Patterns of Eye Movements During Parallel and Serial Visual Search Tasks

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Abstract Eye movements were monitored while subjects performed parallel and serial search tasks. In Experiment 1a, subjects searched for an "O" among "X"s (parallel condition) and for a "T" among "L"s (serial condition). In the parallel condition of Experiment 1b, "ϙ" was the target and "O"s were distractors; in the serial condition, these stimuli switched roles. Displays contained 1, 12, or 24 stimuli, with both target-present and target-absent trials. RT and eye-movement measures (number of fixations, saccadic error, and latency to move) indicated that search efficiency was greatest in the parallel conditions, followed by the serial condition of Experiment 1a and, finally, by the serial condition of Experiment 1b. This suggests that eye movements are correlated with the attentional processes underlying visual search.

How are we able to visually search through our complex environment to find a particular item that we need or want? For example, how are we able to find a pen lying amid papers and books on a cluttered desk? Furthermore, while conducting this search, how do we know that a particular feature in the visual array (e.g., "redness") belongs to one object (e.g., the pen) and not to another (e.g., a book)? Studies attempting to address such questions have made extensive use of the visual search task. In this paradigm, subjects are asked to search stimulus displays for a target among distractors. Typically, both display size (i.e., number of stimuli) and trial type (target present vs. target absent) vary across trials.

A target stimulus in a visual search task may be defined either by a distinct feature (feature search task) or by a particular combination or conjunction of features (conjunction search task). For example, in a feature search task, subjects might be asked to look for a red "O" among blue and green "O"s. Here, the target's colour is a unique feature which distinguishes it from the distractors. In a conjunction search task, the target stimulus might be the same red "O," but this time, the distractors could be blue "O"s and red "X"s. In this case, each distractor shares at least one feature with the target, such that the target can only be defined by a specific conjunction of colour and shape.

In feature search tasks, the target stimulus is typically found quickly and easily; it seems to "pop out" from the background of distractor stimuli. As a result, the number of distractors in the visual array has little effect on subjects' search latencies. In a conjunction search task, on the other hand, average response time usually increases as a linear function of display size. This increase is more pronounced on negative than on positive trials. In fact, the ratio of the slope on negative trials to that on positive trials is roughly 2:1 (Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989).

The feature integration theory of attention was developed by Treisman and her colleagues (e.g., Treisman, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman, Sykes, & Gelade, 1977) to account for such findings. This theory proposes that features are processed automatically and in parallel. Thus, in a feature search task, response times show little effect of display size because the feature characterizing the target stimulus is detected preattentively and then "calls" attention to the position of the target stimulus in the visual field (Treisman & Gormican, 1988). In contrast, the conjunction of features is thought to require focal attention; as a consequence, stimuli are processed serially in a conjunction search task. To perform such a task, the "spotlight" of attention must be focused on each stimulus in turn, allowing its features to be conjoined to form a unitary object. This process continues until the target stimulus is identified or until the subject, having searched the entire array, decides that it is absent (Treisman & Gelade, 1980; Treisman & Gormican, 1988).

In the twenty years since the feature integration theory of attention was first formulated, however, further research has shown that the situation is more complex than the simple parallel-serial dichotomy initially proposed (see Wolfe, in press, for review). For example, it has

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been shown that search becomes more difficult as the individual stimuli become smaller (Duncan & Humphreys, 1989) and as stimulus density increases (Cohen & Ivry, 1991). Target eccentricity also affects performance in both feature search tasks (Scialfa, Thomas, & Joffe, 1994; Viviani & Swensson, 1982) and conjunction search tasks (Carrasco, Evert, Chang, & Katz, 1995; Scialfa & Joffe, in press, submitted). When compared in the same study, however, eccentricity effects are typically much larger in the conjunction search condition than in the feature search condition, where they are small, if not absent (e.g., Scialfa & Joffe, in press, submitted). As well, search difficulty increases with both distractor heterogeneity (feature search task: Treisman, 1988, 1991; conjunction search task: Duncan & Humphreys, 1989, 1992; Treisman & Sato, 1990) and target-distractor similarity (feature search task: Treisman & Gormican, 1988; conjunction search task: Duncan & Humphreys, 1989, 1992). In fact, patterns of response times consistent with serial processing have been observed in feature search tasks when the target and distractors are highly similar (e.g., Nagy & Sanchez, 1990) or when distractors are heterogeneous (e.g., Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). Several recent studies have also reported parallel patterns of response times in conjunction search tasks (McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986; Steinman, 1987; Theeuwes & Kooi, 1994). Even when the expected serial pattern of response times is observed (i.e., an increase with display size showing a 2:1 ratio of negative to positive slopes), the steepness of the slopes relating response time to display size varies across experiments.

Such findings have had important implications for theories of visual search. For example, it is now commonly accepted that different search tasks vary along a continuum of search efficiency, with shorter response times and a shallower slope indicating more efficient search. It has been proposed by Treisman and others (e.g., Poisson & Wilkinson, 1992; Treisman, 1982, 1988; Treisman & Gormican, 1988; Treisman & Souther, 1985; Treisman & Sato, 1990; Zohary & Hochstein, 1989) that subjects may engage in serial processing of groups of stimuli within a display, with the stimuli in each group being processed in parallel. Search efficiency is then determined by the size of these groups, which is thought to vary with target discriminability (Treisman, 1988; Treisman & Gormican, 1988; Treisman & Souther, 1985; Treisman & Sato, 1990; but see Duncan & Humphreys,1989, 1992, for an alternative explanation). For the sake of simplicity, visual search tasks yielding parallel and serial patterns of response times will henceforth be referred to as parallel and serial search tasks, respectively.

