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Eye Movements During Parallel–Serial Visual Search

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Two experiments (one using O and Q-like stimuli and the other using colored–oriented bars) investigated the oculomotor behavior accompanying parallel–serial visual search. Eye movements were recorded as participants searched for a target in 5- or 17-item displays. Results indicated the presence of parallel–serial search dichotomies and 2:1 ratios of negative to positive slopes in the number of saccades initiated during both search tasks. This saccade number measure also correlated highly with search times, accounting for up to 67% of the reaction time (RT) variability. Weak correlations between fixation durations and RTs suggest that this oculomotor measure may be related more to stimulus factors than to search processes. A third experiment compared free-eye and fixed-eye searches and found a small RT advantage when eye movements were prevented. Together these findings suggest that parallel–serial search dichotomies are reflected in oculomotor behavior.

In many visual search experiments, the topic under investigation is not visual search. Instead, these experiments use the search paradigm primarily as a tool with which to study other psychological processes, namely, perception and recognition (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Wolfe & Cave, 1990). The rationale for this use of visual search can be simplified as follows: If the Search Time × Set Size slope resulting from a target defined by feature *A* is shallower than the slope observed for feature *B*, then *A* is more likely to be one of the primitive visual features important for object recognition. Without intending to minimize the importance of a productive theoretical tool, we believe that the actual contribution of search to this literature is therefore mainly to gauge the difficulty of one task relative to another. Given this widespread use of the search paradigm and the popularity of manual reaction times (RTs) as a measure of task difficulty, it is little wonder that search has become so strongly identified with the time taken to press a button in response to a target. However, when the object of investigation shifts to the topic of search itself, it no longer seems sufficient to say that Task B simply takes longer than Task A. Such a RT definition of search collapses a behavior having a richly complex spatial and temporal dynamic into a single measure of response time. Indeed, one might argue that manual RTs document only the completion of search and that this measure does not even describe search as a process. For study of this behavior at the procedural level, dependent measures that vary with the spatiotemporal changes occurring throughout the course of search are needed. We propose here that eye movements may provide such dependent measures.

An analysis of oculomotor variables broadens the study of search along two dimensions: one spatial and the other temporal. Saccadic vectors offer a wealth of spatial information about where a participant is looking during the course of search and, perhaps as important, the number of eye movements that are initiated before the search judgment. Similarly, individual fixation durations provide a straightforward temporal measure of how long participants choose to inspect a display between each of their search movements. Note that these oculomotor measures of saccade number and fixation duration preserve all of the information available from the RT response. In fact, individual search times can be easily redefined by the expression $f_0 + f_i + \ldots + f_n$, where f_0 denotes initial fixation duration, f_i refers to the duration of fixation *i*, and f_n describes the total number of eye movements occurring during a given trial before the manual response.[1] This redefinition of RT into oculomotor variables allows search to be studied at a finer level of resolution than that which is available from a button press. For example, it would be possible to determine from such an analysis whether a 600-ms RT corresponds to two 300-ms fixations or to three faster 200-ms fixations. If no eye movements occurred during search, then oculomotor information would not be available and this analysis would

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[1] For the sake of simplicity, the time taken to execute the *i*th saccade was included in the term f_i.

simply degenerate into a measure of the initial fixation duration, which in this case would be the manual RT.

Using eye movements to study search is not a new idea (see Engel, 1977; Findlay, 1995; Gould, 1973; Gould & Dill, 1969; Jacobs, 1986, 1991; Luria & Strauss, 1975; Megaw & Richardson, 1979; Rayner & Fisher, 1987; Scinto, Pillalamarri, & Karsh, 1986; Widdel, 1983; Williams, 1967; for a review, see Viviani, 1990). However, although this topic has been the focus of many experiments testing a wide variety of search tasks, one popular class of stimuli has largely managed to elude such an analysis. It has long been known that performance in a search task depends on the types of target and nontarget elements appearing in a display (Egeth, Jonides, & Wall, 1972; Neisser, 1967; Schneider & Shiffrin, 1977). Certain combinations promote an easy determination of a target's presence regardless of the number of distractor elements. This response pattern reflects a search process in which each display element is analyzed in parallel. Other target–nontarget combinations show search times that are highly dependent on display size. As the number of nontargets increases, so does the time needed by participants to accurately indicate the presence of a target. This RT × Display Size function, together with a 2:1 ratio of target-absent to target-present search slopes, is believed to describe a serial self-terminating search strategy. The following experiments were designed to fill what was perceived to be a gap in the search literature by assessing whether oculomotor variables can be a useful supplement to RT as a measure of parallel–serial processing.

Experimental Objectives

Before eye movements can be practically used as a measure of search, two questions need to be addressed. First, do eye movements occur with enough frequency during parallel–serial search tasks to justify using this measure? Researchers have argued convincingly that eye movements do not meaningfully contribute to search in these tasks, but they have not supported these arguments by actually observing oculomotor behavior when the eyes are free to move. Instead, they have opted to demonstrate the appearance of search dichotomies at tachistoscopic presentation rates that preclude the presence (and therefore the influence) of eye movements (Klein & Farrell, 1989; Treisman & Gormican, 1988) or to actively monitor eye position as a means of forcing participants to maintain fixation throughout their search (Klein & Farrell). Neither of these approaches, however, provides any indication of how participants choose to deploy their oculomotor resources during a free-eye search task. One goal of this investigation, therefore, is simply to document the natural occurrence of oculomotor behavior in parallel–serial search. Only by explicitly showing the eye movements accompanying search can a proper evaluation of oculomotor contributions to parallel–serial search task differences be conducted.

Second, assuming there are sufficient eye movements during parallel–serial search with which to conduct a meaningful analysis, do these oculomotor variables reflect actual search processes? This question can be addressed in two ways. First, do eye movements vary with the independent experimental manipulations (e.g., changes in display size or parallel–serial search condition) used to operationally define search performance? One hypothesis is that these manipulations affect RTs and eye movements similarly. More specifically, perhaps the characteristic dichotomy between parallel and serial display size functions also appears in oculomotor variables. Alternatively, manipulating these independent variables may have no systematic effect on oculomotor behavior, making eye movements a poor descriptor of search. Even more to the point, rather than showing whether eye movements and RTs are affected similarly by search manipulations, the second way of assessing a relationship is to directly evaluate how strongly the two dependent measures are related to each other. If both dependent variables measure the same process, reliable correlations should be observed between RTs and one or more of these oculomotor variables even in the absence of any experimental manipulation (i.e., within each cell of the experimental design). The presence of meaningful correlations would be consistent with the proposal that eye movements do indeed reflect processes underlying parallel–serial search. However, failing to find a reliable relationship between eye movements and manual RTs would suggest the existence of search processes that cannot be revealed by an oculomotor measure.

Experiment 1: Eye Movements During a Parallel–Serial Search Asymmetry Task

One particularly interesting group of target–nontarget stimuli yields parallel search slopes when one element from the pair is designated the target but yields serial slopes when the target–nontarget assignment is reversed. These search asymmetries were first observed by Beck (1973) but were later studied by many different researchers using a wide variety of stimuli, including the O and Q-like stimuli central to the following discussion (Julesz, 1981; Treisman & Souther, 1985; see also Treisman & Gormican, 1988, for a comprehensive review).

Search asymmetries have played an important role in specifying the set of primitive features available to early vision. Underlying this usage of the asymmetry paradigm is an assumption that search proceeds through a process of comparing display elements against some part or property of the target (Treisman & Gormican, 1988). For example, in the case of O and Q-like stimuli, participants searching for a Q-like target may actually be looking for an intersecting line segment rather than the entire pattern. Because a line segment is not present among the nontarget elements, activity on a feature map sensitive to this property would allow the parallel detection of the target. The existence of a discriminating feature is more difficult to imagine in the reverse case. Instead of a search for the presence of a line segment, a circle target in Q-like nontargets requires a search for the absence of the feature. If such a negative template cannot be constructed, then participants must resort to serially searching for a circle in a field of nontargets also containing circles. In other words, serial search is believed to be a by-product of the target template being shared by the nontarget elements. The importance of this theory in the parallel–serial search literature, combined with the widespread use of these stimuli, prompted the selection of an asymmetry task to test the objectives outlined in the Experimental Objectives section.

Method

Participants. Four participants, 2 men and 2 women, were paid approximately $8/hr for their involvement in this experiment. All of the participants were naive with regard to the questions under study and had normal visual acuity.

Stimuli. Participants were shown displays consisting of two element types. One element was a plain circle with a diameter subtending 2/3° visual angle (the O element). The second element type was identical to the first except for the addition of a single line segment originating at the center of the circle and extending vertically upward for a distance equal to the diameter (the Q-like element). Both element types were white (≈ 20 cd/m^2) and were presented on an otherwise dark background (≈ 0.1 cd/m^2). A Stellar GS-1000 graphics computer was used to generate and present the stimuli. A P22 phosphor and a refresh rate of 74 Hz (noninterlaced) resulted in essentially no ghost images or visible flicker during the presentation of these patterns.

By allowing each element type to serve as the target, we created two search conditions. The parallel search task consisted of a single Q-like target embedded in a field of circle nontargets. Conversely, the serial search task used a circle target and Q-like nontargets. In addition to displays in which a target was present (positive trials), an equal number of displays showed only nontargets (negative trials). Displays could also appear in either of two sizes, 5 or 17 items. Examples of positive parallel and serial search tasks at both display sizes are shown in Figure 1. The cross appearing at the center of each illustration is shown simply to indicate the participant's initial fixation position. During the actual experiment, the fixation cross was removed immediately before the search displays were shown.

The placement of the target and nontarget elements was constrained to 24 possible positions to promote a fairly uniform coverage of the display. These allowable element locations (illustrated in Figure 2) consisted of 16 different angular directions (starting at 0° and stepping in 22.5° increments around the circular display) and four different eccentricities (3°, 4°, 5°, or 6° of visual angle from initial fixation). Both the 5- and the 17-item configurations were chosen randomly from these 24 locations with the following additional constraints. A maximum of four elements could appear at 3° and 6° eccentricities, and up to eight elements could be presented at each of the 4° and 5° eccentricities. Target locations were further constrained to the eight allowable positions at the 4° eccentricity so as to eliminate discriminability factors from the interpretation of the eye data.[2] As a result of these constraints, the minimum separation and the maximum separation between any two elements were 1.7° and 12.0°, respectively, and no elements appeared nearer than 3° from the central fixation cross.

