discriminability along the orientation dimension. They found that in displays containing intermingled moving and stationary items, searching for a salient tilted target (45º vs. vertical) was easier among moving items than among stationary ones. However, when the orientation discrimination to distinguish the search target from the distractors was made more difficult (9º vs. vertical), stationary targets were easier to detect than were moving targets. Similarly, D. E. Williams and Reingold (2001) found that in color × shape × orientation triple conjunction search tasks, changing the discriminability along the shape dimension (high-discriminability: *C* vs. *T*; low-discriminability: *E* vs. *F*) induced different patterns of eye movements. Greater saccadic selectivity towards those distractors sharing shape with the target was observed when more discriminable shapes were employed. Results from both studies pointed to the fact that search performance in conjunction search tasks was strongly influenced by the relative discriminability between different dimensions (see also Theeuwes, 1992). Thus, in Experiment 1, we examined the effect of stimulus discriminability on search performance and saccadic selectivity in a search task with distractor-ratio manipulation.

In Experiment 2, the distractor-ratio manipulation was implemented in the context of within-dimension conjunction searches. Previously-mentioned studies on the distractor-ratio effect (Bacon & Egeth, 1997; Zohary & Hochstein, 1989; Poisson & Wilkinson, 1992; Shen, Reingold, & Pomplun, 2000; current Experiment 1) examined cross-dimension conjunction search tasks only. In Experiment 2, we examined whether the distractor-ratio effect is observed in within-dimension conjunction search tasks.

In a series of experiments, Wolfe, Yu, Stewart, Shorter, Friedman-Hill, and Cave (1990) demonstrated that searches for a conjunction of two features from the same dimension (e.g., color × color, orientation × orientation) were less efficient than searches for a conjunction across two dimensions (e.g., color × orientation). Wolfe et al. (1990; see also Wolfe, Friedman-Hill, & Bilsky, 1994; Wolfe, 1994, 1996) argued that whereas cross-dimension conjunctions can be searched in a parallel fashion, within-dimension conjunctions are necessarily searched in a serial self-terminating fashion. This is because in cross-dimension search tasks, the target receives two sources of top-down activation, one from each dimension, increasing its discriminability from the distractors. For example, in search for a red horizontal target among red vertical and blue horizontal distractors, a parallel color processor could guide attention towards red items whereas the orientation processor could guide attention towards horizontal items. The combination of these activations would guide attention towards the red horizontal item. However, in a within-dimension search task, activation emerges from one dimension only, and the features can be searched only in a serial fashion because it is not possible for one feature module to handle two simultaneous top-down requests for activation (Wolfe et al., 1990; but see Carrasco, Ponte, Rechea, & Sampedro, 1998 for evidence of efficient within-dimension searches). Given the argument by Wolfe and his colleagues (Wolfe et al., 1990; Wolfe et al., 1994; Wolfe, 1994, 1996) that within-dimension conjunction searches are processed in a qualitatively different fashion from cross-dimension conjunction searches, Experiment 2 was designed to examine whether the distractor-ratio effect is also observed in within-dimension conjunction search tasks by employing a color × color within-dimension conjunction search task.

Experiment 1

Experiment 1 was designed to examine the effect of stimulus discriminability on search performance and saccadic selectivity in a search task with distractor-ratio manipulation. Specifically, the current experiment manipulated the discriminability along the shape dimension. Two search conditions, a high-discriminability condition and a low-discriminability condition, were included. As in Shen, Reingold, and Pomplun (2000), *X* versus *O* were used in the high-discriminability condition whereas in the low-discriminability condition, the shapes were *X* versus *K* for half of the participants and *O* versus *Q* for the other half. If the distractor-ratio effect is merely due to the unequal representation of the two subsets of distractors in a search display and participants consistently search through the smaller subset, very similar patterns of search performance and saccadic bias should be observed across the two conditions. However, if stimulus discriminability plays a role in mediating the distractor-ratio effect, lower discriminability along the shape dimension should lead to greater color-shape asymmetry in search performance and saccadic selectivity.

Method

Participants. Eight undergraduate students at the University of Toronto were tested individually in two 1-hour sessions. All participants had normal or corrected-to-normal visual acuity and normal color vision. They were naive with respect to the purpose of the experiment and received $20 for their participation.

Apparatus. The eyetracker employed in the current study was the SR Research Ltd. EyeLink system. This system has high spatial resolution (0.005º) and high sampling rate (250 Hz). 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 our studies. The EyeLink system uses an Ethernet link between the eyetracker and display computers for real-time saccade and gaze-position data transfer. In the present investigation, the configurable acceleration and velocity thresholds were set to detect saccades of 0.5° or greater.

Stimulus displays were presented on two monitors, one for the participant (a 19-inch Samsung SyncMaster 900P monitor with a refresh rate of 120 Hz and a screen resolution of 800 × 600 pixels) and the other for the experimenter. The experimenter monitor was used to give feedback in real-time about the participant's computed gaze position. This feedback was given in the form of a gaze cursor measuring 1° in diameter that was overlaid on the same image being viewed by the participant. This allowed the experimenter to evaluate system accuracy and to initiate a recalibration if necessary. In general, the average error in the computation of gaze position was less than 0.5°.

Stimuli and design. Similar to Shen et al. (2000), four possible targets, a red *X*, a green *X*, a red *O*, and a green *O*, were used. Participants searched for the target item among distractors which shared either color (same-color distractor) or shape (same-shape distractor) with the target. A high-discriminability condition and a low-discriminability condition were included in the current experiment. In the high-discriminability condition, a pair of highly discriminable shapes, *X* versus *O*, was used (see Figure 1A for an example). In the low-discriminability condition, the same-color distractors were chosen to be visually similar to the search target based on the interconfusibility matrix reported by van der Heijden, Malhas, and van den Roovart (1984). When the target shape was *X*, the same-color distractors were *K*s and when the target shape was *O*, the same-shape distractors were *Q*s (see Figure 1B for an example). In both the high- and low-discriminability conditions, items of different colors (red, with CIE *xy*-chromaticity coordinates of .582/.350 and green, with CIE *xy*-coordinates of .313/.545) were matched in luminance (20 cd/m²) and presented on a white background of 60.7 cd/m². In any given display, the search target could be present or absent with equal probability.

For both the high- and low-discriminability conditions, the total number of items presented in a display was fixed at 36. All display items were presented in a 15.5º × 15.5º visual field at a viewing distance of 91 cm. Each individual item subtended 1.0º vertically and 0.8º horizontally. In target-absent trials, 3 to 33 (in multiples of 3) distractors shared color with the target whereas the rest of the distractors shared shape with the target, yielding 11 levels of distractor ratio between the same-color and same-shape distractors (3:33, 6:30, 9:27, 12:24, 15:21, 18:18, 21:15, 24:12, 27:9, 30:6, and 33:3). Target-present trials were created by replacing one of the distractor items in a target-absent display with the search target. Participants performed a total of 1,320 trials in two individual sessions, which amounted to 30 trials for each cell of the design (target presence × distractor ratio × search condition). The high- and low-discriminability conditions were tested in alternating blocks. At the beginning of each session, participants received a practice block of 44 trials, with one trial for each possible combination of target presence, search condition, and distractor ratio.

Proocedure. The experiment was run in a lighted room, with the luminance of the walls being approximately 30 cd/m². Participants were informed of the identities of the target and distractor items before the experiment started. They were asked to look for the search target and indicate whether it was in the display or not by pressing an appropriate button as quickly and accurately as possible. 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. 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.

Results

Trials with an incorrect response (1.7% of the trials in the high-discriminability condition and 3.3% in the low-discriminability condition) were excluded from further analysis. In addition, those trials with a saccade or blink overlapping the onset of a search display (1.1%), or with a response time that was more than 3.0 standard deviations above or below the mean (1.1%) were excluded from further analysis. Following Shen et al. (2000), separate repeated-measures ANOVAs were conducted on response time, number of fixations per trial, and initial saccadic latency with target presence (2: present vs. absent), search condition (2: high- vs. low-discriminability), and distractor ratio (11 levels) as within-subject factors. In addition, the bias in the distribution of saccadic endpoints as a function of search condition and distractor ratio was examined.

Response time and number of fixations per trial. Figure 2 plots the mean and standard error of response time (Panel A) and number of fixations per trial (Panel B) as a function of target presence, search condition, and distractor ratio. The repeated-measures ANOVA revealed a significant target presence × search condition × distractor ratio interaction for both response time, F (10, 70) = 15.50, $p < .001$, and number of fixations per trial, F (10, 70) = 15.73, $p < .001$. It is clear from the figure that, in the high-discriminability condition, response time and fixation number varied quadratically as a function of distractor ratio. Those displays with equal number of same-color and same-shape distractors yielded longer response times and more fixations than did those display with very extreme distractor ratio (i.e., very few same-color distractors or very few same-shape distractors). In addition, longer response times and more fixations were observed in those displays with fewer same-shape distractors than in displays with a comparable number of same-color distractors. A further trend analysis revealed that the quadratic trend accounted for 61.3% of the total variability in response time that was due to the distractor ratio manipulation and 61.9% in fixation number whereas the linear trend accounted for 34.6% of the variability in response time and 30.9% in fixation number only.

In the low-discriminability condition, response time and fixation number increased with increasing number of same-color distractors. Unlike the high-discriminability condition, for both target-absent and target-present trials, there was no drop in response time and fixation number even when there were very few same-color distractors. Trend analysis shows that the linear trend, which accounted for 96.3% of the variability in response time and 93.9% in fixation number, was more pronounced than the quadratic trend, which accounted for only 3.4% of the variability in response time and 5.8% in fixation number.