The major goal of the present experiments was to investigate whether patterns of eye movements distinguish between parallel and serial search processes and between serial search processes which differ in search efficiency. Given this interest, it is important to consider the nature of the link between attention and eye movements. At present, this is a controversial issue. It is generally accepted that eye movements and shifts of attention are at least partially dissociable; this is indicated by the large body of research showing that attention can be shifted covertly in the absence of concomitant eye movements (e.g., Downing, 1988; Posner, 1980; Posner, Nissen, & Ogden, 1978). That some link does exist between shifts of attention and movements of the eyes is suggested by neurophysiological data (e.g., Goldberg & Wurtz, 1972; Mohler & Wurtz, 1976; Wurtz & Mohler, 1976) and by work with neuropsychological populations such as neglect patients (e.g., Johnston & Diller, 1986; Walker & Young, 1996), as well as by work with normal subjects (e.g., Hodgson & Müller, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Posner, 1980; Rizzolatti, Riggio, Dascola, & Umilta, 1987). The exact nature of this relation, however, is subject to debate. For example, both Posner (1980) and Remington (1980) have proposed that attentional shifts are more closely related to the appearance of peripheral stimuli than to movements of the eyes. At the opposite extreme, Rizzolatti and his colleagues (Rizzolatti, Riggio, Dascola, & Umilta, 1987; Rizzolatti, Riggio, & Sheliga, 1994) suggest that visuospatial attention and eye movements are subserved by the same neural circuits, and that a shift of attention corresponds to the programming of an eye movement. They explain covert shifts of attention as cases where an eye movement is programmed but not executed. This position has been widely contested (e.g., Hodgson & Müller, 1995; Klein, 1980; Klein, Kingstone, & Pontefract, 1992; Klein & Pontefract, 1994; Posner, 1980). Instead, a growing body of research suggests that an asymmetry exists in the relation between attention and eye movements. Whereas attention can be shifted covertly in the absence of eye movements, eye movements must be preceded by an attentional shift to the saccadic target (e.g., Hodgson & Müller, 1995; Henderson, 1993; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Schneider & Deubel, 1995; Shepherd, Findlay, & Hockey, 1986).

Within the context of visual search, if attention can be shifted without eye movements, then normal patterns of performance should be observed in parallel and serial visual search tasks, even if eye movements are prevented. To investigate this issue, experiments have been conducted in which eye movements were eliminated by using extremely short exposure durations such as 150 ms (Chmiel, 1989) or 180 ms (Klein & Farrell, Experiment 1, 1989; Treisman & Gormican, 1988) or by instructing subjects not to move their eyes and discarding trials on which eye movements occurred (Klein & Farrell, Experiment 2, 1989; Scialfa & Joffe, submitted). These studies demonstrate that eliminating eye movements has little effect on average response times in parallel search tasks (Chmiel, 1989; Klein & Farrell, 1989). The results for serial search tasks are less consistent. Some studies report that performance is unaffected by eliminating eye movements (e.g., Chmiel, 1989; Klein & Farrell, Experiment 2, 1989), although RT must sometimes be corrected to take into account that subjects' processing of displays was cut short by the brief exposure duration (Treisman & Gormican, 1988). In contrast, a recent study by Scialfa and Joffe (submitted) suggests that preventing eye movements does affect RT and accuracy.

Such studies, although valuable, only address one aspect of the attention-eye movement asymmetry: the ability to shift attention in the absence of eye movements. However, as just discussed, a large body of evidence suggests that when eye movements are executed, they must be preceded by shifts of attention. Thus, when eye movements are permitted during parallel and serial search tasks, they should be at least partially correlated with attentional processes. This means that eye movements may provide a tangible trace of the attentional processes underlying performance in such tasks. Recording eye movements might then allow a more fine-grained analysis of the spatial and temporal aspects of performance than does response time, a global measure which is influenced by a variety of search and decision processes.

In this context, it is important to note that eye movements have been used successfully to investigate the cognitive processes underlying performance in other types of visual search tasks (e.g., Gould, 1967; Gould & Schaffer, 1967; Jacobs, 1987; Nattkemper & Prinz, 1984; Rayner & Fisher, 1987). The visual search tasks employed in such studies include matching tasks, where each display contains a target stimulus as well as an array of stimuli through which the subject must search to determine whether there are any matches for this target (e.g., Gould, 1967; Gould & Schaffer, 1967; Saitoh & Okazaki, 1990). Alternatively, some researchers have studied letter or number visual search tasks, where the subject knows the identity of the target stimulus prior to the beginning of a trial and then searches one or more lines of letters or numbers to determine whether the target is present (e.g., Jacobs, 1987; Nattkemper & Prinz, 1984; Prinz, Nattkemper, & Ullman, 1992; Rayner & Fisher, 1987).

Such visual search experiments have made use of a variety of measures including fixation duration (e.g., Gould, 1967; Gould & Schaffer, 1967; Nattkemper & Prinz, 1984; Rayner & Fisher, 1987), the number of fixations per trial (e.g., Gould, 1967; Gould & Schaffer, 1967; Rayner & Fisher, 1987), and saccade amplitude (e.g., Jacobs, 1987; Nattkemper & Prinz, 1990; Rayner & Fisher, 1987). The consensus emerging from these studies has been that measures of eye movement behaviour are sensitive to manipulations which are thought to affect the cognitive processes underlying performance on such visual search tasks. For example, it has been found that the number of fixations per trial is affected by the degree of target/nontarget similarity (Rayner & Fisher, 1987), as is fixation duration (Gould, 1967; Rayner & Fisher, 1987), a measure which is also affected by the redundancy or predictability of the stimulus display (Nattkemper & Prinz, 1984).

Until recently, few studies have investigated patterns of eye movements during the performance of a parallel or a serial search task under conditions of unlimited exposure with subjects being free to move their eyes (but see Scialfa & Joffe, in press, submitted; Zelinsky, 1996; Zelinsky & Sheinberg, 1995). Thus, the purpose of the present experiments was to determine whether, under such conditions, different patterns of eye movements are observed during parallel and serial search tasks and during serial search tasks that differ in search efficiency.

Subjects in each experiment performed both a parallel and a serial search task while their eye movements were monitored. The eye-movement data were of primary interest; however, response times were also analyzed to ensure that parallel and serial patterns were observed in the appropriate conditions.

In the parallel search condition of Experiment 1a, subjects were instructed to find the capital letter "O" amid distractor "X"s. The stimuli in Experiment 1b were modeled after those used in a study by Treisman and Souther (1985). Here, the target in the parallel search task was a circle with a line cutting through its base (Ϙ), and the distractors were circles (O).

In the serial search condition of Experiment 1a, the target letter was the capital letter "T" with capital letter "L"s serving as distractors. The letters "T" and "L" are composed of the same two features, a horizontal line and a vertical line. These two features must be combined in a very specific fashion during perception for either of these letters to be identified correctly. As a result, the feature integration theory of attention would predict that subjects should engage in serial processing when asked to find a target "T" among distractor "L"s. This prediction receives support from studies by Beck and Ambler (1973) and by Bergen and Julesz (1983); however, both sets of researchers used extremely short exposure durations (40-100 ms), and Beck and Ambler (1973) did not vary display size. Duncan and Humphreys (1989), using an unlimited exposure duration and varying display size from 2 to 6, found that when subjects are asked to search for an "L" among "T"s, response times were rapid and showed little effect of display size. Taken together, these findings suggest that use of the letters "T" and "L" should elicit serial search of stimulus displays, but that it should be a highly efficient serial search (i.e., response times should be fast, with a relatively small effect of display size, but the ratio of the negative to the positive slopes should still be 2 to 1). For the serial search condition of Experiment 1b, we chose target and distractor stimuli which have previously been shown to elicit a pronounced serial pattern of response times (Treisman & Souther, 1985). Here, the target stimulus was a circle (○), whereas the distractors were circles that each had a line bisecting its base (ϙ).