Design. The experiment included 128 target–nontarget configurations, each satisfying all of the previously described criteria. The 128 configurations were evenly divided into 5- and 17-item displays. Each of these 64 trials of a given display size were further divided into 32 positive and 32 negative trials. These configurations, although randomly created within the limits of the position constraints, were generated off-line before testing. Because configurations could be made parallel or serial simply by reversing the element types appearing in the target and nontarget locations, this design decision allowed each participant to view the same 128 configurations in both search tasks. Any difference in the pattern of eye movements between parallel and serial search tasks therefore could not be attributed to a configuration bias. Because the length of the experiment (approximately 2 hr) required participation over the course of 2 days, half of the participants saw parallel displays on the first day and serial displays on the second, whereas the remaining participants performed the tasks in the reverse order. Display size (5 or 17 items) and target condition (positive or negative) were randomly interleaved within each block of parallel or serial search trials.

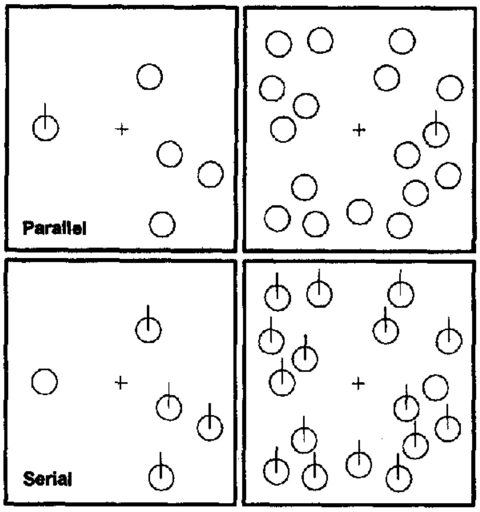

Figure 1. Samples of the 5- and 17-item stimuli used in the target-present trials for parallel (top) and serial (bottom) tasks. The cross appearing at the center of each illustration indicates the participant's initial fixation position. The items in this illustration are not drawn to scale, and the actual displays appeared white on black.

Procedure. The experiment began with calibration of the eye tracker to the participant as she or he made saccades to five stationary targets corresponding to the central fixation cross and points delimiting the 12° field of view in which the search elements would be presented. During calibration and throughout the remainder of the experiment, the participant's head was held immobile by a chin rest and a head restraint. After calibration was completed (approximately 15 min), participants were given a brief description of the experiment. They were told that they would see a succession of multiple-element displays and would have to indicate the presence or absence of a designated target item. If a display contained the target element, the participant was instructed to press a mouse button as quickly but as accurately as possible. Another button was to be pressed if the target element was not present. Participants were then shown a display containing a single centrally located target item and allowed to view this display and

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[2] Postexperiment questioning confirmed that participants were unaware that the target items appeared initially at equally eccentric display locations, suggesting that this factor would not have affected their search strategies.

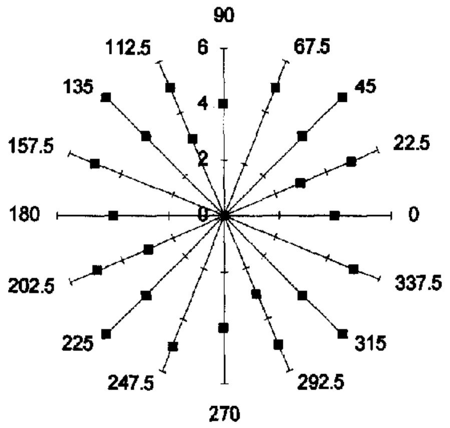

Figure 2. Display items were constrained to the 24 positions represented by the black squares. Item eccentricities are reported in degrees of visual angle; direction is indicated in angular degrees.

ask questions until they felt comfortable with the instructions. Because of the simplicity of the task and a desire to avoid the assessment of overlearned search performance, no practice trials were provided.

Each trial began with the presentation of a central fixation cross for 1.5 s, after which the fixation target was replaced by a search display that remained visible for 3 s. At the end of this time, the stimulus was removed and the fixation cross was redisplayed, regardless of whether a button press occurred during the presentation. Participants were asked to return their gaze to the fixation target and stay fixated there until the next display was presented. This instruction helped to establish a clear baseline eye position measurement needed to accurately detect the next primary saccade. Except for this instruction (and the calibration procedure), no reference was made to eye movements at any time during the experiment.

Saccade recording and extraction. Horizontal and vertical movements of the right eye were recorded with an AMTech E.T.3 two-dimensional eye tracker. The AMTech eye tracker uses a pupil-tracking technique to calculate horizontal eye position. This technique requires illuminating the eye with infrared light emitting diodes (950 nm) and redirecting this light into a lens using an infrared reflecting mirror. The lens images the light onto a linear diode array, creating a reflectance profile of the eye. After proper adjustment, the steepest slopes along this reflectance profile correspond to the margins of the pupil. Horizontal eye position is simply the mean value of these pupil margins. Vertical eye position is calculated off-line using two consecutive horizontal samples and assumptions about pupil symmetry. The spatial resolution of the eye tracker was estimated to be 3 min of visual arc in the horizontal dimension and 15 min in the vertical dimension. The temporal resolution was 10 ms at the experimental sampling frequency of 100 Hz (see Müller, Helmle, & Bille, 1982, for a more complete description of this eye tracker and its operation).

All of the eye movement measures discussed in the following analysis were computed off-line using the eye position data collected from participants during search. Saccades were extracted from these data with a velocity-based computer algorithm. A velocity change was labeled a saccade when three consecutive time samples exhibited minimum velocities of 25°/s, 40°/s, and 25°/s. In general, actual saccade velocities were much faster than these minimum values. Saccade amplitude was defined as the difference between the pre- and postsaccade steady-state fixation baselines. These baselines were calculated by averaging eye position over a 40-ms window. Saccade onset was defined by imposing a 20°/s criterion on the initial component of the velocity increase. The first fixation duration was determined by calculating the time difference between the initial saccade onset and stimulus presentation, which was signaled to the eye tracker by a TTL pulse over the serial port of the display computer at the start of every trial. Initial saccades of less than 1° in amplitude were judged as failures to maintain starting fixation and were excluded from further analysis.

Results and Discussion

Discarded data. Of the 512 trials per search condition, approximately 3% of the parallel search task data and 7% of the serial search task data were discarded because of a loss of the eye position signal by the eye tracker. Track loss was attributed mainly to blinking or excessive squinting by the participant, probably as a result of periodic eye fatigue. It is unlikely that this disproportionate loss of serial trials inflated any task differences between oculomotor variables. Instead, because track loss appears to have been positively correlated with the number of eye movements occurring in a trial, discarding a larger percentage of the serial data would more likely have understated statistical significance. In addition to the data lost because of tracker failure, trials in which participants made a button press error also were excluded from further analysis. The total number of misses and false alarms accounted for only 2% of the remaining serial trials and fewer than 1% of the parallel trials. A more detailed discussion of the trials lost because of manual errors is deferred until Experiment 3 as part of a comparison between free-eye and fixed-eye error rates.

RTs. A 2 × 2 × 2 repeated-measures analysis of variance (ANOVA) performed on the mean RT data yielded a significant main effect of search task, $F(1, 3) = 10.87$, $p = .046$, as well as a marginally significant Task × Display Size interaction, $F(1, 3) = 9.44$, $p = .054$. Both of these trends can be further characterized by a three-way interaction with target condition (positive or negative), $F(1, 3) = 7.63$, $p = .070$. These effects are shown in Figure 3A. Consistent with previous reports of search behavior with similar stimuli (Klein & Farrell, 1989; Treisman & Souther, 1985), these results indicate that increasing the display size from 5 to 17 items had almost no effect on RTs in the parallel search task (−0.14 ms per item for the positive trials and 0.08 ms per item for the negative trials) but yielded longer search times in the positive (17.3 ms per item) and negative (42.6 ms per item) serial data.

Number of saccades. The presence of a Search Task × Display Size × Target Condition interaction and the 2.5:1 ratio of negative to positive serial slopes suggest that the stimuli used in this experiment adequately replicated the RT asymmetry commonly reported in the parallel–serial search literature. New to this literature, however, is an analysis of how many eye movements participants make as they perform these search tasks. As Figure 4A shows, the mean number of saccades initiated before the button press is both consistent and inconsistent with the RT data. As in the case

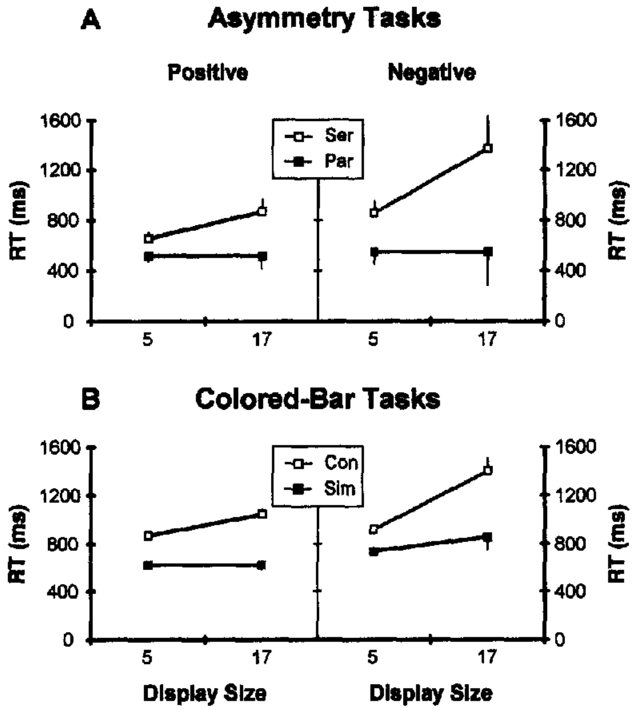

Figure 3. Marginal mean reaction times (RT) for parallel (Par) and serial (Ser) tasks and for simple (Sim) and conjunctive (Con) tasks plotted as a function of display size (5 and 17 items) and target condition (positive and negative). The length of the lines extending above or below the symbols indicates the within-subjects standard error associated with the search task comparisons. (A) Data from the asymmetry experiment. (B) Data from the colored-bar experiment.

of RTs, a repeated-measures analysis of mean saccade number revealed a significant Search Task × Target Condition interaction, $F(1, 3) = 16.84$, $p = .026$, and a relationship between search task and display size approaching reliability, $F(1, 3) = 5.86$, $p = .094$. Unlike the RT results, the three-way interaction failed to reach significance, $F(1, 3) = 3.13$, $p = .175$. The shapes of these interactions are also not typical of those observed for search times. For example, for the Search Task × Display Size interaction, RTs in the parallel task remained constant across changes in display size, but post hoc paired-group t tests indicated significantly fewer saccades at the larger display size in both the positive, $t(3) = 5.94$, $p = .010$, and the negative, $t(3) = 9.39$, $p = .003$, parallel task data. Equally atypical is the fact that saccade number in the serial task was not reliably affected by the addition of nontargets to the display, $t(3) = -0.59$, $p = .594$, for positive trials, and $t(3) = -1.25$, $p = .301$, for negative trials. As can be seen from the individual participant data in Table 1, half of the participants made fewer saccades in the 17-item positive trials, suggesting that this failure to find a display size effect was probably not attributable to a lack of statistical power. A similar argument applied to the negative data is less clear, given the steeper slope (3:1 ratio of negative to positive slopes) described by the Search Task × Target Condition interaction.