Thus, the current analysis indicates that the distractor-ratio effect was strongly influenced by the discriminability of stimulus dimensions. When the stimulus dimensions are highly discriminable, participants might take advantage of the informativeness of the dimensions and achieve greater search efficiency by flexibly searching through the smaller subset. However, when one of the dimensions becomes less discriminable, participants might have to consistently search through the subset of distractors belonging to the dominant dimension (color in the present case).

Initial saccadic latency. Figure 3 shows initial saccadic latency as a function of search condition and distractor ratio in both the target-absent trials (Panel A) and target-present trials (Panel B). As can be seen in the figure, the overall initial saccadic latency was shorter in the low-discriminability condition than in the high-discriminability condition; this difference was more pronounced in target-absent trials than in target-present trials. This was indicated by a significant interaction between search condition and target presence, F (10, 70) = 11.23, p <

.001. The figure also shows that initial saccadic latency varied as a function of distractor ratio. Similar to the above analyses on response time and fixation number, the quadratic trend was more pronounced in the high-discriminability condition (linear trend: 17.0%; quadratic trend: 79.1%) whereas the linear trend was dominant in the low-discriminability condition (linear trend: 81.7%; quadratic trend: 10.9%). This was confirmed by a significant search condition × distractor ratio interaction, F (10, 70) = 4.32, p < .001.

Saccadic selectivity. For each fixation, the distance between the fixation position and every display item was computed and the fixation was assigned to the closest item. The number of fixations assigned to each type of distractors (same-color vs. same-shape distractors) was then summed to assess saccadic selectivity during the search process. 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. Figure 4A plots the observed frequencies of saccades directed towards the same-color distractors for both the high- and low-discriminability conditions. The diagonal line in the figure depicts the probability of fixating same-color distractors in the absence of selectivity (i.e., chance performance). Figure 4B depicts saccadic bias towards the color dimension (the difference between the observed frequency and chance performance) in both conditions.

A repeated-measures ANOVA on saccadic bias with search condition (2: high- vs. low-discriminability) and distractor ratio (11 levels) as within-subject factors revealed a significant main effect of search condition, F (1, 7) = 159.39, p < .001, and distractor ratio, F (10, 70) = 85.62, p < .001, whereas the interaction between the two factors was not significant, F (10,

70) = 1.11, $p = .365$. It is clear from the figure that in the high-discriminability condition, when there were only very few distractors sharing color with the search target, saccadic endpoints were biased towards the color dimension. On the other hand, when there were very few same-shape distractors, a robust bias towards the shape dimension was observed. In the low-discriminability condition, however, a consistent bias towards the color dimension was found, even in displays with very few same-shape distractors. For both the high- and low-discriminability conditions, the change in saccadic bias was almost linear - the linear trend accounted for 99.2% of the total variability in saccadic bias that was due to the distractor-ratio manipulation.

Following Shen et al. (2000), saccadic bias for both the first and subsequent saccades was calculated to examine the temporal dynamics of visual guidance. A 2 (saccade sequence) × 2 (search condition) × 11 (distractor ratio) repeated-measures ANOVA revealed a significant saccade sequence × search condition × distractor ratio interaction, $F(10, 70) = 4.29$, $p < .001$. Figure 5A shows that, in the high-discriminability condition, in those displays with extreme distractor ratios, saccade bias was stronger for the first saccades than for the subsequent ones. Pairwise t-tests revealed a significant difference in saccadic bias for those displays with 6, 9, and more than 21 same-color distractors (i.e., fewer than 15 same-shape distractors), all ts (7) > 2.92, ps < .05. In marked contrast, the spatial bias in the low-discriminability condition was not influenced by the saccade sequence in a trial across the whole range of distractor-ratio manipulation (see Figure 5B).

Discussion

The current experiment examined the effect of stimulus discriminability on search performance and saccadic selectivity in a search task with distractor-ratio manipulation.

Similar to Shen, Reingold, and Pomplun (2000), response time, number of fixations per trial, and initial saccadic latency varied quadratically as a function of distractor ratio in the high-discriminability condition. In the low-discriminability condition, although a quadratic change in these measures were still observed, the linear trend was much more pronounced and accounted for the majority of the variability. The different responses to the distractor-ratio manipulation between the high- and low-discriminability conditions indicate that the distractor-ratio effect was due to the relative discriminability of the two stimulus dimensions and that participants searched through the more informative, but not necessarily smaller, subset of distractors.

The saccadic selectivity analysis provided strong convergent evidence for this hypothesis. In the high-discriminability condition, participants searched through different subsets of distractors on the basis of distractor ratio (i.e., color subset for displays with very few same-color distractors and shape subset for displays with very few same-shape distractors). In marked contrast, in the low-discriminability condition, saccades were consistently biased towards the color dimension, irrespective of the distractor-ratio manipulation. This indicates that, across all displays, participants searched through the subset of distractors which shared color with the target item. The finding of a difference in search performance and saccadic bias between the high- and low-discriminability conditions is consistent with D. E. Williams and Reingold (2001), showing that guided search flexibly accommodates to changes in the informativeness of stimulus dimensions.

One interesting finding to emerge from the current experiment is that, for any given distractor ratio, saccadic bias towards the color subset was stronger (by about 20%) in the low-discriminability condition than in the high-discriminability condition (see Figure 4B).

This was the case even for those displays with very few same-color distractors. It appears that in the low-discriminability condition, given the poor utility of the shape dimension, saccadic selectivity was strongly biased towards the color dimension. Thus, the present experiment demonstrated that a minimal level of discriminability in the non-dominant stimulus dimension is a prerequisite for obtaining the distractor-ratio effect.

Experiment 2

There were two goals in Experiment 2. Given the argument by Wolfe and his colleagues (Wolfe et al., 1990; Wolfe, 1994, 1996) that within-dimension conjunction searches are processed in a qualitatively different fashion from cross-dimension conjunction searches, the first goal of the current experiment was to examine whether the distractor-ratio effect is also observed in within-dimension conjunction search tasks. A color × color within-dimension conjunction search task was adopted. Participants were asked to search for a red/blue target among a group of distractors which shared the red color and another group of distractors which shared the blue color. If the within-dimension conjunction search is carried out in a serial self-terminating fashion across the whole display, search performance and saccadic selectivity should not vary as a function of distractor ratio.

The second goal of the current experiment was to examine how distractor heterogeneity influences search efficiency and saccadic selectivity. Numerous previous studies have demonstrated that distractor heterogeneity, which decreases the grouping of distractors, has a major impact on visual search efficiency (e.g., Duncan & Humphreys, 1989; Kaptein et al., 1995; Palmer et al., 2000; Pashler, 1987). Although the effect of distractor heterogeneity on visual search performance is well established, no previous study so far has examined how distractor heterogeneity influences the patterns of eye movements (fixation number, saccadic latency, and saccadic selectivity) during the search process. Thus, in addition to the distractor-ratio manipulation, the current experiment also manipulated independently the degree of distractor heterogeneity.

Method

Participants. Eight participants from the same subject pool as in the previous experiment participated in two one-hour sessions. They were naïve with respect to the purpose of the experiment and none of them had participated in the previous experiment.

Stimuli and design. Participants performed a color × color conjunction search task. All display items were a cross composed of two bars of different colors (red, blue, green, or yellow). For all participants, the search target was a conjunction of a red bar and a blue bar (red/blue), irrespective of their specific orientations. The distractors were chosen in such a way that a subset of them shared the red color with the target, which conjoined with another non-blue color (i.e., red/yellow or red/green), and the rest distractors shared the blue color with the search target, which conjoined with a non-red color (i.e., blue/yellow or blue/green).

The degree of heterogeneity of the distractors was varied in the current experiment. In one condition, the distractor heterogeneity was relatively low (henceforth the homogeneous condition) - there were only two types of distractors in a single display: either the red/yellow and blue/green crosses in half of the trials or the red/green and blue/yellow combinations in the other half of the trials (see Figure 6A for an example). In a second condition, the distractor heterogeneity was made relatively high by presenting all four types of distractors in a single display (henceforth the heterogeneous condition). Those items with a red bar were split evenly between the red/yellow and red/green combinations whereas those items having a blue bar were divided evenly between the blue/green and blue/yellow combinations (see

Figure 6B for an example). The CIE *xy*-coordinates for the colors were: red (.497, .332), green (.309, .556), blue (.188, .175), and yellow (.439, .461). The items had an average luminance of 23.7 cd/m² and were presented on a white background of 60.7 cd/m².

Each search display consisted of 20 items, presented in a 15.5º × 15.5º field at a viewing distance of 91 cm. Each individual item subtended 1.4º both horizontally and vertically. The minimum distance between the centers of neighboring items was set at 2.3º. In target-absent trials, 2 to18 (in multiples of 2) distractors shared the red color with the search target and the rest of the distractors shared the blue color with the target. Therefore, there were nine possible ratios of distractors having a red bar to distractors having a blue bar (2:18, 4:16, 6:14, 8:12, 10:10, 12:8, 14:6, 16:4, and 18:2).

The current experiment adopted a three-factor within-subject design. These factors were as follows: target presence (2: present vs. absent), search condition (2: homogeneous vs. heterogeneous), and distractor ratio (9 levels). All these factors were completely crossed. Participants performed 33 trials for each cell of the design, constituting a total of 1,188 experimental trials. They completed the experiment in two individual sessions. At the beginning of each session, participants received 36 practice trials, with one trial for each cell of the design. The same apparatus and experimental procedure as in the previous experiment were followed.