Three measures of eye-movement behaviour were employed in the present experiment – the number of fixations per trial, saccadic error, and the latency to move. The number of fixations per trial was chosen because, like response time, it is a global measure of search performance. If patterns of eye movements are correlated with the attentional processes underlying visual search, the number of attentional shifts required to detect the target may be correlated with the number of fixations per trial. In the two parallel search conditions, where few, if any, attentional shifts should be needed, subjects should make few fixations per trial, and the number of fixations per trial should increase little with display size. In the two serial search conditions, where subjects are thought to make serial shifts of attention, the number of fixations per trial should be greater and should increase with display size. Furthermore, if, as expected, the two serial search tasks differ in efficiency, this increase should be more pronounced in Experiment 1b than in Experiment 1a.

As a more fine-grained spatial measure of search performance, we examined saccadic error. In many eye movement studies, researchers have been interested in the distance between the landing place of the first saccade and the location of some pre-determined target stimulus within a display (e.g., Deubel, Wolf, & Hauske, 1984; Findlay, 1982; He & Kowler, 1989). In the present study, we wished to determine whether the first saccade on positive trials in the parallel and serial search conditions moved the eyes in the direction of the target stimulus; we did this by calculating the distance in degrees of visual angle between the gaze position following the first saccade and the target position. The more quickly information concerning the target stimulus is available following the presentation of a stimulus display, the closer the landing site of the first saccade should be to the target, and the less the saccadic error. In the parallel search conditions, where the target stimulus "pops out" and is quickly located, the first saccade should be quite accurate, and the eyes should land close to the target stimulus. The presence and location of the target stimulus in a serial search display, however, is determined after a serial search of the stimulus array. As a result, in the two serial search conditions, subjects should, on average, have less information to guide the first saccade and the eyes should land farther from the target location. The greater the efficiency of a particular search, however, the larger the size of the stimulus subgroups which can be processed in parallel. Thus, if serial search is more efficient in Experiment 1a, target information would be more likely to be picked up prior to the first saccade than it would in Experiment 1b. To the extent that this is true, saccadic error should be lower in the first than in the second experiment.

As a fine-grained temporal measure of eye movement behaviour, we chose to investigate the saccadic response time (RT) or latency to move. Numerous studies of eye-movement behaviour have been concerned with the length of time subjects take before making a first saccade upon the presentation of a stimulus display (e.g., Abrams, 1992; Findlay, 1981, 1992; Findlay, Brogan, & Wenban-Smith, 1993). In addition to other factors, the time between the onset of the display and the occurrence of the first eye movement is thought to reflect the time needed for subjects to determine the direction and size of the following saccade (Abrams, 1992; Findlay, 1992). In the present studies, we investigated latency to move to see whether these aspects of processing varied across search conditions.

METHOD

The same general method was used in both Experiment 1a and 1b. Any differences between the two experiments are noted where applicable.

Subjects

Twelve students in the Department of Psychology at the University of Toronto took part in each experiment, for a total of twenty-four subjects (fourteen female and ten male). Twenty of these subjects participated to fulfill a course requirement or to obtain bonus points toward their final grade in Introductory Psychology. The remaining four subjects were paid $10 for their participation. Subjects had normal or corrected-to-normal vision and were tested individually.

Materials and design

Eye movements were monitored using a model RK-416 Iscan pupil-center eye tracking system. This video-based eye tracker provides the pupil size and coordinates every 16.67 ms. Calculation of pupil position was accurate to one degree of visual angle. A 386 IBM-compatible computer presented the stimulus displays and recorded subjects' eye movements and responses. Stimulus displays were presented on two monochrome VGA monitors, one for the subject and one for the experimenter. Subjects viewed the displays with both eyes, but only the movements of the right eye were monitored and recorded.

Along with the stimulus displays, the experimenter's monitor showed the subject's gaze position in real time; this was indicated by a circular cursor with a diameter of one degree of visual angle. For a more detailed description of the eye-tracking system used in the present experiments, see Stampe (1993).

In the parallel search condition of Experiment 1a, the target stimulus was the capital letter "O;" capital letter "X"s served as distractors. In the serial search condition, the capital letter "T" was the target stimulus, and capital letter "L"s were distractors. Letters subtended 1.4° of visual angle horizontally and 1.8° vertically. In Experiment 1b, the target in the parallel search condition was a circle measuring 1.4° in diameter with a line extending 0.5° above and below the circle's base (φ). The distractor stimuli were circles with a diameter of 1.4° (O). In the serial search condition, the same two stimuli were used (the circle and the circle with the line), except that this time, the circle (O) was the target stimulus and circles with lines (φ) served as distractors.

Displays contained 1, 12, or 24 stimuli and were created using an imaginary 6 x 6 grid of possible stimulus locations. On positive trials, the target stimulus appeared in one of 16 positions, consisting of four positions in each of the four corners of the grid. Positive displays of size 1 were created by placing the target in each of the 16 possible positions. To create positive displays of sizes 12 and 24, the target was first placed in one of the possible locations; distractor stimuli were then randomly assigned to the remaining 35 positions. For displays of 12 and 24 stimuli, two different positive arrays were created for each target position. Negative displays were generated by replacing the target stimulus in each positive display with a distractor. This procedure yielded a total of 160 stimulus displays – 32 displays of size 1 (16 target positions x 2 trial types (positive vs. negative)), and 64 displays of both size 12 and size 24 (16 target positions x 2 arrays per position x 2 trial types (positive vs. negative)). The same stimulus configurations served as both parallel and serial search displays in both experiments, with the target and distractor stimuli being changed as necessary (i.e., "O" and "X"s, "T" and "L"s, "φ"s and "O"s).

There were two blocks of trials for each type of search task (parallel and serial), each block containing 96 trials. The particular displays appearing in each block, and their order, were uniquely determined for each subject. The 32 single-stimulus displays were always assigned to both blocks. As discussed above, two different positive displays were created for each possible target location for displays of size 12 and 24. One member of each of these pairs was randomly selected to appear in the first block; the corresponding negative displays were assigned to the second block. The positive versions of the unselected displays appeared in the second block, whereas their matching negative displays were assigned to the first. Once the displays had been assigned to blocks, their order within each block was randomized, with the restriction that there be no more than 4 trials of a particular display size or of a particular trial type (positive vs. negative) in a row.

Twenty-four practice trials were also created; the set of practice trials contained an equal number of displays for each trial type (positive vs. negative) by display size (1, 12, 24) combination. The same practice displays were used in both search conditions of both experiments, except that the identity of the target and distractor stimuli changed as necessary.