One reason for why there were fewer 17-item eye movements during parallel search was an increase in the number of zero-saccade trials at the larger display size. In the case of target-present search, participants abstained from making an eye movement in 54% of the 17-item trials but in only 7% of the 5-item trials. Similarly, eye movements were not observed in 60% of the 17-item negative trials compared with only 20% of the 5-item negative trials. This trend toward more zero-saccade trials for the 17-item data did not characterize eye movements during serial search. Instead, these saccade number distributions appeared quite similar between the two display sizes. A possible explanation for this relationship between saccade number and display size is deferred until the General Discussion section so that these results may be contrasted with data from an identical analysis described in Experiment 2.

Despite their unfamiliar form, the interactions shown in Table 1 and Figure 4A suggest that the parallel–serial search dichotomy observed for mean RTs also exists for the number of eye movements preceding the manual search judgments. Specifically, the difference in number of saccades initiated during search was smaller between parallel and serial search tasks in the 5-item trials than in the 17-item trials. Also similar to the RT data is the fact that in the serial search condition, negative saccade number slopes were three times more steep in the target-absent trials than in the target-present trials, a relationship diagnostic of serial processing. Both of these effects (the Search Task × Display Size interaction and the ratio of negative to positive serial slopes) persisted even after a reanalysis of the data which

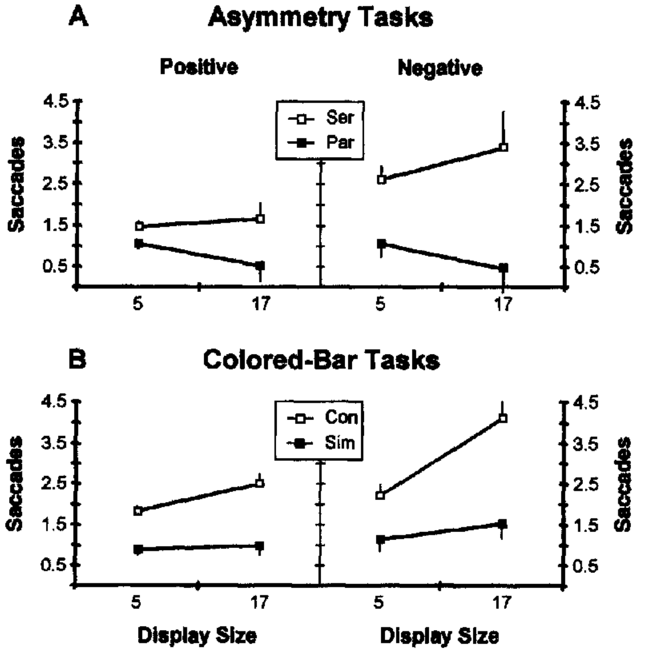

Figure 4. Mean number of saccades occurring before the reaction time button press as a function of search task, display size, and target condition. (A) Asymmetry data. (B) Colored-bar data. Ser = serial; Par = parallel; Con = conjunctive; Sim = simple.

Table 1
Mean Number of Saccades Made by Individual Participants as a Function of Search Condition in Experiment 1

Participant	Positive trials			Negative trials		
	5 items	17 items	Slope	5 items	17 items	Slope
			Parallel search			
1	1.07	0.57	−0.04	1.03	0.24	−0.07
2	1.00	0.19	−0.07	0.84	0.31	−0.04
3	1.16	0.77	−0.03	1.17	0.61	−0.05
4	1.00	0.53	−0.04	1.19	0.66	−0.04
M	1.06	0.52	−0.05	1.06	0.46	−0.05
			Serial search			
1	1.52	1.80	0.02	2.90	3.13	0.02
2	1.47	1.07	−0.03	2.06	1.94	−0.01
3	1.37	1.01	−0.03	2.07	2.46	0.03
4	1.57	2.79	0.10	3.45	6.07	0.22
M	1.48	1.67	0.02	2.62	3.40	0.06

excluded saccades initiated within 200 ms of the button press (as a control for motor response latencies), suggesting that these oculomotor patterns occurred during actual search. Together, these findings indicate that the saccade number variable is sensitive to many of the manipulations that have been previously used to operationally define search.

Fixation durations. A RT measure can be redefined as the number of saccades occurring during search and the latencies of these eye movements. Such a redefinition has a clear implication for the relationship between these two oculomotor variables. Given a RT measure and the number of saccades accompanying search, it is possible to accurately describe fixation duration. For example, the only way that parallel search slopes could remain flat despite fewer eye movements in the 17-item trials is if fixation durations were to increase with distractor number. Similarly, steep RT increases with display size and relatively flat saccade number slopes must mean longer oculomotor fixations in the serial search condition. Evidence for both of these predictions is shown in Figure 5A for trials in which eye movements were observed. Participants viewing a 17-item display took dramatically longer to launch their initial saccades than did those viewing a display containing only 5 items. This difference is reflected by a robust main effect of display size, as determined from a three-way repeated-measures ANOVA, $F(1, 3) = 308.50$, $p < .001$. Durations in the serial task increased at a rate of approximately 21 ms per item regardless of the presence or absence of the target. Parallel task slopes for the positive and negative trials were more shallow, about 16 and 15 ms per item, respectively. This interaction between search task and display size also proved to be significant by ANOVA, $F(1, 3) = 27.79$, $p = .013$. Specifically, initial fixation durations were almost identical between tasks at the smaller display size, but in the 17-item trials serial fixation durations were 84 ms (positive trials) and 95 ms (negative trials) longer than parallel fixation durations. Because of the similarity between target-present and target-absent trials, neither two-way, $F(1, 3) \leq 0.12$, $p \geq .749$, nor three-way, $F(1, 3) = 0.28$, $p = .632$, interactions with target condition even approached reliability. This latter observation has an important implication for whether fixation durations reflect search manipulations. Although these findings provide some suggestion of a parallel–serial search dichotomy appearing in initial fixation durations, unlike the RT and saccade number data these data failed to show a 2:1 ratio of negative to positive search

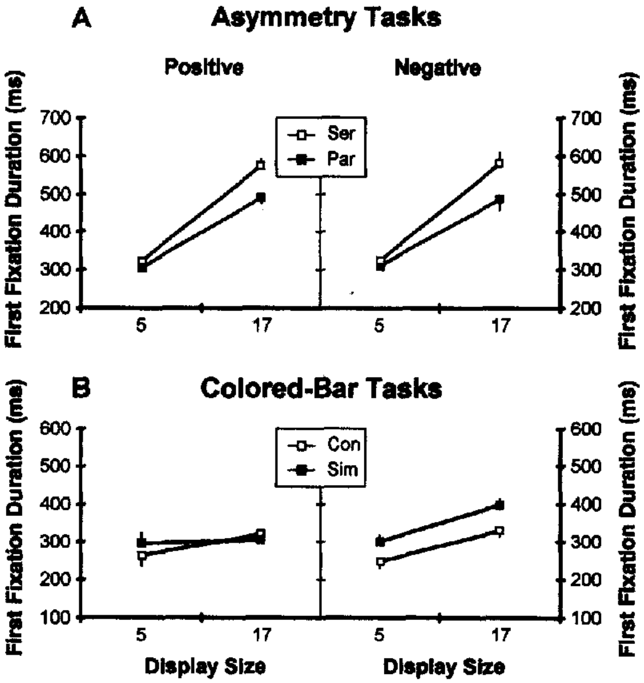

Figure 5. Average first fixation durations plotted as a function of search task, display size, and target condition. Note the dramatic latency increase with display size for both serial (Ser) and parallel (Par) asymmetry tasks (A) but the relatively small effect observed for colored-bar tasks (B). Con = conjunctive; Sim = simple.

slopes. Given the theoretical importance of this relationship to definitions of search, it is therefore unlikely that the variability in durations observed here reflects actual underlying search processes.

An identical analysis of subsequent saccades produced even fewer reasons to believe that a fixation duration measure is adequate to describe search. This measure of average subsequent fixation durations included data from every saccade occurring during search, except for the first and last fixations of a trial. Latency data from the final eye movements were excluded because of their premature termination by the RT button press. Because duration is measured only until the RT response, inclusion of these data would have artificially lowered the estimated mean fixation time. The results of this analysis showed no meaningful interactions between any of the experimental search manipulations. Specifically, search task failed to interact with either display size, $F(1, 3) = 2.77$, $p = .195$, or target condition, $F(1, 3) = 0.71$, $p = .462$. Only the three-way interaction was found to be marginally significant, $F(1, 3) = 5.94$, $p = .093$. What this comparison between initial and subsequent fixation durations suggests is that the relevance of this oculomotor variable to search, assuming that there is any, is probably limited to the latency of the saccade immediately following stimulus presentation.

Relating oculomotor metrics to asymmetry search. It would be tempting to conclude that the previously described changes in number of saccades and, to a lesser extent, initial fixation duration directly reflect the spatiotemporal processes that underlie search movements. Unfortunately, such a statement about search behavior at this point would be premature. So far, these oculomotor measures have been shown to vary only with many of the independent manipulations used to elucidate properties of visual search. This correspondence, however, does not necessitate a relationship between search and oculomotor variables. An example of this lack of relationship is the effect of display size on initial fixation duration and manual response time. Although both dependent measures increase in the serial condition with the number of nontargets added to the display, it is possible that decision factors underlie the search time increase but that the oculomotor system is influenced by more sensory factors. Given the failure to find an effect of target condition on initial fixation duration, it is indeed quite likely that such a dissociation exists, at least for this one oculomotor measure. In other words, the observation of search dichotomies in eye movements should be considered only a minimum criterion that must be met before an oculomotor variable can be used as a measure of parallel–serial search processes.

Although by no means a critical test, showing a meaningful correlation between eye movements and search would be a far more compelling criterion on which to base a relationship. To determine whether such a relationship exists, we made multivariate correlations between the raw RT data and the oculomotor measures of saccade number and initial fixation duration. Data from each cell of the experimental design were analyzed separately so as to prevent the variance associated with the independent manipulations from accentuating these relationships. The R values for saccade number, initial fixation duration, and combined saccade number–duration correlations are shown in Table 2 for individual participants. Two parametric statistical tests were used to interpret the significance of these correlations. The first was simply an F test indicating whether the relationship between RT and both oculomotor variables (expressed by the combined R values) differed significantly from zero for individual participants. With the exception of Participants 1 and 4 in the positive 5-item trials, analysis of the serial data indicated that the multiple correlations were both reliable and consistent between participants. This consistency was far less evident in the parallel data; uniformly reliable results were obtained only for participants in the positive 17-item trials. To assess whether these relationships represent meaningful effects, a Fisher R-to-Z transform was used to normalize the R values so that they would meet the conditions of standard statistical tests. These normalized values were then compared across participants with a t test to determine whether the averaged R value differed from zero. These results, obtained for all three correlations, showed generally reliable saccade number relationships in both the serial data (all p values $\leq .009$) and the parallel data (all p values $\leq .030$, with the exception of $p = .080$ in the positive 5-item parallel trials). No such relationships were observed for initial fixation duration, for which only a correlation in the negative 17-item trials reached marginal significance, $t(3) = 3.10$, $p = .053$.