Results

Trials with an incorrect response were excluded from further analysis. This resulted in the exclusion of 2.1% of the trials in the homogeneous condition, and 3.1% in the heterogeneous condition. In addition, trials with a saccade or a blink overlapping the onset of a search display, or with an excessively long or short response time, were dropped from analysis.

These exclusions accounted for 0.7% and 0.6% of all trials, respectively. Similar to the previous experiment, search performance measures (response time, number of fixations per trial, and initial saccadic latency) were subjected to separate 2 (target presence: present vs. absent) × 2 (search condition: homogenous vs. heterogeneous) × 9 (distractor ratio) repeated-measures ANOVAs. Following that, the bias in the spatial distribution of saccadic endpoints was examined as a function of search condition and distractor ratio.

Response time and number of fixations per trial. Figure 7 plots response time (Panel A) and number of fixations per trial (Panel B) as a function of target presence and distractor ratio in both the homogeneous condition and the heterogeneous condition. Figure 7 shows that response time and fixation number varied as a function of distractor ratio, with longer RTs and more fixations for displays in the middle range of distractor ratio than for displays with extreme distractor ratios. Unlike the previous experiment on cross-dimensional searches, the response time and fixation number curves in the current experiment were relatively symmetrical. This is confirmed by a trend analysis, showing a strong quadratic trend, accounting for 97.9% of the total variability in response time and 97.0% in fixation number, and a weak linear trend, only accounting for 0.4% of total variability in response time and 0.8% in fixation number. In addition, the distractor-ratio effect was stronger in target-absent trials than in target-present trials. This was indicated by a significant interaction between target presence and distractor ratio for response time, F (8, 56) = 37.38, $p < .001$, and for fixation number, F (8, 56) = 14.23, $p < .001$.

Figure 7 also shows that visual search was less efficient in the heterogeneous condition than in the homogeneous condition; this effect was more pronounced in target-absent trials than in target present trials. This was indicated by a significant target presence × search condition interaction for both response time, F (1, 7) = 21.84, $p < .001$, and fixation number, F (1, 7) = 14.35, $p < .001$. It is clear from the figure that the effect of distractor heterogeneity was observed across the whole range of distractor-ratio manipulation, all *t*s (7) > 2.70, *p*s < .05, except for those displays with four red items, $t < 1$. In addition, there was a significant search condition × distractor ratio interaction for response time, F (8, 56) = 3.03, $p < .05$, and for fixation number, F (8, 56) = 2.37, $p < .05$, showing that the effect of distractor heterogeneity was more pronounced in displays with a distractor ratio approaching 1:1 than in displays with extreme distractor ratios.

Initial saccadic latency. Figure 8 shows initial saccadic latency as a function of target presence, search condition, and distractor ratio. The repeated-measures ANOVA revealed a significant main effect of search condition, F (1, 7) = 13.65, $p < .01$, with longer latencies in the heterogeneous condition than in the homogeneous condition, and a significant main effect of distractor ratio, F (8, 56) = 7.47, $p < .001$, with longer initial saccadic latency in displays with a distractor ratio approaching 1:1. Further trend analysis revealed that the quadratic trend accounted for 94.1% of the total variability in saccadic latency that was due to the distractor ratio manipulation whereas the linear trend accounted for 0.2% only.

Saccade selectivity. To quantitatively examine saccadic selectivity in within-dimension conjunction searches, saccadic bias towards one particular color feature value (the red color) at each level of the distractor ratio manipulation was determined. Saccadic bias was calculated as the observed probability of fixations on those items having a red bar (see Figure 9A) relative to the chance performance. Figure 9B plots saccadic bias towards red items as a function of the number of red items in both the homogeneous condition and the heterogeneous condition.

A 2 (search condition: homogeneous vs. heterogeneous) × 9 (distractor ratio) repeated-measures ANOVA revealed that saccadic bias varied as a function of distractor ratio, F (8, 56) = 255.11, $p < .001$. Figure 9B shows that when there were very few red items in a search display, participants' saccadic endpoints were biased towards the subset of red items. In contrast, when there were very few blue items, saccadic endpoints were biased towards the blue subset. Although the main effect of search condition was not significant, F (1, 7) = 2.12, $p = .189$, there was a significant interaction between distractor ratio and search condition, F (8, 56) = 7.92, $p < .001$. Figure 9B shows that the saccadic bias curve assumed a slanted 8-shape, indicating stronger guidance in the homogeneous conditions than in the heterogeneous condition. More specifically, for those displays with 4, 6, or 8 red items, the bias in saccadic endpoints towards the red items was stronger in the homogeneous condition than in the heterogeneous condition, all *t*s (7) > 3.13, *p*s < .05. On the other hand, for those displays with 12, 14, or 16 red items, the bias towards the blue items was stronger in the homogeneous condition than in the heterogeneous condition, all *t*s (7) > 2.15, *p*s < .069. These observations was confirmed by a further trend analysis, showing that the linear trend, F (1, 7) = 13.74, $p < .01$, the quadratic trend, $F < 1$, and the cubic trend, F (1, 7) = 7.45, $p < .05$, accounted for 44.2%, 0.1%, and 51.1% of total variability for this interaction, respectively.

Similar to the previous experiment, saccadic bias for both the first and subsequent saccades within a trial was calculated to examine the influence of saccade sequence on eye guidance. Figure 10 shows that, unlike the previous experiment (see also Shen et al., 2000), there was little evidence for an effect of saccade sequence on the selectivity in distribution of saccadic endpoints: there was neither a main effect of saccade sequence, F (1, 7) = 3.02, p =

.126, nor any significant interactions between saccade sequence and other factors, all *F*s (8, 56) < 1.87, *p*s > .082.

Discussion

The current analyses showed that response time, number of fixations per trial, and initial saccadic latency varied as a function of the ratio between the red and blue items. Search was more efficient when there were either very few red items or very few blue items than when the two types of distractors were equally represented in a display. Saccadic selectivity analysis revealed that participants consistently searched through the smaller subset of distractors. Thus, the flexibility in the guidance of visual attention occurs not only in the cross-dimension tasks (current experiment 1, see also Bacon & Egeth, 1996; Poisson & Wilkinson, 1992; Shen et al., 2000; Zohary & Hochstein, 1989) but also in within-dimension conjunction search tasks. It is important to notice that the overall search performance of the current experiment was still very poor. This might be consistent with the argument by Wolfe and his colleagues (Wolfe et al., 1990; Wolfe, 1994) that within-dimension conjunction searches are carried out in a serial self-terminating fashion (but see Carrasco et al., 1998; Linnel & Humphreys, 2001). However, one important implication of the current experiment is that this kind of search could be carried out within a subset of distractors, instead of in an item-by-item fashion across the whole display as argued by the original feature-integration theory (Treisman & Gelade, 1980) and the guided-search model (Wolfe et al., 1990; Wolfe, 1994).

The current experiment also examined the effect of distractor heterogeneity on search performance and saccadic selectivity. Longer response times and more fixations were observed in the heterogeneous condition than in the homogeneous condition whereas the initial saccadic latency did not differ between the two search conditions. Guidance analysis revealed that saccadic bias was stronger in the homogeneous condition than in the heterogeneous condition, despite the fact that in both search conditions, there were the same number of red items and blue items in any display of a given distractor ratio. Thus, it appears that distractor homogeneity may enhance subset-selective processing, perhaps by more easily segregating the relevant and irrelevant subsets.

General Discussion

Consistent with previous studies (e.g., Bacon & Egeth, 1997; Egeth, et al., 1984; Kaptein, et al., 1995; Poisson & Wilkinson, 1992; Shen, Reingold, & Pomplun, 2000; Zohary & Hochstein, 1989), the current study found that in a conjunctive search task response time and patterns of eye movements were strongly influenced by the ratio between two types of distractors. When the total number of items presented in a display was kept constant, faster manual response time, shorter initial saccadic latency, and fewer fixations were observed when either type of distractors was rare than when the two types of distractors were equally represented. The spatial distribution of saccadic endpoints also changed flexibly as a function of distractor ratio. In the color × shape conjunction search tasks (Experiment 1; see also Shen et al., 2000), when there were only very few same-color distractors in a display, saccades were biased towards the color dimension. When most of the distractors shared color with the search target, saccadic endpoints were biased towards the shape dimension, unless the discriminability along the shape dimension was low. This shows that participants searched though the more informative, but not necessarily smaller, subset of distractors. This finding also demonstrates that a minimum level of discriminability in the non-dominant stimulus dimension is a prerequisite for obtaining such flexibility. In the color × color within-dimension conjunction search task (Experiment 2), saccades were reliably biased towards the smaller subset of distractors. Thus, the current analyses suggest that subset-selective searches can be flexibly applied to both between-dimension and within-dimension searches (i.e., subset-switching account, Zohary & Hochstein, 1989; Bacon & Egeth, 1997). As argued earlier, this pattern of saccadic selectivity rules out the distractor-grouping account (Poisson & Wilkinson, 1992) as a viable explanation for the distractor-ratio effect.