Procedure

Each subject performed both a parallel and a serial search task, with the order of these tasks being counterbalanced across subjects. Subjects were told that they would see displays consisting of 1, 12, or 24 stimuli and that their task was to determine, as quickly and accurately as possible, whether a target stimulus was present in each display. They were told the identity of both target and distractor stimuli, and were informed that the target would not be present on every trial. Because the stimuli in Experiment 1b were not familiar, subjects in this experiment were shown a drawing of each stimulus ("φ" and "O"), prior to the practice trials.

Following the instructions, subjects placed their chins on a chin rest. A mild restraint was placed over their heads to reduce head movements during the course of the experiment. A nine-point calibration was then performed (see Stampe, 1993). After this calibration, subjects went through the practice trials for the first type of visual search task. They were then presented with two blocks of 96 trials each, with a calibration being performed at the beginning of each block. Upon completing the second block of trials, subjects received instructions for the remaining visual search task. They were told that, as in the first half of the experiment, they would see displays of stimuli and would be searching for a particular target stimulus. They were then told the identity of the target and distractor stimuli for the second visual search task. After the instructions, subjects performed a block of practice trials followed by two blocks of experimental trials; a calibration was done before each block.

The same trial sequence was followed in all conditions. At the beginning of each trial, a prompt appeared on the computer screen, instructing subjects to "Press a button to start." Subjects held a 3-button response box in their lap. Upon seeing the prompt, they pressed one button with their left thumb; this caused a stimulus display to appear on the computer screen in front of them after a 200-ms delay. The display remained on the screen until subjects responded by pressing one of two buttons with their right thumb. One of the buttons was used to indicate that the target was present, the other to indicate that it was absent. The particular buttons used to respond on positive and negative trials were counterbalanced across subjects. The interval between the presentation of the stimulus display and the button-press was recorded as the response time. Between trials, a fixation point was presented in the centre of the computer screen and was used to correct for drift due to head movements (see Stampe, 1993).

Results and Discussion

Trials on which subjects responded incorrectly were excluded from the analysis of the response time and eye movement data (1.1% of trials in Experiment 1a and 2.2% of trials in Experiment 1b). There was no evidence of a speed-accuracy tradeoff in either experiment. For each subject, data were discarded for trials on which response latencies fell more than two standard deviations above or below that subject's mean for a given condition (5.0% of trials in Experiment 1a and 4.4% of trials in Experiment 1b). Data from the remaining trials were analyzed using repeated measures ANOVAs, with a separate analysis being performed for each experiment. In addition to these separate analyses, an overall ANOVA was performed for each dependent measure to compare performance across experiments. For each analysis (1a, 1b, and overall), post hoc comparisons between pairs of means were carried out using the Newman-Keuls test with $p < 0.05$. In the following discussion, the main effects and lower-order interactions from each analysis will only be mentioned in the absence of a significant higher-order interaction.

Response Time (RT) and the Number of Fixations per Trial

For each experiment, RT and the number of fixations per trial were analyzed using a repeated measures ANOVA which crossed search type (parallel or serial) with trial type (positive or negative) and display size (1, 12, or 24 stimuli). In addition, an overall ANOVA was performed for both RT and the number of fixations per trial; these ANOVAs crossed the between-subjects factor of experiment (1a or 1b) with search type, trial type, and display size.

All three analyses (1a, 1b, and overall) revealed a significant search type x trial type x display size interaction for both RT (1a: $F(2, 22) = 26.13$, $MS_e = 766.98$, $p < 0.001$; 1b: $F(2, 22) = 36.90$, $MS_e = 12830.44$, $p < 0.001$; overall: $F(2, 44) = 50.28$, $MS_e = 6798.71$, $p < 0.001$) and the number of fixations per trial (1a: $F(2, 22) = 70.71$, $MS_e = 0.01$, $p < 0.001$; 1b: $F(2, 22) = 55.01$, $MS_e = 0.23$, $p < 0.001$; overall: $F(2, 44) = 84.34$, $MS_e = 0.12$, $p < 0.001$). As Figure 1 illustrates, display size had little effect on RT or on the number of fixations per trial on positive and negative trials in the parallel search condition of both experiments. Post hoc contrasts revealed that neither average RT nor mean number of fixations per trial increased significantly as the display size grew from 1 to 12 and from 12 to 24. This was true for both positive and negative trials in both experiments, a pattern of results which is consistent with a parallel search strategy. In contrast, in the serial search condition of both experiments, average RT and the mean number of fixations per trial increased significantly with each increment in display size, with this effect being more pronounced on negative than on positive trials. The slope of the best-fitting line relating mean RT to display size was approximately 5.24 ms on positive trials and 9.35 ms on negative trials in Experiment 1a; in Experiment 1b, the slope of this line was 27.20 ms on positive trials and 58.29 ms on negative trials. The slope on positive trials divided by that on negative trials equals 0.56 in Experiment 1a and 0.47 in Experiment 1b. Both of these values are quite close to 0.5, suggesting serial, self-terminating search processes (Sternberg, 1969; Treisman & Gelade, 1980).

A comparison of the panels in Figure 1 indicates that the increase in average RT and the mean number of fixations per trial with display size is greater in the serial search condition of Experiment 1b than in that of Experiment 1a. This explains the significant search type x trial type x display size x experiment interaction seen in the overall analysis of both measures (RT: $F(2, 44) = 22.31$, $MS_e = 6798.71$, $p < 0.001$; number of fixations: $F(2, 44) = 27.43$, $MS_e = 0.12$, $p < 0.001$) and suggests that the two serial search tasks differed in search efficiency. We interpret the smaller effect of display size and the faster RTs in Experiment 1a as evidence that search efficiency was greater in Experiment 1a than in Experiment 1b.

To investigate further the similar pattern of results shown by RT and number of fixations, trials were pooled across search type, trial type, and display size, and a Pearson r was calculated for each subject. The average correlation between RT and the number of fixations per trial was 0.69 (range: 0.45 to 0.83) for Experiment 1a and 0.94 (range: 0.81 to 0.98) for Experiment 1b. The lower average correlation in Experiment 1a is thought to result from a restriction in the range of the two dependent measures due to the greater efficiency of serial search in this experiment. This interpretation is supported by the finding that the average standard deviations across subjects for response time and number of fixations per trial were 521.46 and 2.50, respectively, in Experiment 1b, but were only 162.54 and 0.85 in Experiment 1a. Thus, the moderate to high average correlations, in combination with the similar patterns observed in the analyses of variance, indicate that RT and the number of fixations per trial are sensitive to similar aspects of the attentional processes underlying parallel and serial search.