Also informative from the standpoint of relating eye movements to RTs is whether correlations are more pronounced in some search conditions than in others. These qualitative comparisons yielded several interesting observations. First, saccade number correlated more highly with RT in the serial trials than in the parallel trials. The opposite trend, however, was observed for initial fixation duration (higher correlations in the parallel data), although the differences were less consistent. A similar situation was found for the target condition manipulation. Once again, saccade number correlated more highly with RT in target-absent trials, whereas relationships with fixation duration, although in general weak, tended to be stronger in target-present trials. A final comparison between the two display size manipulations yielded somewhat more consistent patterns between the oculomotor measures, at least in the case of the parallel data. Both saccade number and initial fixation duration correlated more highly with RT in the 17-item parallel trials than in the 5-item parallel trials. This trend, however, persisted in the serial trials only for saccade number; RT and fixation duration remained noncorrelated regardless of display size.

These rather complicated correlational data can be summarized by three simple observations. First, saccade number correlations increased with the amount of variability in the RT data. Paired-group t tests indicated that variability in the serial task, $t(3) = 9.39$, $p = .003$, the 17-item trials, $t(3) = 9.39$, $p = .003$, and the target-absent data, $t(3) = 9.39$, $p = .003$, was greater than variability in the respective parallel task, 5-item trials, and target-present data. As shown in Table 2, in each of these cases of increased RT variability,

Table 2
Coefficients of Multiple Correlation for Reaction Times and Oculomotor Measures (Saccade Number and Initial Fixation Duration) as a Function of Search Condition in Experiment 1

	Positive trials						Negative trials					
Participant	Saccades[a]	Durations[b]	Combined[c]	*F*	*df*	*p*	Saccades[a]	Durations[b]	Combined[c]	*F*	*df*	*p*
						Parallel 5-item search						
1	.10	.20	.25	0.77	2, 24	.475	.42	.05	.42	2.48	2, 23	.106
2	.06	.21	.27	0.92	2, 24	.412	.33	.06	.43	1.87	2, 17	.184
3	.40	.59	.76	19.64	2, 28	<.001	.62	.22	.68	9.76	2, 23	<.001
4	.23	.05	.28	1.07	2, 26	.357	.48	.06	.61	6.65	2, 23	.005
t	2.52	2.10	2.46				6.27	1.29	6.49			
p	.08	.13	.08				<.01	.29	<.01			
						Parallel 17-item search						
1	.48	.72	.80	10.50	2, 12	.002	.61	.68	.79	2.43	2, 13	.235
2	.43	.98	.99	99.29	2, 6	.002	.80	.68	.93	19.39	2, 6	.002
3	.70	.44	.88	30.08	2, 18	<.001	.73	.39	.81	13.24	2, 14	<.001
4	.42	.18	.75	7.49	2, 12	.008	.19	.11	.41	1.53	2, 15	.244
t	5.72	2.04	3.63				3.75	3.10	4.28			
p	.01	.13	.03				.03	.05	.02			
						Serial 5-item search						
1	.34	.28	.37	1.94	2, 24	.166	.75	.17	.77	19.51	2, 27	<.001
2	.42	.10	.43	3.30	2, 29	.051	.41	.28	.57	6.91	2, 29	.004
3	.44	.05	.52	4.02	2, 22	.033	.58	.34	.68	10.64	2, 25	<.001
4	.22	.24	.38	2.14	2, 26	.138	.73	.28	.75	17.90	2, 28	<.001
t	6.71	0.18	10.80				6.06	0.27	10.29			
p	<.01	.86	<.01				<.01	.80	<.01			
						Serial 17-item search						
1	.85	.01	.86	34.19	2, 24	<.001	.81	.13	.81	25.93	2, 28	<.001
2	.58	.41	.81	18.54	2, 20	<.001	.86	.06	.88	42.51	2, 26	<.001
3	.81	.38	.82	16.47	2, 16	<.001	.75	.08	.75	14.19	2, 22	<.001
4	.77	.07	.83	28.98	2, 26	<.001	.85	.10	.88	42.62	2, 25	<.001
t	7.83	0.05	31.29				16.85	0.86	12.47			
p	<.01	.97	<.01				<.01	.45	<.01			

Note. *F* tests for individual participants were conducted on the combined *R* data. The *t* test values describe across-subject comparisons with averaged *R* values after adjustment with a Fisher *R*-to-*Z* transform.
[a] *R* values for saccade number correlations. [b] *R* values for initial fixation duration correlations. [c] *R* values for combined saccade number and initial fixation duration correlations.

the relationship between saccade number and search time also improved. With only one notable exception (the display size manipulation in the parallel data), this pattern failed to characterize the initial fixation correlations. The implication of this observation is clear: the greater the RT variability, the greater the opportunity for saccade number to capture the additional systematic variance. The second summary observation is equally straightforward; the relationship between RT and saccade number was both significant (as evidenced by within- and across-subject statistics) and meaningful (the number of saccades could account for up to 67% of the search time variability). Finally, the previously described observations generally did not extend to initial fixation duration, indicating that variability in this measure may not reflect actual search behavior.

Despite this correlational evidence for a relationship between saccade number and RT, it is still unclear whether these two behaviors share a common search function. As an illustration of this potential problem, consider a scenario in which an eye movement is initiated according to a fixed timetable, possibly every 200 ms. Because RTs are longer in serial tasks (relative to parallel tasks), a greater opportunity would exist in this condition for a stereotypical oculomotor process to generate more saccades (thereby explaining the high correlations between number and search times), even though these eye movements may have nothing to do with search. To explore this possibility, we computed the Euclidean distance (in degrees of visual angle) between the target and the first and last saccade landing positions (endpoints) for every trial in which an eye movement was observed. The resulting mean endpoint errors are shown in Figure 6A for the positive asymmetry data.[3] If the eye movements initiated before the manual RT response were in fact dissociated from actual search, then there would be no reason to expect any systematic relationship between the landing position of a saccade and the location of the target. However, if eye movements and RTs reflect a common underlying search process, then final saccades should land closer to the target

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[3] Because endpoint error is not defined when a target is absent from a display, this accuracy measure is available only for positive data.

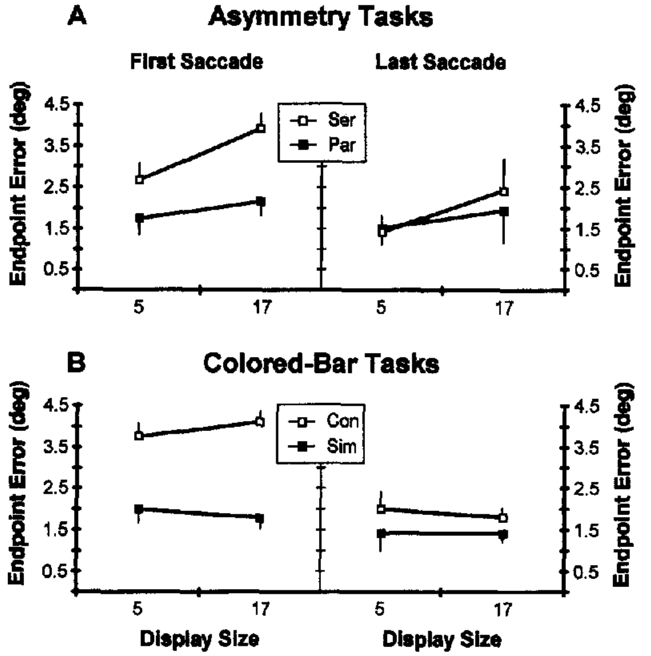

Figure 6. Mean endpoint errors following the first and last saccades of a trial as a function of display size and search task. Only data from the positive trials are shown because of the inability to compute endpoint errors for the target-absent data. (A) Asymmetry experiment. (B) Colored-bar experiment. Ser = serial; Par = parallel; Con = conjunctive; Sim = simple; deg = degree.

than those executed initially during the trials. This latter hypothesis is clearly supported by the data. A repeated-measures ANOVA revealed a highly significant Saccade (first vs. last) × Search Task × Display Size interaction, $F(1, 3) = 77.96$, $p = .003$, indicating that in the serial 17-item trials, initial saccades were less accurate than those at the time of the search judgments.[4] Note also that similar patterns of error in the parallel data reflect the fact that first saccades in this condition were also typically the last. A second analysis (not shown) tested whether oculomotor convergence toward the target existed for individual trials. The difference between the first and last saccade endpoint errors was computed for each trial in which there were two or more eye movements. Results from this analysis yielded mean error differences of 1.7° in the parallel condition, $t(3) = 4.31$, $p = .023$, and 2.5° in the serial condition, $t(3) = 10.82$, $p = .002$; both were significantly greater than zero (the difference expected if eye movements were unrelated to search). These accuracy results, particularly the improvement in serial targeting behavior over time, complement the results of the earlier correlational analysis and provide converging evidence for a functional relationship between oculomotor behavior and search.

Experiment 2: Eye Movements During Simple and Conjunctive Searches

The possibility exists that the Search Task × Display Size interactions observed for saccade number and initial fixation duration in the asymmetry experiment may not describe interactions underlying oculomotor search dichotomies with other stimuli. With the redefinition of search into two oculomotor components, there now exist multiple ways in which to construct standard RT functions. For example, suppose that search conditions *A* and *B* yield identical linearly increasing RT slopes as a function of display size. It is still unclear from this information whether the eye movement patterns appearing in search *A* are the same as the ones appearing in search *B*. In fact, with just the two oculomotor measures of saccade number and fixation duration, there are practically an infinite number of ways to construct a serial search slope (an identical argument can be made for the parallel search function). To test the hypothesis that ocular fixations can discriminate between search conditions having similar RT functions, we conducted an analysis identical to the one presented above, using new data obtained from simple–conjunctive search tasks. If these simple–conjunctive stimuli yield unique oculomotor signatures, then it may be possible to use saccade metrics to identify and study procedurally distinct subclasses of search that would not be apparent from an analysis of RTs.