The observed change in search performance measures and saccadic selectivity as a function of distractor ratio is not consistent with the original feature-integration theory (Treisman et al., 1977; Treisman & Gelade, 1980; Treisman, 1988). This is because the feature-integration theory argues that to search for a conjunctively defined target, attention is deployed serially to each item in the display until the target is detected in target-present trials, or an exhaustive search is performed in target-absent trials. Focal attention is required to integrate individual stimulus features (such as color, shape, size, orientation, etc.) into a unitary object and only then can that item be compared against the search target. However, the current experiments (see also Bacon & Egeth, 1997; Egeth et al., 1984; Kaptein et al., 1995; Poisson & Wilkinson, 1989; Zohary & Hochstein, 1989) clearly demonstrated that participants could search through a subset of distractors (e.g., red items or *X*s), instead of conducting a serial self-terminating search over the whole search display. Upon seeing a search display, participants may first make a global assessment of all items in that display. In those trials with a strong disparity between the two types of distractors, a figure-ground segregation process may occur, with all of the items in a smaller or more salient subset forming the figure and being examined serially whereas the rest distractors forming the ground and being rejected in parallel.

Findings of the present investigation are consistent with the current theories of visual search (e.g., Wolfe et al., 1989; Wolfe, 1994; Duncan & Humphreys, 1989; Treisman & Sato, 1990). In particular, given the dominance of the guided-search model proposed by Wolfe and his colleagues (Cave & Wolfe, 1990; Wolfe et al., 1989; Wolfe, 1994; Wolfe & Gancarz, 1996), and given that this model has been specified in some detail, including a computational implementation, the present results are discussed within the framework of this model. According to the guided-search model, in a display with extreme distractor ratio, the bottom-up activation would be relatively large at locations occupied by the smaller subset of distractors, explaining the higher proportion of saccades landing on these items. To account for the finding that most search functions (i.e., RT, initial saccadic latency, fixation number, and saccadic bias) in the color × shape conjunction search tasks were asymmetrical, the guided-search model can have the activation due to color be larger than that due to shape (Cave & Wolfe, 1990; Wolfe, 1994). In fact, the low-discriminability condition in Experiment 1 can be viewed as one extreme condition in which the bottom-up activation due to the shape dimension is greatly diminished or turned off. The current Experiment 2 demonstrated that the distractor-ratio effect is also observed in the within-dimension conjunction searches. The guided-search model can account for this finding by assuming that participants conduct a separate evaluation of the number of red items and blue items in a display and then search through the smaller subset of distractors. This flexible change in search behaviors can be seen as another exception (see also the efficient within-dimension conjunction search with practice by Carrasco et al., 1998 and with part-whole configuration by Wolfe et al., 1994) to the general nature of inefficient within-dimension conjunction searches (Wolfe et al., 1990).

Results from the present study provide additional implications for current visual search theories. For example, the current experiments examined the temporal dynamics of visual guidance within a single trial. In the high-discriminability cross-dimension conjunction search tasks (see also Shen et al., 2000), first saccades in those displays with extreme distractor ratios produced stronger bias than did the subsequent ones. However, in the low-discriminability cross-dimension search task and within-dimension conjunction search task, saccadic bias did not differ between the first and subsequent saccades. The guided-search model (Wolfe, 1994; Wolfe et al., 1989; Wolfe & Gancarz, 1996) can easily account for the existence of a sequential effect by arguing that attention and saccades move from locations with highest activation values (i.e., stronger saccadic bias) to lower ones on the activation and saccade maps. However, it is unclear why the sequential effect was not observed in the other two conditions. Future studies may further investigate this issue.

In addition, the guided-search model argues that a preattentive parallel process guides the subsequent serial shift of attention through display items. However, the current version of the model is somewhat vague with respect to the interface and the interaction between these two processing stages. For example, the current experiments (see also Shen et al., 2000) revealed a quadratic change in initial saccadic latency as a function of distractor ratio, with longer initial saccadic latency in those displays with an approximately 1:1 distractor ratio and shorter latencies in displays with extreme distractor ratios. These findings can be explained in several ways by the current version of the guided-search model. It may be speculated that the stronger activation peak associated with extreme distractor ratios will result in faster latency. Alternatively, it is possible that the time required for extracting an activation and saccade map vary with distractor ratios. That is, useful preattentive information may be developed over time, instead of being available immediately to participants irrespective of specific display composition (see also Friedman-Hill & Wolfe, 1995; Shen et al., 2000). Future developments of the guided-search model should be more explicit with respect to the interaction between and time course of the preattentive stage and the serial stage of processing.

Acknowledgements

Preparation of this manuscript was supported by a grant to Eyal M. Reingold from the Natural Science and Engineering Research Council of Canada (NSERC) and a grant to Marc Pomplun from the Deutsche Forschungsgemeinschaft (DFG).

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Figure Caption

Figure 1. Sample search displays used in Experiment 1. Target was a green *X* and the distractors were red *X*s and green *O*s (in the high-discriminability condition; Panel A) or green *K*s (in the low-discriminability condition; Panel B). Both examples corresponded to a trial with a distractor ratio of 33:3 between the same-color distractors and same-shape distractors.

Figure 2. Response times (in ms; Panel A) and number of fixations per trial (Panel B) as a function of target presence and the number of same-color distractors in both the high-discriminability condition and the low-discriminability condition in Experiment 1.

Figure 3. Initial saccadic latency (in ms) as a function of the number of same-color distractors in target-absent (Panel A) and target-present trials (Panel B) in both the high-discriminability condition and the low-discriminability condition in Experiment 1.

Figure 4. Panel A: Relative frequency of saccades directed towards the same-color distractors as a function of stimulus discriminability and the number of same-color distractors in Experiment 1. The diagonal line indicates chance performance. Panel B: Saccadic bias (the difference between the observed frequency and chance performance) as a function of stimulus discriminability and the number of same-color distractors in Experiment 1.

Figure 5. Saccadic bias of the first and subsequent saccades as a function of the number of same-color distractors in the high-discriminability condition (Panel A) and the low-discriminability condition (Panel B) in Experiment 1.

Figure 6. Sample search displays used in Experiment 2. Target was a red-blue conjunction. In the homogeneous condition (Panel A), only two types of distractors were used whereas

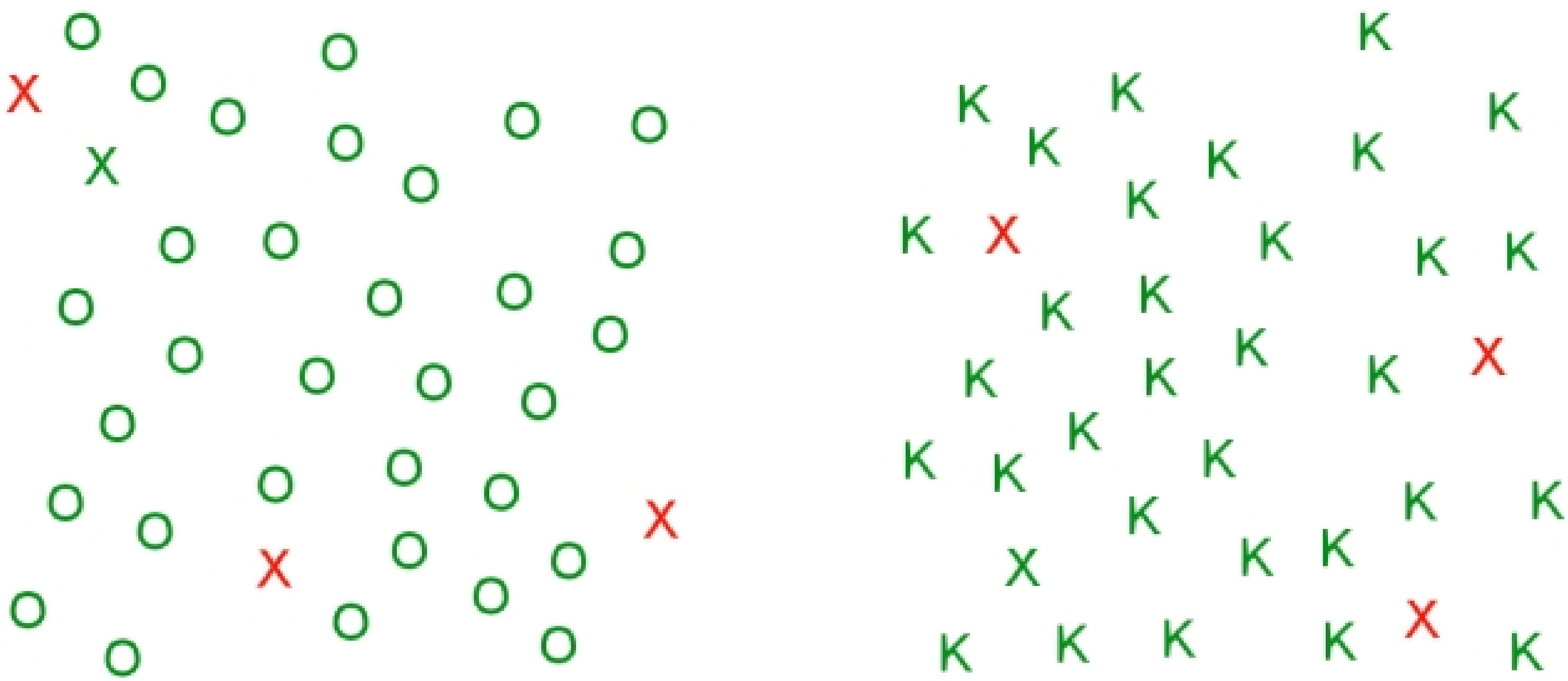
in the heterogeneous condition (Panel B), four types of distractors were used. Panel A corresponded to a search display with a distractor ratio of 2:18 between the red and blue items whereas Panel B illustrated a search display with a distractor ratio of 10:10.

Figure 7. Response times (in ms; Panel A) and number of fixations per trial (Panel B) as a function of target presence and the number of red distractors in the homogeneous condition and the heterogeneous condition in Experiment 2.