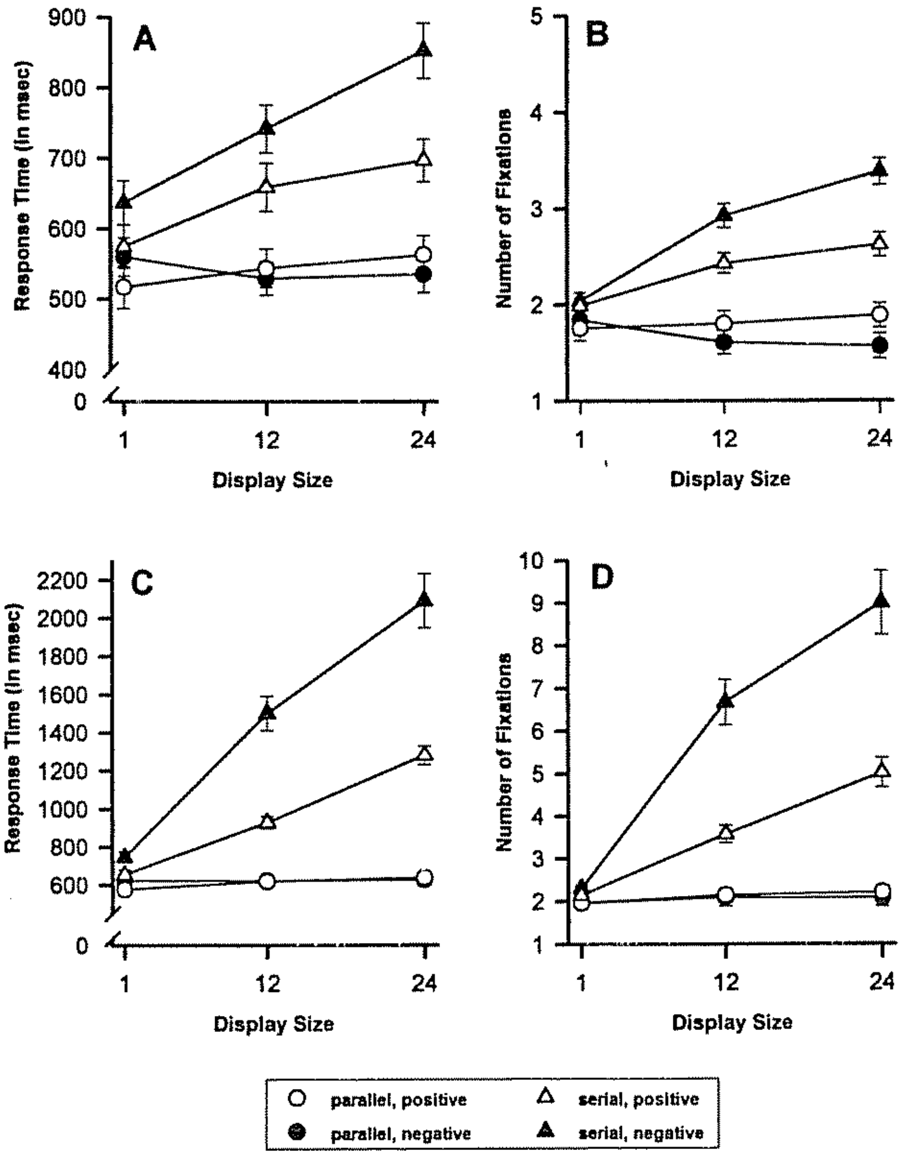

Figure 1. Average (±SEM) response time and number of fixations per trial as a function of display size on both positive and negative trials in the parallel and serial search conditions of Experiment 1a (Panels A and B) and Experiment 1b (Panels C and D)

Saccadic Error

Saccadic error was calculated as the distance in degrees of visual angle between the target position and the average position of the pupil during the fixation following the first saccade. Because saccadic error could only be determined for trials on which a target was present, negative trials were excluded from analysis. In addition, saccadic error could not be calculated for trials on which the eyes did not move (henceforth, single-fixation trials). For this reason, 9.2% of trials were dropped for Experiment 1a and 8.9% were dropped for Experiment 1b. If, for any subject, the exclusion of single-fixation trials meant that less than a quarter of the original 32 trials remained in any of the relevant conditions, then that subject's data were not included in the analysis for this variable. On the basis of this criterion, the data from three subjects were excluded in Experiment 1a, and the data from one subject were excluded in Experiment 1b. For each experiment, the remaining data were analyzed using a 2 (search type) x 3(display size) repeated-measures ANOVA. The overall ANOVA crossed experiment (1a or 1b) with type of search and display size.

All three analyses (1a, 1b, and overall) revealed a significant search type x display size interaction (1a: $F(2, 16) = 32.71$, $MS_e = 0.11$, $p < 0.001$; 1b: $F(2, 20) = 71.68$, $MS_e = 0.28$, $p < 0.001$; overall: $F(2, 36) = 94.38$, $MS_e =$

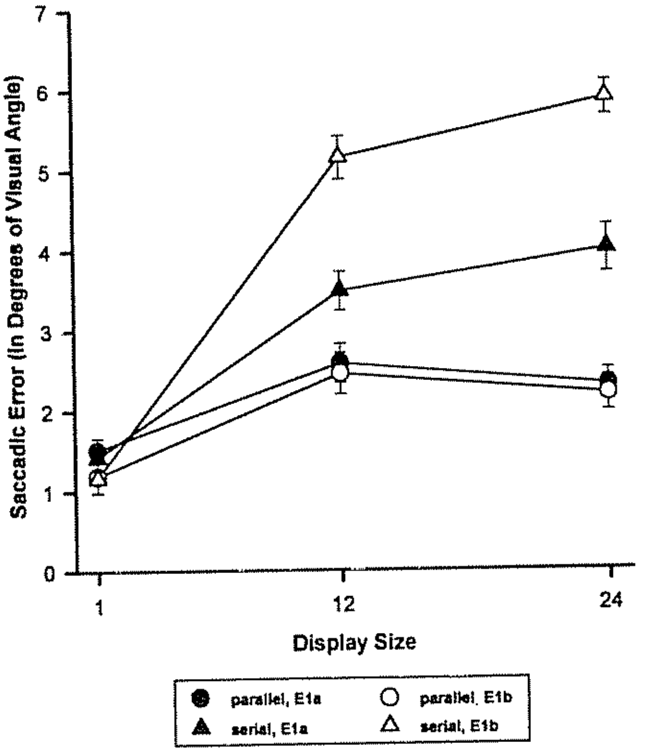

Figure 2. Average (±SEM) saccadic error as a function of display size on positive trials in the parallel and serial search conditions of Experiments 1a and 1b.