A distinction between simple and conjunctive searches dates back to the seminal work of Treisman and Gelade (1980) and the original formulation of feature integration theory. According to this theory, the search for a unique or simple feature in a multiple-element display can proceed independently of the number of accompanying distractors. However, when the target of a search task is a conjunction of features, RTs increase linearly with display size. Although the hypothesized basis for this dichotomy has undergone some modification over the years (Treisman, 1988), the original explanation posited that attention must serially visit each conjunctive element before its component features can be recognized as a holistic object but that the recognition of a simple target can occur preattentively and in parallel across the entire display. For the sake of clarity in drawing comparisons between the following results and findings from the previous experiment, the current dichotomy is described in terms of diverging simple and conjunctive slopes, and the designation of parallel–serial search is reserved for references to asymmetry tasks. This distinction, however, does not suggest a theoretical difference between these two types of search dichotomies.

Method

Two male and 2 female participants, none of whom took part in the asymmetry tasks, were paid approximately $8/hr for their involvement in this experiment. All of the participants were unaware of the questions under investigation and had normal visual acuity.

The search stimuli used in this experiment were horizontal and

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[4] Because participants were not instructed to make an eye movement to the target, referring to endpoint error as accuracy does not seem entirely appropriate. However, given the evidence indicating that saccades were used to actively search for the target, we continue to refer to endpoint error as an accuracy measure.

vertical bars. The bars subtended 2/3° visual angle in length and 1/4° visual angle in width. Each element type could appear as either red or green, depending on the condition. Both colors were drawn at a luminance of 5.5 cd/m^2 on a 0.1-cd/m^2 black background by the computer used to create the asymmetry stimuli.

The colored–oriented bars were combined to form simple and conjunctive search displays. Four variations of the simple display were used in this experiment. A red vertical target might appear in homogeneous fields of green vertical or red horizontal distractors, or a green horizontal target might appear among red horizontal or green vertical distractors. The target in each of the simple variations could be defined by a unique feature (e.g., the feature "red" in the case of a vertical red target among vertical green distractors). Conjunctive displays appeared in only two variations. A field of green vertical and red horizontal distractors accompanied either a red vertical or a green horizontal target. Participants viewed the simple and conjunctive displays separately in two counterbalanced sessions. Within each session, trials of a particular task variation were blocked and counterbalanced across participants. A sample of the target element preceded each block of trials.

All other aspects of the experimental design, procedure, and saccade extraction were identical to the descriptions provided for the asymmetry tasks, including the use of 128 trials per search task, two display sizes (5 or 17 items), and positive and negative target conditions. The placement of elements in the display also followed the same configuration constraints as in the asymmetry tasks, although new configurations were generated for this experiment. Examples of simple and conjunctive search tasks at both display sizes are shown in Figure 7.

Results and Discussion

Discarded data. The number of trials lost because of tracking failure was more of a problem in this experiment than in the previous one. Out of the combined 512 trials for all 4 participants, track loss occurred in approximately 18% of the conjunctive trials and 12% of the simple trials. Although these percentages may seem excessive, it is important to remember that a trial was discarded if the participant blinked at any time before making the search judgment. This precaution was thought to be necessary because blinks are inherently ambiguous in both the spatial and the temporal domains and therefore may lead to overestimation of the number of saccades made during a trial and underestimation of the duration of true fixations. It is believed that the larger percentage of conjunctive search failures (relative to those in simple searches) is probably related to the larger number of eye movements occurring in the more difficult task, although it is unclear why more failures overall occurred for the colored-bar stimuli. The percentage of button press errors, however, was comparable to the response accuracy in the asymmetry tasks. Participants made incorrect responses (combined misses and false alarms) in fewer than 3% of the conjunctive trials and in only 0.5% of the simple trials. Trials in which the eye signal was lost or an error occurred were not included in the RT or eye movement analyses.

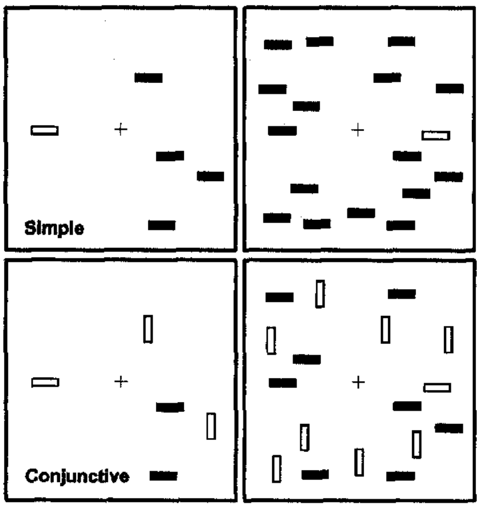

Figure 7. Simple (top) and conjunctive (bottom) search tasks for 5- and 17-item target-present displays. The target in all four panels is the unfilled horizontal bar, which corresponds to a green bar in the actual task. Items are not drawn to scale.

RTs. The four variations of simple search used in this experiment complicated the RT results. Recall that participants searched for either a red vertical bar among green vertical or red horizontal distractors or a green horizontal bar among red horizontal or green vertical distractors. Because two of these search tasks involved a color discrimination but the other two required an orientation judgment, it is possible that RT differences existed between these simple search conditions. To test for this possibility, we compared mean RTs using a three-way ANOVA with color–orientation, display size, and target condition as within-subject variables. This analysis indicated no evidence for RT differences in any of these tasks ($p \geq .113$ for all task comparisons). More to the point of this article, we conducted a similar analysis on the number of saccades executed during these simple searches. In general, the results again were unsupportive of differences between the color and orientation conditions. With the exception of a Color–Orientation × Target Condition interaction approaching significance at $p = .087$ (slightly more eye movements in the negative orientation condition), all other comparisons yielded p values $> .102$. Given the failure to find convincing simple task differences, separate eye movement analyses for the color and orientation data did not seem warranted. Instead, both tasks were collapsed into a single measure of simple search for comparisons with the conjunctive search results.

The data points in Figure 3B represent the marginal mean RTs from all four participants collapsed across the two conjunctive and four simple task variations. A repeated-measures analysis of the data revealed all of the familiar indications of a search dichotomy, summarized by a significant interaction between search task, display size, and target condition, $F(1, 3) = 24.75$, $p = .016$. Furthermore, the increase in RT with display size in the conjunctive search condition was 2.7 times larger in the negative trials than in the positive trials. No display size effect was found for the simple search condition. These differences between simple and conjunctive search slopes are quantitatively similar to the parallel–serial search dichotomy observed in the asymmetry experiment, although y intercepts appeared to be more elevated in the colored-bar data. Specifically, the y intercepts for positive and negative trials were about 100 ms and 200 ms greater, respectively, in the simple search condition than in the corresponding parallel search condition. Conjunctive search intercepts also were greater than serial search intercepts by about 200 ms in positive trials, but this difference decreased to only 60 ms in negative trials.

Number of saccades. The functions relating search task and display size to the number of eye movements occurring during search bear a striking resemblance to the RT data. Both saccade number and RT results show the characteristic divergence between slopes suggestive of parallel and serial processes. This dichotomy is illustrated for mean saccade number in Figure 4B. A repeated-measures ANOVA confirmed that saccade number increased with display size more in the conjunctive search condition than in the simple search condition, $F(1, 3) = 17.77, p = .024$. As with the RT data, this effect also interacted with target condition, yielding a reliable three-way relationship, $F(1, 3) = 27.71, p = .013$. This latter interaction reflects the fact that the ratio of negative to positive saccade number slopes was 2.7:1 in the conjunctive search condition, nearly identical to the corresponding relationship found for mean RTs. Neither of these results was found to depend on the oculomotor behavior occurring within 200 ms of the button press, again indicating the presence of a simple–conjunctive search dichotomy even in a population of saccades that were likely to have been initiated during search.

The shape of this saccade number dichotomy is in sharp contrast to the interactions found for the asymmetry tasks. Instead of participants making fewer saccades at the larger display size, as was the case in the parallel task, saccade number was unaffected when more distractors were added to the simple search displays, $t(3) = -3.39, p = .259$, for positive trials and $t(3) = -1.93, p = .149$, for negative trials (both determined by post hoc paired-group t tests). The reason for this difference can again be attributed largely to the frequency of zero-saccade trials. The more frequent occurrence of zero-saccade trials in the 17-item parallel task resulted in a smaller mean saccade number for that condition. However, the percentage of simple trials without eye movements was roughly the same for the 5- and 17-item displays (26% of the positive 5-item trials compared with 20% of the 17-item trials and 35% of the negative 5-item trials compared with 31% of the 17-item trials). Instead, distributions of saccade number differed between serial and conjunctive tasks. Increasing the number of nontargets resulted in significantly more saccades in the conjunctive positive trials, $t(3) = -4.06, p = .027$, and negative trials, $t(3) = -5.62, p = .011$, but no such increase was found in the serial task (see Figure 4).

Fixation durations. A repeated-measures analysis of the initial fixation duration data yielded a significant three-way interaction among the search conditions, $F(1, 3) = 33.78$, $p = .010$. Despite this result, however, it is clear from Figure 5B that these oculomotor trends do not reflect typical parallel–serial search dichotomies. For example, no evidence was found for a Search Task × Display Size interaction in either the positive or the negative data, $p \geq .367$ (as determined by separate two-way ANOVAs). Also peculiar was the finding of longer target-absent durations in the easier simple search condition than in the more difficult conjunctive search condition, $F(1, 3) = 20.55, p = .020$. A comparison of display size effects between these duration results and those of the corresponding asymmetry analysis yielded other interesting observations. Although initial durations tended to increase with display size in the colored-bar experiment, this effect was only a fraction of what was observed in the asymmetry experiment. Initial fixation durations at the larger display size increased by only 9 ms in the positive trials and 96 ms in the negative trials for the simple tasks, a small effect compared with the respective 187- and 177-ms increases found in the positive and negative trials for the parallel tasks. Larger differences were observed for the more difficult search tasks. Durations in positive and negative trials increased with display size by 254 ms and 256 ms, respectively, for the serial tasks but by only 57 ms and 82 ms, respectively, for the conjunctive tasks.

The fact that initial fixation durations were relatively unaffected by the colored-bar search manipulations did not force subsequent fixations to play a more prominent role. When durations following the initial saccade were averaged (again excluding final fixations because of their premature termination by the RT button press) and analyzed, no significant effects were found. As in the case of the asymmetry results, mean noninitial fixation durations failed to differ for search task, display size, target condition, or their two- and three-way interactions, $F(1, 3) \leq 4.27$, $p \geq .131$, for all effects.