Figure 8. Initial saccadic latency (in ms) as a function of target presence (Panel A: target-absent; Panel B: target-present) and the number of red distractors in the homogeneous condition and the heterogeneous condition in Experiment 2.

Figure 9. Panel A: Relative frequency of saccades directed towards the red distractors as a function of search condition and the number of red distractors. The diagonal line indicates chance performance. Panel B: Saccadic bias (the difference between the observed frequency and chance performance) as a function of search condition and the number of red distractors in Experiment 2.

Figure 10. Saccadic bias of the first and subsequent saccades as a function of the number of red distractors in the homogeneous condition (Panel A) and in the heterogeneous condition (Panel B) in Experiment 2.



A B

Figure 1

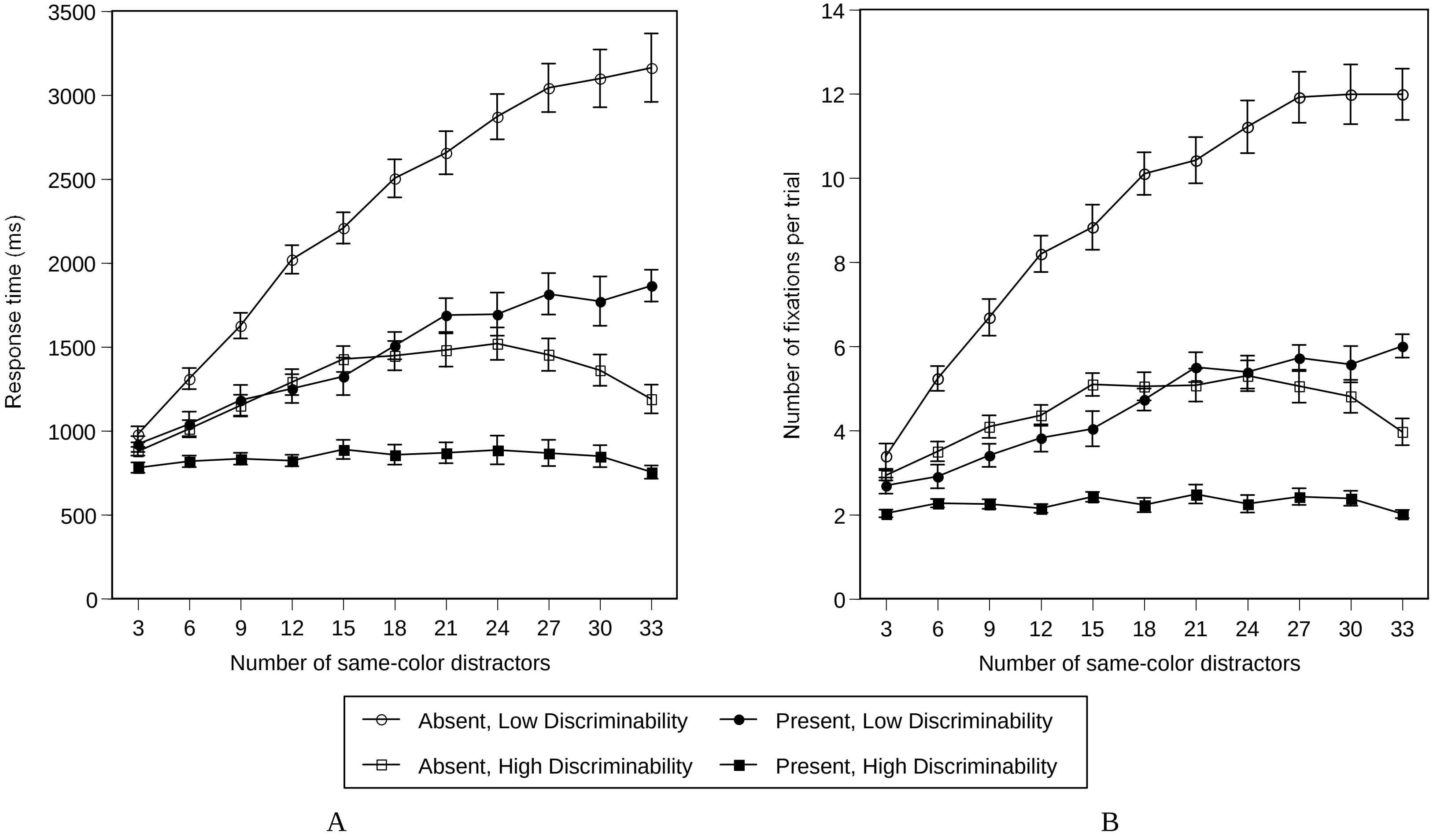

Response time (ms)
Number of same-color distractors
Number of fixations per trial
Number of same-color distractors
Absent, Low Discriminability
Present, Low Discriminability
Absent, High Discriminability
Present, High Discriminability
A
B