0.21, $p < 0.001$). As illustrated in Figure 2, average saccadic error was lowest for displays of size 1 in the parallel and serial search conditions of both experiments. In fact, post hoc comparisons from the overall analysis showed no significant differences among any of the means for displays of size 1. This suggests that performance on single-stimulus trials relies on processes which are qualitatively different from those underlying performance on trials with multiple stimuli. The presentation of a single stimulus in the periphery appears to elicit an automatic orienting response in which subjects move their eyes toward that stimulus (Becker, 1989; Klein et al., 1992; Posner, Nissen, & Ogden, 1978).

In the two parallel search conditions, increasing display size had little effect on average saccadic error. Post hoc contrasts showed that the difference in average saccadic error between displays of size 12 and size 24 was nonsignificant in both experiments. These contrasts did reveal, however, a slight (less than one degree) but significant increase between displays of size 1 and those of sizes 12 or 24. This is likely due to the "global effect," a phenomenon in which the trajectory of an initial saccade toward a target is affected by the presence of additional stimuli (e.g., Coren & Hoenig, 1972; Deubel et al., 1984; Findlay, 1982; Ottes, van Gisbergen, & Eggermont, 1984).

The increase in average saccadic error between displays of size 1 and 12 was significant in the two serial search conditions and was more pronounced than in the parallel search condition of either experiment. This suggests that, during the programming of an initial saccade, subjects had more information about the target stimulus in the two parallel search conditions than in the two serial search conditions. This also reinforces the claim that the parallel search targets could be detected preattentively, whereas determining the presence or absence of the serial search targets required a serial search strategy. This latter conclusion receives further support from the finding that average saccadic error increased significantly between displays of size 12 and 24 in the two serial search conditions. As shown in Figure 2, the increase in average saccadic error between displays of size 1 and 12 was greater in the serial search condition of Experiment 1b than in that of Experiment 1a, explaining the significant search type x display size x experiment interaction from the overall analysis, $F(2, 36) = 13.36$, $MS_e = 0.21$, $p < 0.001$. This indicates that subjects had less information about the target to guide the initial saccade in Experiment 1b than in Experiment 1a, providing additional support for the claim that search efficiency in the serial search condition was greater in the first than in the second experiment.[1]

Latency to Move

As discussed above, the results from the analysis of saccadic error suggest that single-stimulus displays triggered an automatic orienting response that was unaffected by the type of search. Therefore, the data from this display size do not help distinguish between parallel and serial search processes or between serial search processes which differ in search efficiency. As a result, the data from displays of size 1 were not included in the analysis of latency to move. In addition, latency to move could not be determined for single-fixation trials (12.1% of trials in

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[1] The display size of 1 was included in the present studies in the interest of comparability with previous experiments in the literature. Given that performance on single-stimulus trials appears to reflect an orienting response as opposed to a visual search of the stimulus array, it was decided to redo the analysis of average saccadic error without this display size and to exclude it from the analysis of latency to move. In all three analyses (1a, 1b, and overall) of saccadic error, the effect of display size went from significant to nonsignificant without the display size of 1. The display size x experiment and search type x display size x experiment interactions from the overall analysis also became nonsignificant. The experiment x search type interaction, however, was significant with or without the display size of 1, indicating that the difference in average saccadic error between parallel and serial search tasks was greater in the second experiment than in the first. Thus, the conclusion that search efficiency was greater in the serial search condition of Experiment 1a than in that of Experiment 1b remains unchanged.

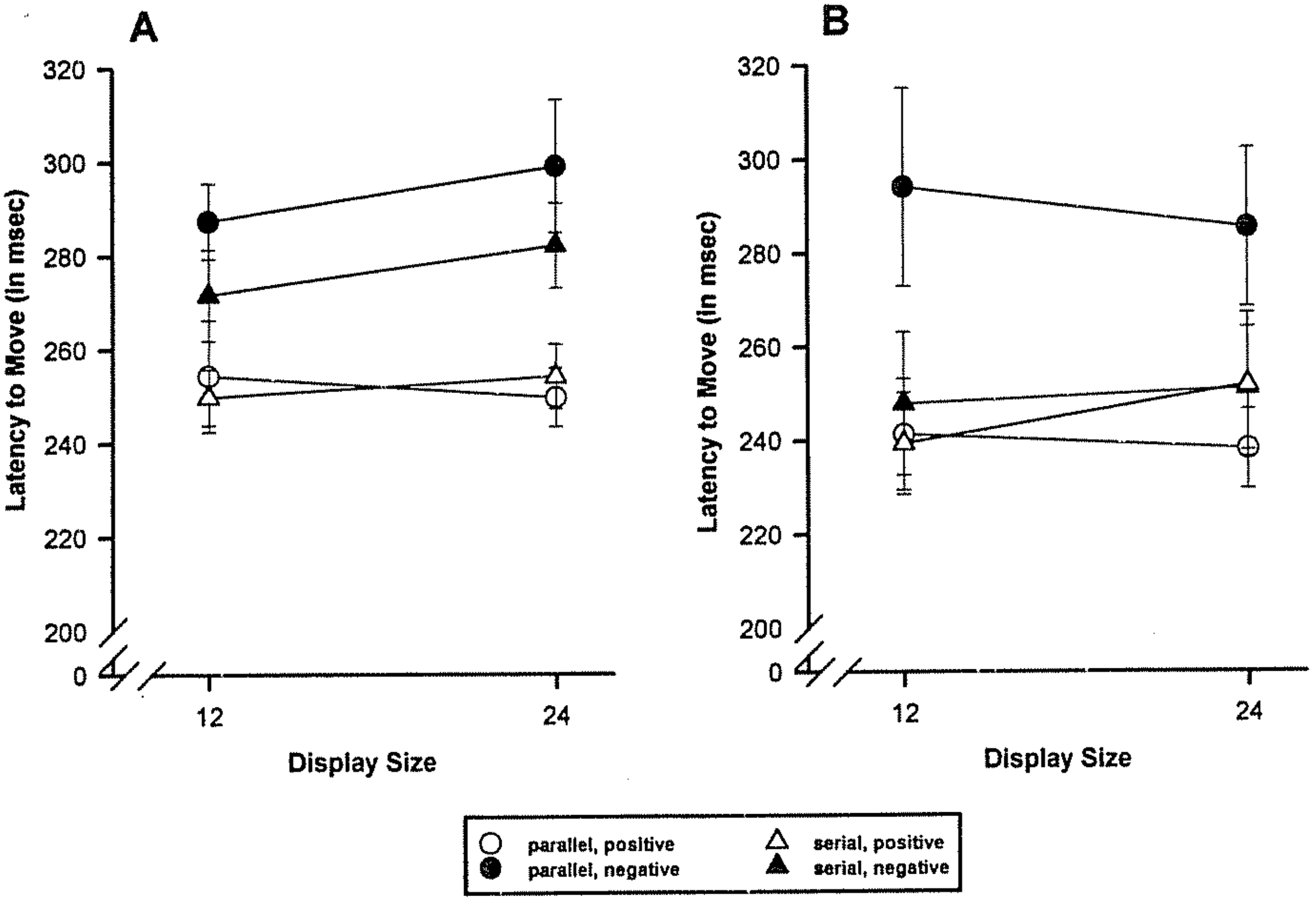

Figure 3. Average (±SEM) latency to move as a function of display size on positive and negative trials in the parallel and serial search conditions of Experiments 1a (Panel A) and 1b (Panel B).