Relating oculomotor metrics to colored-bar search. The number of saccades initiated during the colored-bar search tasks faithfully describe the RT functions commonly associated with parallel–serial processing. However, this observation suggests only that saccade number is sensitive to the manipulations shown to affect RT measures of search. To test whether oculomotor measures reflect actual search (rather than stimulus changes linked to the experimental manipulations), we correlated saccade number and initial fixation durations with the RT data for individual participants and search conditions (Table 3). In general, these data were more variable than were data from the corresponding asymmetry analysis (refer back to the earlier analysis for more detailed information as to how these correlational data were treated). Specifically, R values varied considerably between participants for a given search condition (as indicated by F tests). However, despite this variability, when multiple correlation coefficients were averaged across participants (with a Fisher R-to-Z transform) and tested for their difference from zero, the results obtained were at least marginally significant for all of the saccade number, $t(3) \geq 2.49$, $p \leq .082$, and combined number–duration, $t(3) \geq 2.58$, $p \leq .088$, comparisons. None of the relationships between initial fixation duration and RT even approached reliability, $t(3) \leq 1.76$, $p \geq .177$.

Table 3

Coefficients of Multiple Correlation for Reaction Times and Oculomotor Measures (Saccade Number and Initial Fixation Duration) as a Function of Search Condition in Experiment 2

	Positive trials						Negative trials					
Participant	Saccades[a]	Durations[b]	Combined[c]	F	df	p	Saccades[a]	Durations[b]	Combined[c]	F	df	p
Simple 5-item search												
1	.15	.05	.16	0.16	2, 13	.853	.59	.53	.69	4.43	2, 10	.042
2	.52	.03	.53	4.86	2, 25	.017	.71	.36	.72	11.48	2, 22	<.001
3	.14	.08	.17	0.32	2, 21	.731	.51	.89	.89	42.81	2, 22	<.001
4	.65	.31	.73	8.62	2, 15	.003	.30	.31	.36	0.52	2, 17	.618
t	2.58	1.20	2.49				5.17	0.77	4.09			
p	.08	.32	.09				.01	.50	.03			
Simple 17-item search												
1	.34	.01	.37	1.18	2, 15	.334	.89	.46	.89	16.59	2, 9	.001
2	.29	.35	.48	4.09	2, 27	.028	.94	.21	.95	104.49	2, 23	<.001
3	.01	.04	.04	0.02	2, 26	.997	.11	.10	.21	0.55	2, 23	.587
4	.28	.12	.31	0.73	2, 14	.502	.80	.52	.92	35.16	2, 13	<.001
t	3.13	1.58	3.13				3.07	0.03	3.52			
p	.05	.21	.05				.05	.98	.04			
Conjunctive 5-item search												
1	.47	.01	.48	3.92	2, 27	.032	.45	.12	.46	3.16	2, 24	<.061
2	.67	.02	.67	9.72	2, 24	.001	.53	.48	.71	11.08	2, 22	<.001
3	.15	.20	.23	0.60	2, 22	.558	.39	.02	.40	2.45	2, 26	.106
4	.47	.34	.50	3.03	2, 18	.073	.08	.39	.39	1.62	2, 18	.225
t	3.67	1.76	4.46				3.59	1.36	4.95			
p	.04	.18	.02				.04	.27	.02			
Conjunctive 17-item search												
1	.50	.59	.86	38.11	2, 27	<.001	.72	.08	.80	22.86	2, 26	<.001
2	.88	.16	.90	46.00	2, 21	<.001	.81	.32	.81	15.77	2, 17	<.001
3	.77	.02	.80	20.79	2, 23	<.001	.68	.16	.69	13.07	2, 29	<.001
4	.55	.12	.69	6.94	2, 15	.007	.65	.26	.89	35.45	2, 19	<.001
t	4.72	1.55	8.82				12.34	0.28	9.63			
p	.01	.22	<.01				<.01	.80	<.01			

Note. F tests for individual participants were conducted on the combined R data. The t test values describe across-subject comparisons with averaged R values after adjustment with a Fisher R-to-Z transform.

[a] R values for saccade number correlations. [b] R values for initial fixation duration correlations. [c] R values for combined saccade number and initial fixation duration correlations.

As in the case of the asymmetry data, the strength of the correlations between saccade number and search time also increased with variability in the RT measure. Post hoc paired-group t tests confirmed that RT variability was greater for the 17-item conjunctive displays (positive and negative) than for all of the other search conditions, $t(3) \geq 2.35$, $p \leq .050$ (the only exception being data from the target-absent 17-item simple displays, which showed both high RT variability and pronounced R values). This trend is expressed in Table 3 by the uniformly high subject correlation coefficients specific to these tasks. The observation of stronger relationships in tasks having greater search time variability suggests shared variance between the RT and saccade number measures and is a particularly convincing example of search behavior reflected in an oculomotor variable. However, correlations between initial fixation duration and RT deviated from this trend, indicating a dissociation between this oculomotor measure and search.

To ground the previous correlational arguments in a more objective measure of this search–saccade relationship, we compared mean endpoint errors for the first and last eye movements of a trial. As before, the purpose of this comparison was to determine whether initially inaccurate fixations become aligned with the location of the target at the time of the RT button press. Such an alignment would suggest an association between the processes controlling search movements and those responsible for programming oculomotor behavior. Evidence for such a relationship is shown in Figure 6B. A measure of mean accuracy for the final fixation indicated an improvement of almost 2° over the initial fixation in the conjunctive search condition. The reliability of this difference was confirmed by a significant Saccade (first vs. last) × Search Task × Display Size interaction, $F(1, 3) = 10.17, p = .050$, as determined from a repeated-measures ANOVA. An analysis in which final saccade endpoint errors were subtracted from first saccade endpoint errors and averaged across all the trials also supported an oculomotor convergence toward the target by yielding error differences reliably greater than zero for both the simple (2.1°), $t(3) = 4.47, p = .021$, and the conjunctive (2.6°), $t(3) = 9.83, p = .002$, search tasks. These findings, when considered alone, might indicate only modest support for a relationship between eye movements and the time taken to make a target judgment. However, when viewed together with the correlational data and the presence of dichotomies in saccade number slopes, these observations provide convincing evidence for a search process reflected in oculomotor behavior.

Experiment 3: Search Without Eye Movements

Any conclusions drawn from the asymmetry and colored-bar experiments depend on the premise that the stimuli used in these tasks reflect the search dichotomies commonly reported in the visual attention literature. As already discussed, there is good reason to believe that this is the case. Parallel and simple tasks yielded flat RT functions showing little or no dependence on display size, whereas search times in the serial and conjunctive tasks rose significantly with increasing numbers of distractors. Furthermore, the ratio of negative to positive search slopes in the more difficult tasks showed at least the 2:1 ratio expected from a serial self-terminating process (2.5:1 in the serial search and 2.7:1 in the conjunctive search). Nevertheless, one might still argue that another defining characteristic of this search dichotomy is a dissociation from oculomotor behavior. Because parallel–serial search paradigms are commonly used to infer the covert movements of an attentional mechanism, researchers have been careful to demonstrate the persistence of search dichotomies in the absence of accompanying eye movements (Klein & Farrell, 1989; Treisman & Gormican, 1988). The fact that eye movements were made in the current experiments might therefore raise the suspicion that these tasks do not capture a pure parallel–serial search dichotomy and instead reflect behavior distinct to oculomotor search. In other words, if participants were prevented from making saccades in these tasks, then their resulting search functions would no longer indicate separate parallel and serial processes. A corollary to this argument might also suggest that participants do not normally make eye movements during parallel–serial search tasks and that the reason that they were observed in the current experiments is that the tasks could not be performed in their absence, presumably because of placement of the elements over too wide a visual angle.

In response to these potential concerns, the current set of control experiments established a baseline measure of search performance by having participants repeat the previous tasks without making eye movements. If when prevented from making saccadic eye movements, participants still demonstrated parallel–serial and simple–conjunctive search differences, then the dichotomies reported in Experiments 1 and 2 could not be mere artifacts of forced oculomotor behavior. It would also follow from this finding that participants in the earlier tasks chose to supplement a covert search of the displays with overt ocular refixations, even though this latter behavior was not necessary to the successful completion of the tasks.

Method

The 8 participants who were involved in the asymmetry and colored-bar tasks returned for these control experiments. Approximately 10 months had elapsed between the earlier experiments and the control experiments. Participants were paid $8/hr as compensation for their time.

The displays used in the control tasks were identical to the ones viewed previously by the participants, including the same target–nontarget configurations and order of trial presentations. With the following two exceptions, all other aspects of the stimuli, design, and procedures described for the asymmetry and colored-bar experiments were also used in the control experiments. First, participants were explicitly instructed not to make eye movements during the presentation of the search stimuli. Because most of the participants had difficulty recalling the earlier procedure, the original task instructions were also repeated at this time. The second exception to the earlier methodology was the addition of a central fixation cross to the search displays. This addition was made to help participants avoid making eye movements during search. Participants were not provided with feedback as to how well they were able to follow the instruction regarding no eye movements.

Although it would have been easier to use brief stimulus presentations to prevent eye movements during search, two reasons led to the rejection of this paradigm. The first was a desire to keep the control tasks as similar as possible to the original experimental conditions. The information available from a brief presentation ($\leq$180 ms) would have been likely degraded relative to that in the original 3-s exposures. Such degraded information might also have resulted in artificially high percentages of incorrect responses. Second, Klein and Farrell (1989, Experiment 1) showed that 180-ms stimulus exposures yielded an atypical pattern of serial search times. Instead of the expected 2:1 ratio of negative to positive serial search slopes, they found equivalent slopes in the target-absent and target-present trials. Overall, serial search slopes were also reported to be shallower than slopes obtained during free-eye search with the same stimuli. Because either of these differences could have compromised the control experiments, we decided to use the original 3-s exposure durations while monitoring for oculomotor behavior throughout search. This design was almost identical to the fixed-eye paradigm adopted by Klein and Farrell in their second experiment.

Results and Discussion

Errors. Participants were reasonably successful at maintaining fixation throughout the control experiments, despite reports of a strong urge to make saccades. Eye movements in both the asymmetry and colored-bar tasks occurred in approximately 5% of the total trials. Trials in which saccades were detected (a 1° or greater deviation in eye position from the fixation cross) did not appear biased toward a particular search task (parallel–serial or simple–conjunctive) or target condition (positive or negative) and instead appear to have been reflexive motor responses to display onset. Data from these eye movement trials were excluded from all further analyses.