Figure 2

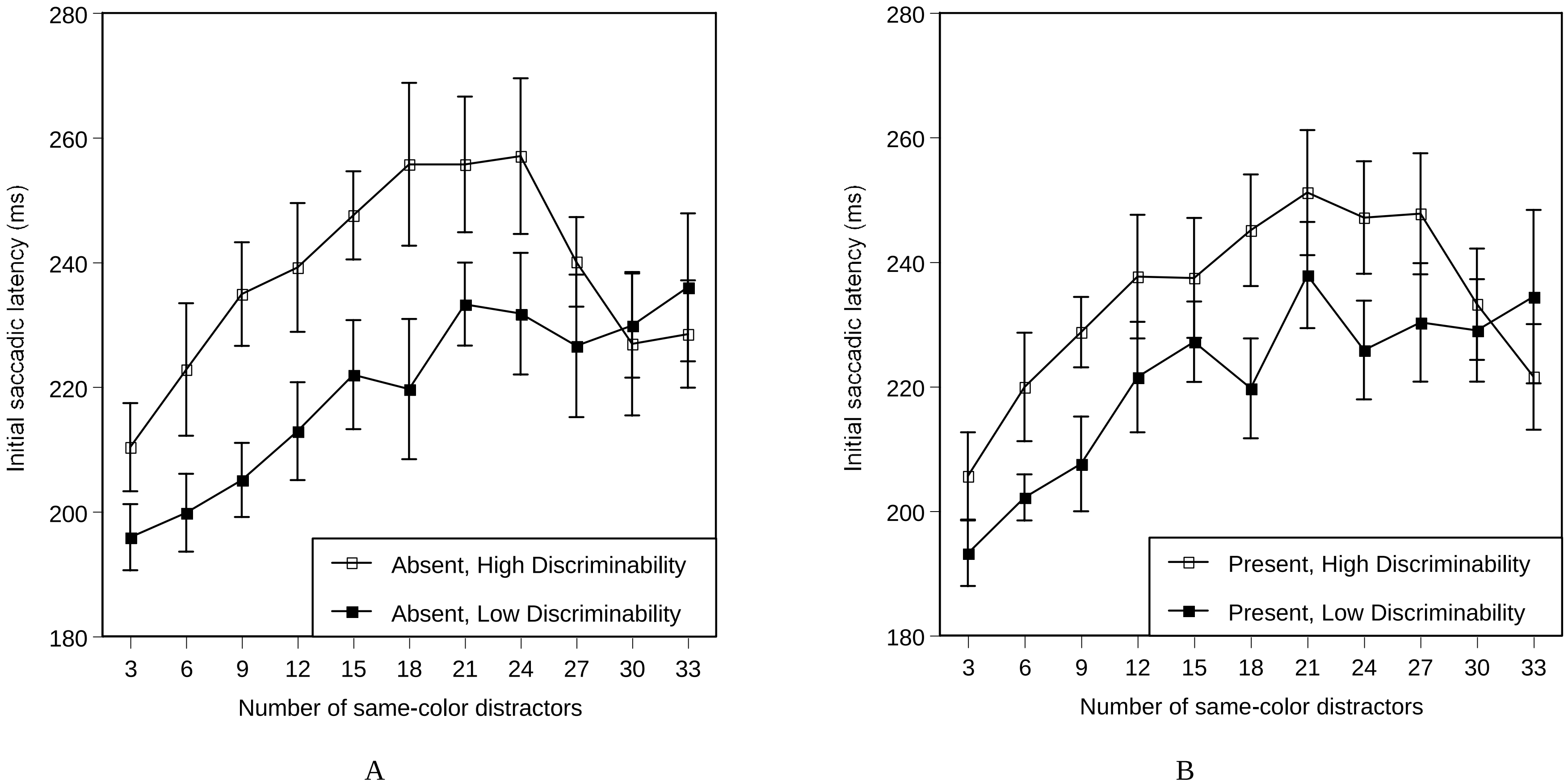
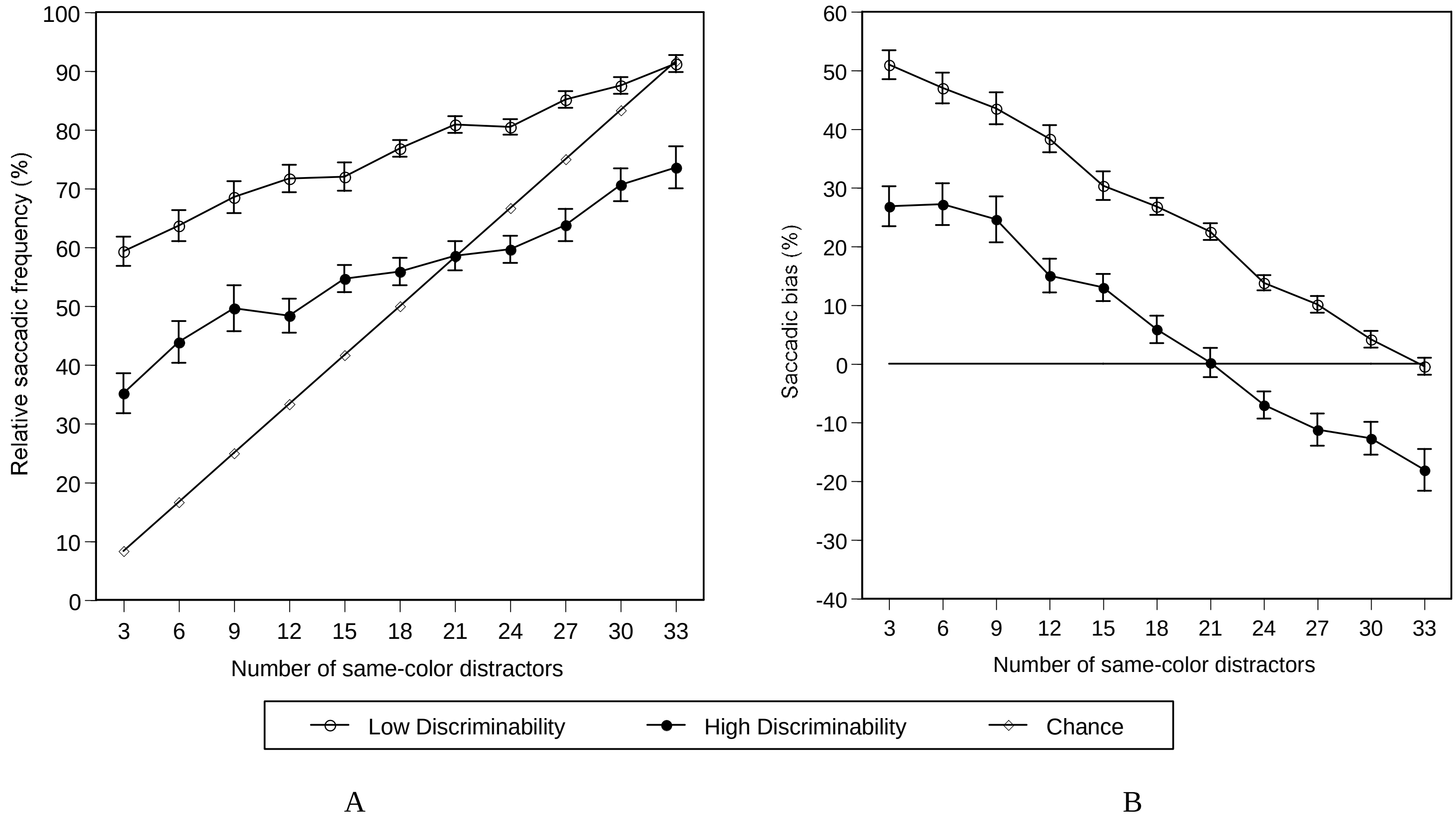
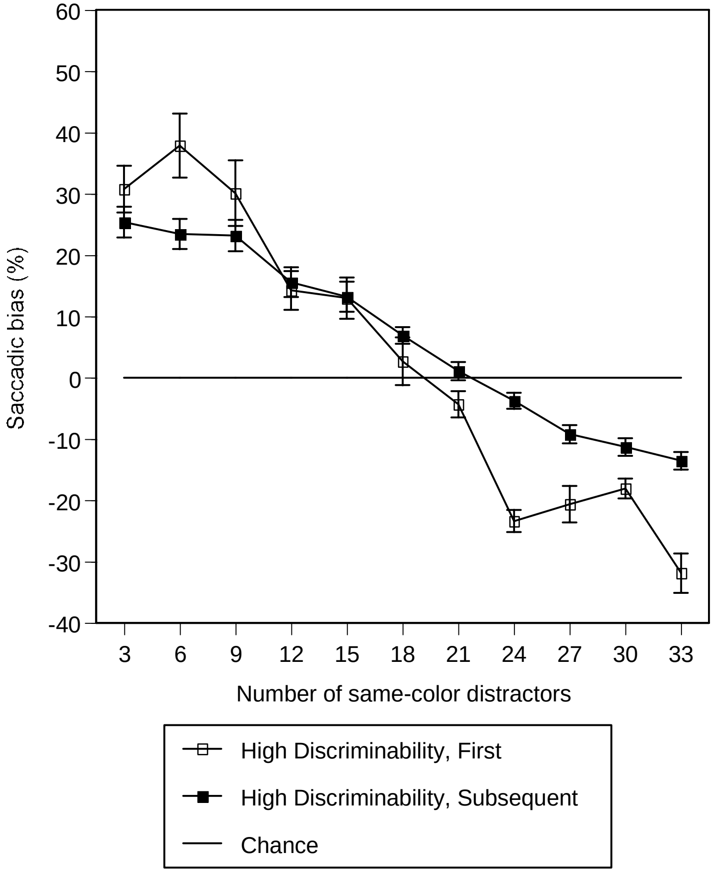

280
260
240
220
200
180
Initial saccadic latency (ms)
3
6
9
12
15
18
21
24
27
30
33
Number of same-color distractors
Absent, High Discriminability
Absent, Low Discriminability
A
Present, High Discriminability
Present, Low Discriminability
B

Figure 3



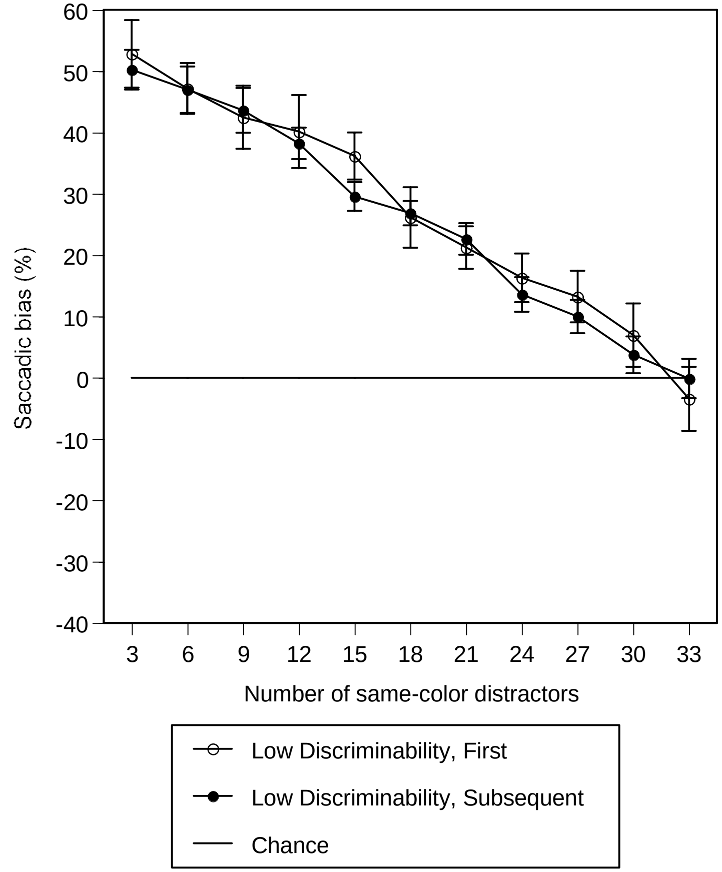
Relative saccadic frequency (%)
100
90
80
70
60
50
40
30
20
10
0
3
6
9
12
15
18
21
24
27
30
33
Number of same-color distractors
Saccadic bias (%)
60
50
40
30
20
10
0
-10
-20
-30
-40
Number of same-color distractors
Low Discriminability
High Discriminability
Chance
A
B

Figure 4



60
50
40
30
20
10
0
-10
-20
-30
-40
Saccadic bias (%)
3 6 9 12 15 18 21 24 27 30 33
Number of same-color distractors
High Discriminability, First
High Discriminability, Subsequent
Chance