Experiment 1a and 7.7% of trials in Experiment 1b). The data from four subjects in Experiment 1a and from two in Experiment 1b were excluded from analysis because dropping such trials meant that less than a quarter of the original trials remained in one or more of the relevant conditions. For both Experiments 1a and 1b, the remaining data were analyzed using a 2 (search type) x 2 (trial type) x 2 (display size) repeated-measures ANOVA. An overall ANOVA was also performed which crossed the between-subjects factor of experiment (1a or 1b) with these three variables.

Figure 3 shows average latency to move as a function of display size for each search type by trial type combination in both Experiment 1a and 1b. An examination of this figure reveals a striking difference between the two experiments, a difference reflected by the significant search type x trial type x experiment interaction from the overall analysis, $F(1, 16) = 5.29$, $MS_e = 372.28$, $p < 0.04$. In the parallel search condition of both experiments, average latency to move was significantly longer on negative than on positive trials. The difference between positive and negative trials was also significant in the serial search condition of Experiment 1a; however, it was nonsignificant in Experiment 1b.

The large difference between average latency to move on positive and negative trials in the two parallel search conditions suggests that subjects were aware soon after trial onset that no target was present, meaning that there was little impetus for them to plan and execute a saccade quickly. Such a pattern of results is consistent with parallel processing of stimulus displays. In the serial search condition of Experiment 1a, the finding that average latency to move was longer on negative than on positive trials indicates that information about the target's absence was sometimes available soon enough to influence the programming of the first saccade. Average latency to move was still shorter on serial-negative than on parallel-negative trials, however, suggesting that such information was available less often in the serial search condition. In the serial search condition of Experiment 1b, the lack of a significant difference between the average latency to move on positive and negative trials indicates that information concerning target absence was probably not available quickly enough to influence the programming of an initial saccade. The finding that the average latency to move was affected by the absence of the target in the serial search condition of Experiment 1a but not in that of Experiment 1b supports our suggestion that search efficiency was greater in the first than in the second experiment.

General Discussion

In keeping with the results of past research, average RT showed little effect of display size in the parallel search conditions of Experiments 1a and 1b, a pattern consistent with parallel processing of stimulus displays (e.g., Treisman & Gelade, 1980; Treisman & Gormican, 1988). In contrast, in the two serial search conditions, average RT increased as a function of display size, with this increase being approximately twice as great on negative trials as on positive trials. This indicates that subjects in both serial search conditions relied on a serial, self-terminating processing strategy (e.g., Sternberg, 1969; Treisman & Gelade, 1980). As previously discussed, however, the increase in average RT with display size was more pronounced in Experiment 1b than in Experiment 1a, suggesting that the two tasks differed in search efficiency. The results for the global eye-movement measure – the average number of fixations per trial – are very similar to those for the RT data. In the parallel search condition of both Experiments 1a and 1b, subjects made few fixations regardless of display size. In the two serial search conditions, however, the average number of fixations per trial increased with display size, with this increase being greater on negative trials. As with average RT, the increase in the average number of fixations per trial was more pronounced in the serial search condition of Experiment 1b than in that of Experiment 1a.

The landing place of the first saccade relative to the target position can be used as an indicator of subjects' knowledge about the target location. The average error of the first saccade was quite low for all display sizes in the two parallel search conditions, suggesting that the location of the target stimulus was quickly available following the onset of a positive trial. Saccadic error did increase slightly (by approximately one degree of visual angle) between single-stimulus displays and those with 12 or 24 stimuli; for these latter two display sizes, saccadic error was equal. This increase can be explained by the global effect, a phenomenon where the trajectory of a saccade toward a target is influenced by the presence of additional stimuli (e.g., Coren & Hoenig, 1972; Deubel et al., 1984; Findlay, 1982; Ottes et al., 1984). In the two serial search conditions, the increase in saccadic error between displays of 1 and 12 stimuli was greater than that observed in the parallel search conditions; in addition, this increase was more pronounced in the serial search condition of Experiment 1b (approximately 4 degrees) than in that of Experiment 1a (approximately 2 degrees). In both serial search conditions, saccadic error also increased between displays of 12 and 24. The greater effect of display size in the serial search condition of Experiment 1b than in the serial search condition of Experiment 1a indicates that information concerning the location of the target stimulus was sometimes available soon enough to influence the programming of the first saccade in Experiment 1a, but was less frequently available in Experiment 1b.

Whereas saccadic error provides information concerning cognitive processes on trials where the target is present, latency to move may be a particularly important indicator of subjects' knowledge about the absence of the target. The average latency to move was longer on negative than on positive trials in both parallel search conditions, suggesting that information concerning the absence of the target stimulus was available soon after trial onset. There was little difference in the average latency to move on positive and negative trials in the serial search condition of Experiment 1b; the difference between positive and negative trials in Experiment 1a fell at an intermediate value. This suggests that information concerning target absence was sometimes available prior to the first saccade in Experiment 1a but was not available in Experiment 1b.

The distinct patterns of eye movements observed in the parallel and serial search conditions of the present two experiments support the claim that eye movements are correlated with the attentional processes underlying performance on such tasks. These findings are consistent with recent work by other researchers. Scialfa and Joffe (in press, submitted) held display size roughly constant and varied target eccentricity and trial type while subjects performed parallel and serial search tasks. They found that the number of eye movements per trial increased as a function of eccentricity in the serial search condition, but not in the parallel search condition.

Zelinsky and Sheinberg (1995) used a methodology more similar to that of the present experiments. They had subjects perform both a parallel and a serial search task, while manipulating display size (5 vs. 17) and trial type. The number of saccades per trial increased slightly with display size in the serial search condition, but this increase was nonsignificant. In the parallel search condition, the number of saccades per trial was inversely related to display size. In both search conditions, latency to move increased as a function of display size, especially in the serial search condition, but showed little effect of trial type. At first glance, these findings seem quite inconsistent with those from the present experiments; however, these discrepancies can be reconciled by considering differences across studies in the structure of the stimulus displays.