Table 4 summarizes the incorrect manual responses for the free-eye and fixed-eye experiments in both the asymmetry and the colored-bar search tasks. Errors in the positive and negative target conditions are indicated by misses and false alarms, respectively. It is clear from these data that

Table 4
Percentages of Errors (Misses and False Alarms) in Fixed-Eye and Free-Eye Tasks as a Function of Search Condition

	Misses				False alarms			
	Parallel–simple		Serial–conjunctive		Parallel–simple		Serial–conjunctive	
Participant	Fixed	Free	Fixed	Free	Fixed	Free	Fixed	Free
				Asymmetry data				
1	1.78	0.00	4.84	1.72	0.00	1.67	1.67	0.00
2	4.76	1.56	6.78	3.13	0.00	1.56	0.00	1.56
3	0.00	0.00	3.13	3.64	0.00	0.00	1.56	0.00
4	0.00	0.00	1.82	4.84	0.00	0.00	0.00	1.67
M	1.64	0.39	4.14	3.33	0.00	0.81	0.81	0.81
				Colored-bar data				
1	0.00	0.00	4.84	0.00	0.00	1.85	3.23	1.75
2	0.00	0.00	0.00	1.85	0.00	0.00	0.00	0.00
3	3.45	0.00	26.98	3.70	0.00	0.00	15.87	4.26
4	1.56	1.64	6.78	6.00	0.00	0.00	4.84	1.96
M	1.25	0.41	9.65	2.89	0.00	0.46	5.98	1.99

participants were able to perform all of the tasks at a high level of accuracy without the aid of eye movements. In none of the search tasks did the percentage of errors exceed 10%. In fact, with the exception of the fixed-eye conjunctive data, error rates were less than 5% for all of the tasks. Even this tendency toward more errors during the conjunctive search was largely the product of 1 participant's difficulty in maintaining fixation. Had this participant's data been removed from the analysis, fixed-eye conjunctive misses would have decreased to a mean of 3.8% and false alarms would have decreased to 2.7%.

Data from a comparison of percentages of misses in the fixed-eye search tasks suggest that a larger percentage of errors appeared in the more difficult search tasks than in the easier ones, although a paired-group analysis was able to confirm this trend only for the asymmetry data, $t(3) = -7.35, p = .005$. No reliable difference was found between the simple and conjunctive tasks, $t(3) = -1.62, p = .204$. More relevant from the perspective of a control experiment was a comparison of free-eye (original) and fixed-eye (control) errors. An analysis of percentages of misses by a two-way (Search Task × Free vs. Fixed) repeated-measures ANOVA failed to yield a main effect of eye condition (free vs. fixed) or an Eye Condition × Search Task interaction on either the asymmetry data, $F(1, 3) \leq 0.80, p \geq .437$, or the colored-bar data, $F(1, 3) \leq 1.50, p \geq .308$. Similarly, the percentages of false alarms did not differ in free-eye and fixed-eye conditions for either serial or conjunctive searches, $t(3) = -1.53, p = .224$. Because of the absence of errors in the negative parallel and simple search data, it was impossible to perform more comprehensive tests of significance for misses and false alarms. In general, however, the findings provide little reason to suspect that differential patterns of errors in the original and control experiments meaningfully affected search behavior.

RTs. The fact that participants could perform these search tasks without making eye movements is not that surprising given the large number of zero-saccade trials for the free-eye data. A more interesting question is whether the free-eye search times differed from the fixed-eye ones. Depending on the direction of such a difference, statements can be made about the relationship between eye movements and search efficiency. To address these questions, Figure 8 shows the mean RTs from the fixed-eye control experiments superimposed over the original asymmetry and colored-bar results. For the fixed-eye asymmetry data (Figure 8A), a repeated-measures ANOVA revealed the expected Search Task × Display Size interaction, $F(1, 3) = 116.24, p = .002$, as well as a marginally significant three-way interaction with target condition, $F(1, 3) = 6.74, p = .081$. As predicted by a serial search process, the negative search slope of 16.4 ms per item was found to be in a 2.3:1 ratio with the positive slope of 7 ms per item. A similar pattern of results was observed for the fixed-eye colored-bar data (Figure 8B). Again, a repeated-measures analysis indicated a relationship between task and number of distractors, $F(1, 3) = 68.04, p = .004$, which was further qualified by a significant Search Task × Display Size × Target Condition interaction, $F(1, 3) = 19.75, p = .021$. The ratio of negative to positive conjunctive search slopes (4.4:1) was higher than that expected from a self-terminating serial process, possibly suggesting a shift in the target-absent response criteria (a explanation consistent with the trend in Table 4 toward fewer errors in the negative trials).

In a similar experiment, Klein and Farrell (1989) found that when participants were prevented from making eye movements but given up to 3 s to respond (i.e., not a brief presentation paradigm), search patterns conformed to the expected serial–parallel search dichotomy. They also reported a trend toward shorter fixed-eye RTs (relative to those in a free-eye control task) for their largest display condition. The current data are in agreement with both of

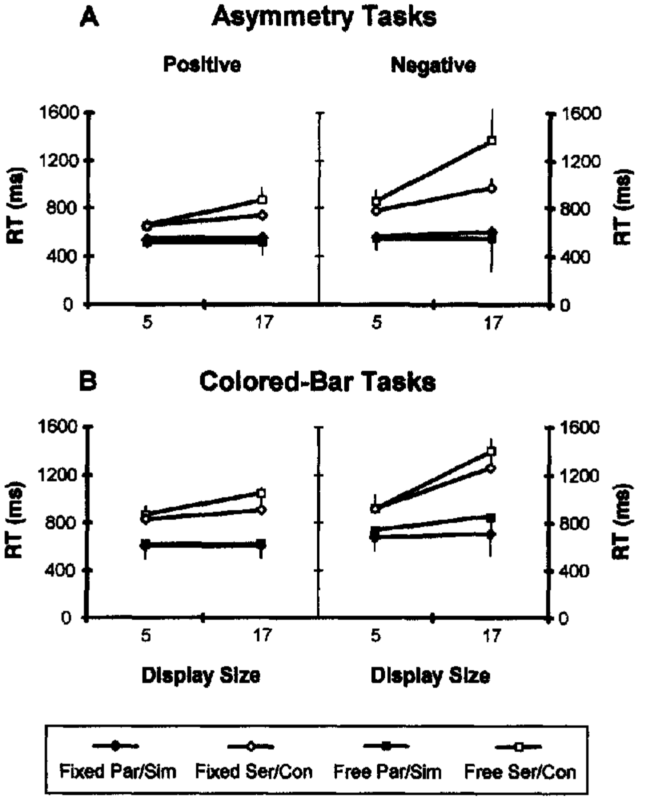

Figure 8. Mean reaction times (RT) for the free-eye (squares) and fixed-eye (diamonds) tasks in the asymmetry (A) and colored-bar (B) experiments. Par = parallel; Sim = simple; Ser = serial; Con = conjunctive.

these earlier observations. Whereas parallel and simple slopes were clearly unaffected by the presence or absence of saccades, serial and conjunctive searches may actually have been faster without eye movements. When this observation was tested, marginally significant Search Task × Display Size × Free versus Fixed interactions were found in the positive trials for the asymmetry tasks, $F(1, 3) = 12.00, p = .041$, and for the colored-bar tasks, $F(1, 3) = 5.71, p = .097$, but not in the negative trials for either the asymmetry, $F(1, 3) = 2.63, p = .203$, or the colored-bar, $F(1, 3) = 0.43, p = .560$, experiments. If these three-way interactions are real, then an argument can be made for the counterintuitive claim that serial and conjunctive search times increase with display size faster when the eyes are free to move, at least for trials in which a target is present in the display.

If serial and conjunctive slopes were more shallow in the control experiments, how might this difference between free-eye and fixed-eye tasks be explained? The extended period of time that elapsed between the original and control experiments, together with the moderate number of trials asked of participants, makes it improbable that this result is attributable to practice effects alone; in addition, the low percentage of fixed-eye errors makes it unlikely that these faster RTs are attributable entirely to less accurate responses in the absence of eye movements. Related to this latter point, Klein and Farrell (1989) suggested that this trend in their data might have been attributable to participants' finding it difficult to maintain fixation for extended periods of time during a fixed-eye task. According to this view, when a change in gaze seemed imminent, participants might have prematurely terminated the trial by guessing, a strategy that would have given rise to a trade-off between manual RTs and search accuracy.

Although none of the above-described possibilities should be ruled out, the availability of oculomotor data in the free-eye condition allows an alternative explanation for the fixed-eye RT advantage to be explored. Every saccade occurring during search causes the stimulus display to streak across the retina at speeds approaching 500°/s. Given this unfavorable viewing condition, it is quite reasonable to assume that the capacity for search and perhaps vision in general becomes diminished during these brief periods. Because one of these visual interruptions accompanies every saccade, search tasks that result in more eye movements may owe some portion of their duration to the time required to physically move the eyes in their orbits. The validity of this measure is based on the assumptions that the capacity to process visual information is reduced during a saccade and that meaningful search behavior cannot proceed in the absence of this visual input.[5]

To estimate the time devoted to moving the eyes from one fixation to the next, we use the equation $D = 2.2A + 21$, where D is the duration of a saccade (in milliseconds) and A is the amplitude of the saccade in degrees (Hyde, 1959). Because this analysis is more concerned with mean duration, $\bar{D}$, a measure of mean amplitude, $\bar{A}$, will be substituted for A. The equation used to estimate the total difference ($\bar{D}_{\text{diff}}$) in mean saccade durations between search conditions is therefore

$$\bar{D}_{\text{diff}} = \sqrt{[\bar{N}_{\text{par}}(2.2\bar{A}_{\text{par}} + 21) - \bar{N}_{\text{ser}}(2.2\bar{A}_{\text{ser}} + 21)]^2},$$

where $\bar{N}_{\text{par}}$ and $\bar{N}_{\text{ser}}$ are the mean numbers of saccades occurring in the parallel and serial search conditions, respectively and $\bar{A}_{\text{par}}$ and $\bar{A}_{\text{ser}}$ are the mean amplitudes in the parallel and serial search conditions, respectively.

On the basis of this measure of saccade duration, search time differences between the positive parallel and serial tasks attributable to differential numbers of saccades were 11 ms for 5-item displays and 31 ms for 17-item displays, accounting for about 1.7 ms per item of the RT slope. These estimates were larger for the negative data, with serial search times being longer than parallel search times by 45 ms in the 5-item trials and 82 ms in the 17-item trials (almost 3.1 ms per item). For the positive colored-bar data, the potential contributions of eye movements to simple–conjunctive search task differences were 26 ms for the 5-item displays and 42 ms for the 17-item displays, a slope of 1.3 ms per item. These differences were also more

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[5] The first assumption is in agreement with the many reports of saccadic suppression in the eye movement literature (see Carpenter, 1988, for a recent review). Support for the second assumption can be found in van Duren (1993).

pronounced for the negative data. When a target did not appear among the distractors, participants performing the conjunctive task spent an average of 120 ms (or 9% of their mean RTs) making saccades, an increase accounting for about 5 ms per item of the search slope.