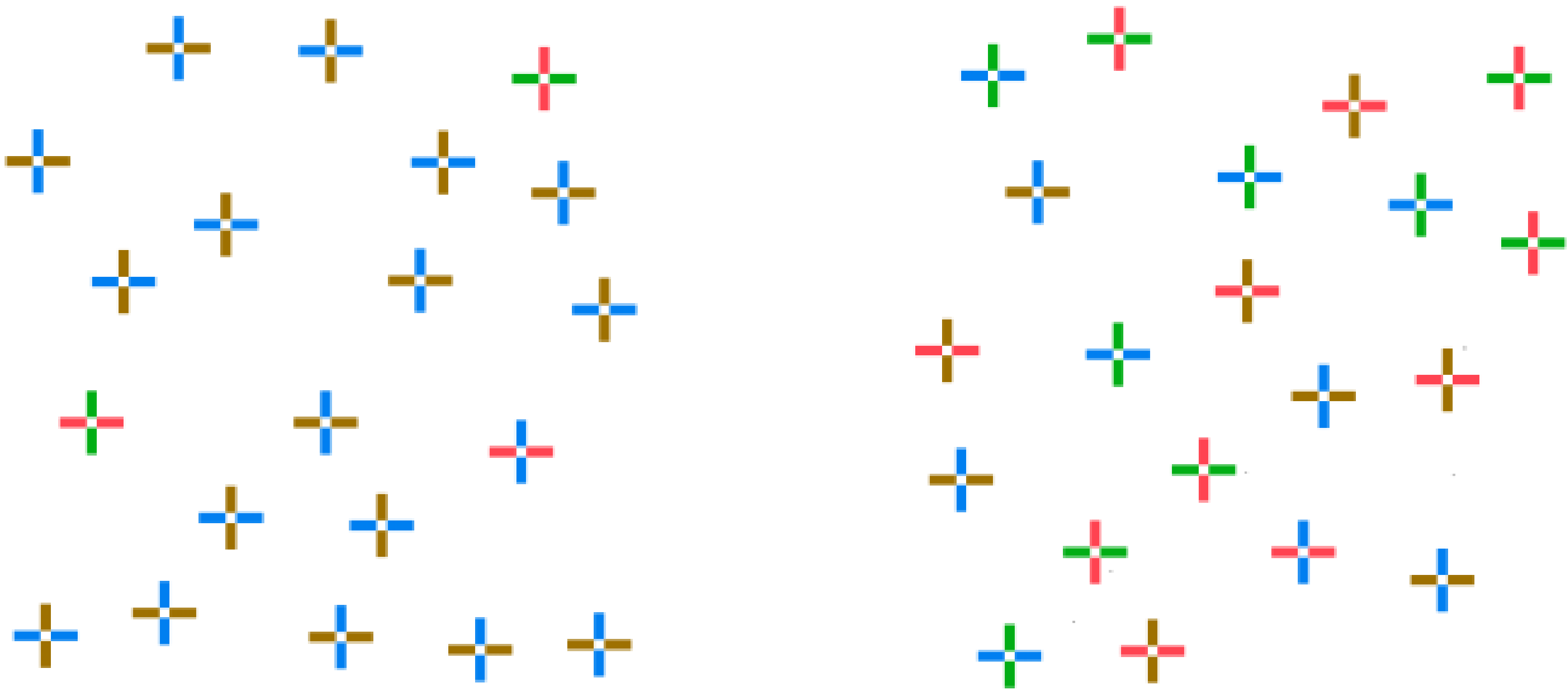
A



60
50
40
30
20
10
0
-10
-20
-30
-40
Saccadic bias (%)
3 6 9 12 15 18 21 24 27 30 33
Number of same-color distractors
Low Discriminability, First
Low Discriminability, Subsequent
Chance

B

Figure 5



A B

Figure 6

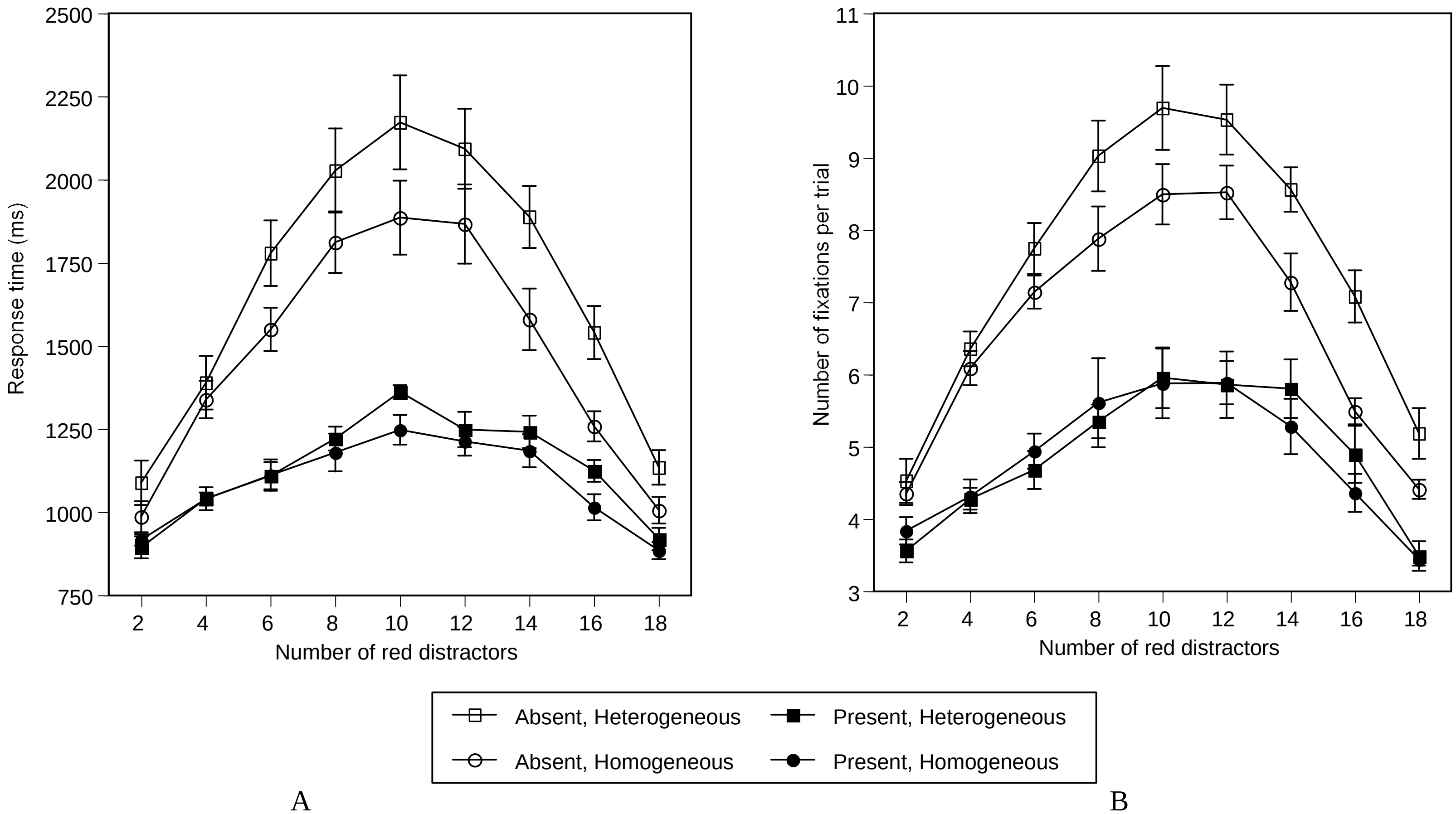

2500
2250
2000
1750
1500
1250
1000
750
Response time (ms)
2
4
6
8
10
12
14
16
18
Number of red distractors
11
10
9
8
7
6
5
4
3
Number of fixations per trial
Number of red distractors
Absent, Heterogeneous
Present, Heterogeneous
Absent, Homogeneous
Present, Homogeneous
A
B