Zelinsky and Sheinberg used displays in which stimuli could appear no closer to the central fixation than 3° of visual angle. This meant that there was an empty area at the centre of each display. This empty region was very noticeable for the display size of 17, where stimulus density was higher. As a result, the stimulus arrays for this display size formed the configuration of a ring. No such configuration was apparent for the display size of 5. Thus, in Zelinsky and Sheinberg's experiment, the variable of display size was confounded with this configurational difference. This contrasts with the present experiments, in which the stimuli for the display sizes of both 12 and 24 formed a relatively uniform field.

A close inspection of Zelinsky and Sheinberg's data suggests that the "ring" configuration in displays of size 17 may have increased the proportion of single-fixation trials and lengthened the latency to move. That is, it may have inhibited saccadic eye movements. In the serial search conditions in our experiments, the number of fixations per trial increased as a function of display size. In Zelinsky and Sheinberg's experiment, the configurational effect may have attenuated this increase. In the parallel search conditions in our experiments, the number of fixations per trial showed no effect of display size; here, the configurational effect of Zelinsky and Sheinberg may have been responsible for the inverse relation they observed. Thus, if the results by Zelinsky and Sheinberg were corrected to take into account this hypothesized configurational effect, they would be consistent with those in the present experiments. Further research will be needed to investigate this post hoc explanation.

The current research has introduced the use of saccadic error as an informative measure in the study of parallel and serial search tasks. These experiments also extend prior research by comparing eye movements in two serial search tasks. The eye-movement measures employed in these experiments showed different patterns across these two tasks. In each case, the observed differences indicate that information concerning the presence or absence of the target stimulus was more quickly available in Experiment 1a than in Experiment 1b. Thus, the present two experiments demonstrate that eye movements can distinguish between serial search tasks which differ in search efficiency. The finding that eye movements can allow more than a coarse distinction between parallel and serial processing, that they can reflect varying levels of search efficiency, is important given the growing consensus that there is a continuum of search efficiency (Duncan & Humphreys,1989, 1992; Treisman, 1988; Treisman & Gormican, 1988; Treisman & Souther, 1985; Treisman & Sato, 1990; Wolfe, in press). A consistent finding has been reported recently by Scialfa and Joffe (submitted) who found that patterns of eye movements change as a result of extended practice in a serial search task.

Futher investigation of patterns of eye movements should provide valuable insights into parallel and serial search processes by allowing a more fine-grained analysis of the temporal and spatial aspects of search performance. As illustrated in the present two experiments, patterns of eye movements reveal effects that would be obscured by more global measures such as response time. For example, the current experiments demonstrated that differences between parallel and serial search tasks and between serial search tasks which differ in efficiency are evident at early stages in processing, as shown by the analyses of latency to move (temporal measure) and saccadic error (spatial measure). There is already a long and successful tradition of studying eye movements during visual search tasks other than parallel and serial search tasks (e.g., Gould, 1967; Gould & Schaffer, 1967; Jacobs, 1987; Nattkemper & Prinz, 1984; Rayner & Fisher, 1987). Given the results of the present two experiments, we believe that eye movements can also be used profitably to investigate parallel and serial visual search and to further explore the processes subserving visuospatial attention.

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Sommaire

Les deux présentes expériences visaient à déterminer si les modèles de mouvements oculaires étaient reliés aux processus d'attention favorisant la recherche visuelle parallèle et en série. C'est dans ce but que nous avons comparé des modèles de mouvements oculaires dans les tests de recherche visuelle parallèle et dans les tests de recherche visuelle en série qui ne semblaient pas avoir la même efficacité. Au cours de l'expérience 1a, les sujets recherchaient un "O" parmi des "X" et un "T" parmi des "L" lors d'une recherche parallèle, puis lors d'une recherche en série. Dans la recherche parallèle de l'expérience 1b, la cible était le "⚲" et les leurres des "O". Dans la recherche en série ces stimuli changeaient de rôle. Les présentations comportaient 1, 12 ou 24 stimuli. Dans certains essais les deux cibles étaient présentes et dans d'autres elles étaient absentes. Les mesures dépendantes étaient le temps de réponse (TR), le nombre de fixations par essai, l'erreur saccadée (la distance, en degrés, de l'angle visuel entre l'emplacement de la cible et le point de chute de la première saccade), et l'attente (le temps écoulé entre l'apparition de la présentation et le premier mouvement oculaire).

Le TR et le nombre de fixations par essai ont été très peu influencés par la taille de la présentation au cours de la recherche parallèle des deux expériences, mais ont augmenté, en tant que fonction de la taille de la présentation, lors de la recherche en série des deux expériences. Pour les deux mesures, l'augmentation reliée à la taille de la présentation lors de la recherche en série était plus marquée dans l'expérience 1b que dans l'expérience 1a. L'erreur saccadée a donné un modèle de résultats semblable, n'étant que très peu affectée par la taille de la présentation dans la recherche parallèle des deux expériences, et augmentant de façon significative selon la taille de la présentation dans la recherche en série des deux expériences. Cette fois encore, l'augmentation était plus prononcée dans la recherche en série de l'expérience 1b. L'attente moyenne était beaucoup plus longue dans les essais négatifs que dans les essais positifs lors de la recherche parallèle des deux expériences. La différence entre les essais positifs et négatifs était également importante dans la recherche en série de l'expérience 1a, mais ne l'était pas au cours de l'expérience 1b. Dans l'ensemble, la recherche était la plus efficace dans les deux conditions de recherche parallèle, suivi de la condition de recherche en série de l'expérience 1a, et finalement, de la condition de recherche en série de l'expérience 1b.

Les modèles distincts de mouvements oculaires observés dans la recherche parallèle et dans la recherche en série appuient l'hypothèse qui veut que les mouvements oculaires soient reliés au processus attentionnel gouvernant l'exécution de ce type de tests. Ces conclusions démontrent également que les mouvements oculaires permettent davantage qu'une grossière distinction entre le processus parallèle et le processus en série et qu'ils peuvent refléter la variation des niveaux d'efficacité de recherche dans les tests de recherche en série. Cette constatation est importante dans la mesure où le consensus se fait de plus en plus sur l'idée que de tels tests varient selon le continuum d'efficacité de recherche (Duncan et Humphreys, 1989 et 1992, Treisman et Gormican, 1988, Treisman et Sato, 1990, par exemple). Étant donné les résultats des deux présentes expériences, nous croyons que d'autres recherches sur les modèles de mouvements oculaires pourraient fournir des renseignements valables sur les processus de recherche parallèle et de recherche en série et, de façon plus générale, sur les processus gouvernant l'attention viospatiale.