Despite these measurable oculomotor contributions to search, it is nevertheless clear from these estimates that saccade durations cannot account for all of the slope differences reported between the free-eye and control experiments. For example, the free-eye negative conjunctive slope increased at a rate of 40 ms per item, whereas the increase in the fixed-eye conjunctive slope was only 29 ms per item, a difference of 11 ms for each additional element appearing in the display. However, on the basis of this saccade duration estimate, eye movements can account for less than half of this difference, approximately 5 ms per item. Still, it is important to note that these estimates are conservative. Visual thresholds may become elevated for approximately 40 ms preceding a saccade and for up to 100 ms after its completion (Latour, 1962; Volkmann, Schick, & Riggs, 1969). Because this visual decrement would accumulate with each additional eye movement, the inclusion of a suppression term in the equation given above would substantially increase the differential effect of saccade number on parallel and serial search times. In fact, with the addition of even a 30-ms suppression term, this potential oculomotor contribution increases to over 9 ms per item. It is therefore possible that the presence of eye movements, in addition to factors such as trade-offs between speed and accuracy, accounts for a significant part of the RT differences observed between free-eye and fixed-eye searches.

An analysis of control task RTs clearly showed the presence of a parallel–serial search dichotomy, even in the absence of eye movements. This finding not only implies that the specific tasks selected for the asymmetry and colored-bar experiments reflected true search dichotomies but also suggests that participants chose to make eye movements during these tasks and that this oculomotor behavior may normally accompany unlimited-duration search. In fact, if the earlier observation about faster fixed-eye RTs is correct, then this decision to use saccades during search was actually counterproductive to the instructions to answer as quickly as possible. It is not clear why participants might opt to make costly saccades in a task that does not require eye movements. Perhaps the reason is that most search tasks are of unknown dimension and are not confined to 12° of visual angle on a computer screen. Given this uncertainty, the use of eye movements might therefore simply reflect a default strategy by which people naturally search their environments.

General Discussion

Participants Make Eye Movements During Response-Terminated Parallel–Serial Search Tasks

The purpose of this study was to address two specific experimental objectives: survey the oculomotor behavior accompanying parallel–serial search and assess the extent to which eye movements might usefully supplement RTs as a method of understanding underlying search processes. With regard to the first objective, data from Experiment 3, in addition to showing that participants could accurately perform both the asymmetry and the colored-bar tasks without the aid of eye movements, also provided an opportunity to compare free-eye and fixed-eye searches for the same participants viewing the same stimuli. What resulted from this comparison was oculomotor evidence for a form of task-dependent search behavior. When participants were instructed not to make eye movements during their searches, RTs were less affected by increasing display size than when the task permitted oculomotor behavior. Two conclusions can be drawn from this finding. First, the current data confirm the long-standing belief that parallel and serial searches can occur even in the absence of eye movements. However, the data also imply that participants nevertheless elect to use eye movements as part of their natural search behavior, even though this activity may be counterproductive to the timely completion of the instructed task.

Experiments 1 and 2 detailed this oculomotor behavior for two typical parallel–serial search tasks. Unfortunately, a brief summary of these results is complicated by different patterns of eye movements in the two experiments. For example, increasing the number of colored-bar distractors resulted in more saccades in the conjunctive task, but participants viewing the O and Q-like stimuli failed to demonstrate this display size effect in the equally difficult serial search condition. A similar discrepancy between asymmetry and colored-bar tasks was found for initial fixation durations. Fixation durations increased with display size at least four times faster in the target-present asymmetry trials than in the target-present colored-bar trials. Although the fact that different participants took part in the asymmetry and colored-bar experiments makes it impossible to conduct a meaningful statistical comparison of these effects, it nevertheless appears that two distinct oculomotor signatures may exist in tasks having otherwise similar RT search functions.

Yet to be determined are why these differences were observed and what they might mean for search. Because the specific tasks assigned to participants in the two experiments were identical (to indicate the presence or absence of a designated target), the reason for these oculomotor differences must be related to properties of the stimulus displays. Although specifying the many ways in which these stimuli differed is clearly beyond the scope of the current study, one straightforward explanation for the discrepant eye movement patterns may be that the multicolored conjunctive displays were simply more stimulating to the oculomotor system than were the displays in the serial asymmetry task. Whereas the conjunctive displays consisted of oriented red and green bars, targets in the serial displays appeared in uniform fields of identical Q-like elements. The importance of this difference can best be understood within the context of a competitive network underlying saccadic target selection (such as the one suggested by Sheinberg & Zelinsky, 1993, for the superior colliculus). Given this framework, the increase in fixation duration with display size observed in the asymmetry tasks may reflect the computation time required to enhance a single display element above some oculomotor threshold, thereby suggesting a saccadic target. In the case of the asymmetry stimuli, for which the initial activation of the display elements might be subthreshold, saccade latencies corresponding to the time course of this competitive enhancement might be expected. In contrast, the onset of a colored-bar display might give rise to multiple activation peaks surpassing the oculomotor threshold almost immediately. Participants in this case might instead commence their search without delay by executing a series of eye movements directed to each of the potential targets, thereby accounting for the greater occurrence of saccades initiated during the conjunctive task.

Parallel–Serial Search Dichotomies Are Reflected in the Number of Saccades Initiated During Search

A comparison between Experiments 1 and 2 demonstrated how stimulus factors may affect saccadic search while remaining unexpressed in RT measures. The fact that oculomotor search is highly sensitive to stimulus factors, however, should not be interpreted as suggesting that eye movements are a poor indicator of parallel and serial processes. On the contrary, because a measure of oculomotor search encodes more bits of information than does a RT metric, search processes may still be analyzed despite the presence of stimulus variability. When the eye movement data were subjected to the standards used to demonstrate a search dichotomy in RTs, the number of saccades initiated during search was found to reveal many of the task distinctions indicative of parallel and serial processing. Specifically, Search Task × Display Size interactions were observed in both the asymmetry and the colored-bar data, indicating that saccade number increased with display size more quickly in the difficult search conditions than in the easier ones. Ratios of negative to positive slopes (2.5:1 and 2.7:1 ratios in the serial and conjunctive data, respectively) also suggested that this increase in the number of saccades may reflect a serial self-terminating search. Note that this latter effect, by far the more convincing indicator of an underlying search process, did not appear in the fixation duration data (the serial and conjunctive search duration slopes were remarkably similar between the positive and the negative trials).

The existence of a parallel–serial search dichotomy in a measure of saccade number implies that some part of the corresponding RT estimate may be attributable to eye movements and that researchers collecting response-terminated measures of search may wish to consider this factor when reporting their RT data. We assessed this potential contribution, consistent with the free-eye versus fixed-eye RT differences observed in Experiment 3, by estimating the time during search in which the eyes were in motion. If it is assumed that search is interrupted during saccades, then the estimates suggest that eye movements added to serial (conjunctive) free-eye search slopes about 1.7 (1.3) ms per item when the target was present in the display and about 3.1 (5.0) ms per item when the target was absent. The significance of these effects is relative to preconceptions about the role of eye movements in search. If eye movements are thought to underlie the majority of parallel–serial search task differences, then these results probably are disappointing. However, if it is assumed that eye movements make no contribution at all to search task differences, then these effects, although small, may be even more interesting.

Oculomotor Metrics Provide a Useful Supplement to RTs as a Measure of Search Behavior

Showing that eye movements and RTs respond similarly to many of the same experimental manipulations technically implies only that the two behaviors share a common theoretical or computational origin. Although it might be argued that this commonality in itself suggests a fundamental association between these measures, two additional sources of information contributed evidence for a more functional relationship. The first line of evidence was provided in the form of significant correlations between saccade number and RT. Combining the coefficients of determination across participants yielded R^2 values of up to .67 for the asymmetry data and .62 for the colored-bar data, meaning that 67% of the RT variability in a search task could be described simply by a measure of saccade number. The strength of these correlations also suggested that the time taken by participants to make a target judgment could be reliably predicted by the number of eye movements accompanying search. The second source of evidence linking eye movements to search came from an analysis of first and last saccade endpoint errors. Participants were looking closer to the target during their final fixations of a trial than during their initial fixations. If eye movements were dissociated from search, such an alignment between gaze and target position would not be expected. This accuracy finding, when combined with the correlational evidence and the similar oculomotor and RT responses to task manipulations, provides converging support for the legitimacy of saccade number as a measure of underlying search processes.

Given this relationship, it is possible to redefine search in terms of eye movements rather than RTs. As discussed in the introductory section of this article, one potential advantage of this redefinition is the greater spatiotemporal resolution that an oculomotor measure brings to the study of search behavior. For example, models assuming a spotlight metaphor of search (Treisman & Gormican, 1988; Wolfe & Cave, 1990) attribute RT increases with set size to the larger number of serial search movements required before the target is detected or a negative judgment can be made. According to this variable number model, the number of search movements required for a serial task will be directly proportional to the number of elements appearing in the display. However, hidden within this proposition is the assumption that the visual span surrounding each search locus encompasses roughly the same number of elements regardless of display size. It is just as reasonable to assume that a larger display size might cause more items to fall within a fixed-size search window because of a corresponding increase in element density. If this were indeed the case, then the greater processing demands associated with the additional elements might be reflected in the time needed after each search movement to decide whether a target is present or absent. According to this variable duration hypothesis, increased RTs are a result of longer latency search movements rather than an increase in the number of movements accompanying search.

Because the variable number and variable duration models both predict longer search times with increasing task difficulty, distinguishing between these hypotheses with a RT measure would not be trivial. However, with oculomotor metrics, it is possible to weight the relative degrees of importance of these two search components. Translated into eye movements, the variable number model predicts more saccades at the larger display size but little or no change in the duration of these saccades. Alternatively, if search follows a variable duration model, then fixation durations should increase with display size while saccade numbers remain relatively unaffected. Although the increase in initial fixation durations observed in the asymmetry data appears to be evidence for the variable duration model, it is important to keep in mind that this measure did not yield the expected ratio between negative and positive slopes, nor did it correlate reliably with search times. Given that this duration increase is likely attributable to stimulus factors rather than to search, it is possible that this variable contributes to the dichotomy between parallel and serial search RTs without actually reflecting a true search process. With regard to the number of eye movements initiated during search, even after saccades that may have been executed concurrently with the button press were discounted, the number of eye movements made in the 17-item task was still significantly larger than that made in the 5-item task. This oculomotor behavior, observed in both the asymmetry and the colored-bar data, is consistent with the variable number model and suggests that the dominant response to increasing task difficulty is for participants to make additional search movements.

In summary, eye movements normally accompany response-terminated parallel–serial search. This assertion does not imply that oculomotor behavior underlies the distinction between these processes. Our own estimates suggest that saccades can account for only a fraction of this difference, and the fact that search dichotomies persist in the absence of eye movements makes such a statement clearly untenable. What this observation does imply, however, is that an oculomotor metric, when available, may be used as an alternative measure of search behavior, a conclusion supported by an analysis of saccade accuracy and correlational evidence showing a relationship between RTs and number of saccades. Given this choice of methodologies, the decision of which dependent measure to use should therefore be based on the type of information best suited to answering the experimental objectives in question. It is our belief that as the study of search broadens to include more natural experimental settings and questions of spatiotemporal dynamics, oculomotor measures will become accepted tools with which to further understand how targets are detected in complex scenes.

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