Figure 7

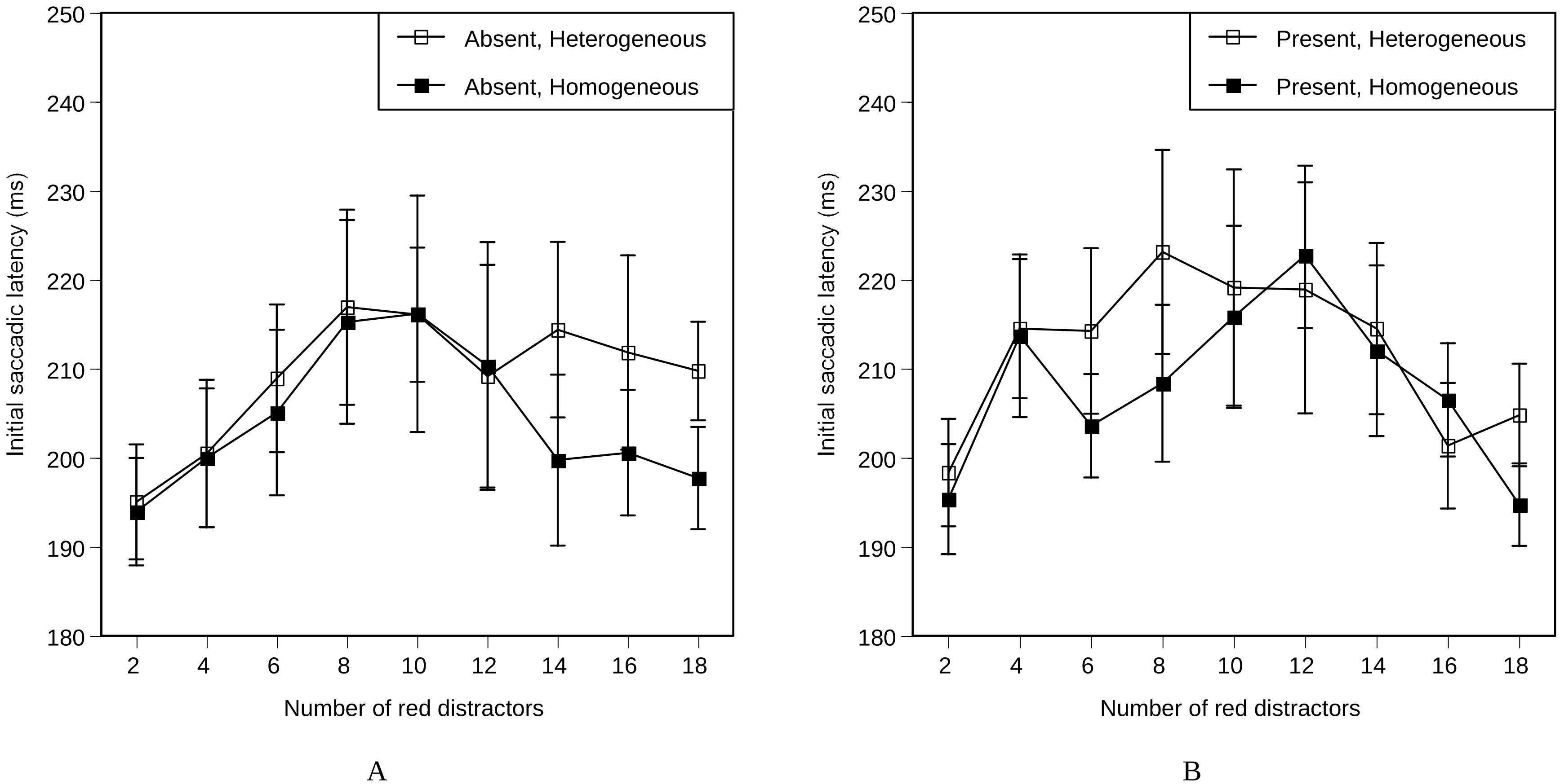
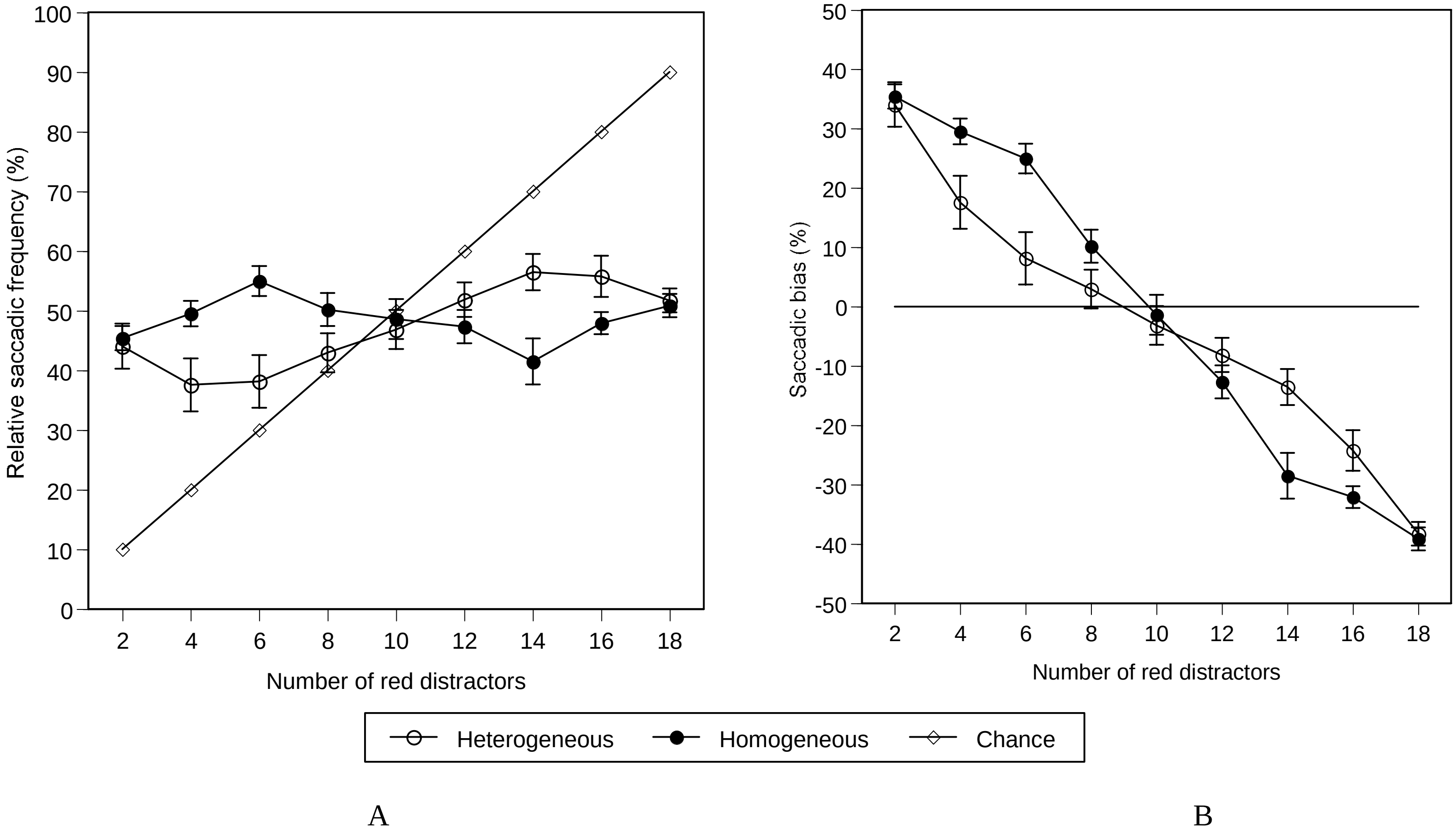

Initial saccadic latency (ms)
250
240
230
220
210
200
190
180
2 4 6 8 10 12 14 16 18
Number of red distractors
Absent, Heterogeneous
Absent, Homogeneous
A
Initial saccadic latency (ms)
250
240
230
220
210
200
190
180
2 4 6 8 10 12 14 16 18
Number of red distractors
Present, Heterogeneous
Present, Homogeneous
B

Figure 8



100
90
80
70
60
50
40
30
20
10
0
Relative saccadic frequency (%)
2
4
6
8
10
12
14
16
18
Number of red distractors
50
40
30
20
10
0
-10
-20
-30
-40
-50
Saccadic bias (%)
Number of red distractors
Heterogeneous
Homogeneous
Chance
A
B

Figure 9

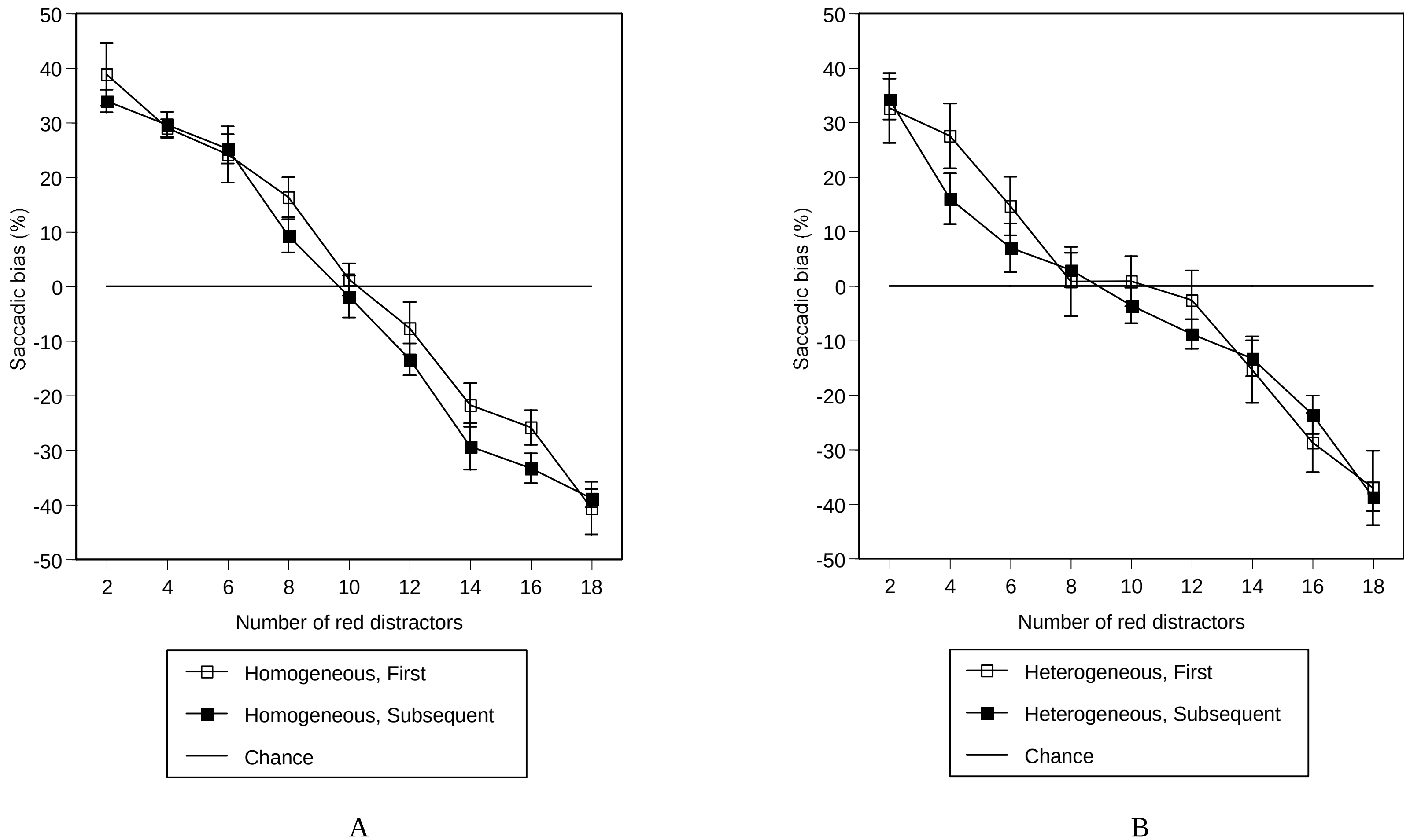

50
40
30
20
10
0
-10
-20
-30
-40
-50
Saccadic bias (%)
2
4
6
8
10
12
14
16
18
Number of red distractors
Homogeneous, First
Homogeneous, Subsequent
Chance
A
Saccadic bias (%)
Number of red distractors
Heterogeneous, First
Heterogeneous, Subsequent
Chance
B

Figure 10