Searching for an O in an array of Cs: Eye movements track moment-to-moment processing in visual search

CARRICK C. WILLIAMS

Mississippi State University, Mississippi State, Mississippi

AND

ALEXANDER POLLATSEK

University of Massachusetts, Amherst, Massachusetts

We examined how closely the underlying cognitive processing in a visual search task guides eye movements by comparing two different search tasks. In the extended search task, participants searched for an O in eight clusters of Landolt Cs with varying gap widths (four characters per cluster, arranged to look like words in text). In the single-cluster task, participants searched a single cluster (identical to the ones in the extended search). The key manipulation was gap size; although gap orientation for the distractors varied within a cluster, gap size was constant within a cluster but differed in size from cluster to cluster. The principal findings were that (1) gaze durations in the extended search were almost completely a function of the difficulty of the cluster (i.e., the gap size of the Cs) and (2) the effect of gap size on gaze durations in the extended search was very similar to its effect on response times in the single-cluster search. Thus, it appears that eye movements in the search task are determined almost exclusively by the ongoing cognitive processing on that cluster.

Searching for a target object is a task people do many times every day, and consistent with the importance of the task, it is one of the most widely studied areas in cognitive psychology (Duncan & Humphreys, 1989; Schneider & Shiffrin, 1977; Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989; see Wolfe, 1998, for a review). However, although most visual searches that people perform outside the laboratory involve movements of the eyes (and head) that aid in the search, a large majority of the studies of visual search do not record eye movements. Often, in these studies, the problem of not knowing where the eyes are fixating is dealt with by presenting an array that is to be searched briefly, so that it is seen within a single fixation of the eyes (e.g., Cave & Zimmerman, 1997; Kim & Cave, 1995). However, as a result, these studies involve quite small arrays that are different from those involved in most visual search tasks in the environment. Thus, we have an incomplete knowledge of what occurs in the visual search task in the environment when it involves eye movements and, perhaps, more global search strategies (Findlay, 1995; Findlay & Gilchrist, 1998).

In some recent studies, not only have eye movements been permitted, but also attempts have been made to incorporate eye movements into the study of visual search (e.g., Bertera & Rayner, 2000; Findlay, 1997; Findlay, Brown, & Gilchrist, 2001; Greene & Rayner, 2001a, 2001b; Motter & Belky, 1998; Scialfa & Joffe, 1998; Zelinsky, 1996).

One problem that arises with attempting to use eye movements as a tool is that the objects in typical search arrays are randomly distributed across the entire display. As a result, the experimenter often does not know what kinds of global strategies the person is employing (if any) and, thus, does not know what the participant intends to do. In addition, with the usual crowded search array, it is quite difficult to determine which element or elements the participant intended to fixate. Both of these problems make it difficult to relate the eye movement record to ongoing cognitive processing.

In a few studies, an attempt has been made to examine the relationship between the currently fixated information and the information in a subsequent fixation target, using post hoc analyses. Hooze and Erkelens (1999) found that fixation time on a particular item was highly influenced by the difficulty of the visual discrimination (i.e., how difficult the item was to discriminate from the target), with items more similar to the target being viewed longer than less similar items. They also found that people tended to direct eye movements to distractors that were more closely related to the target, indicating that targets of saccades were not random. In addition, the length of a fixation on an item directly influenced the selectivity of the next eye movement: the longer the fixation on the current item, the more similar to the target the next item fixated tended to be. In other words, saccades appeared to be more intelligently guided the longer a fixation was.

C. C. Williams, cwilliams@psychology.msstate.edu

Shen, Reingold, Pomplun, and Williams (2003) attempted to replicate the findings of Hooze and Erkelens (1999), using different types of search arrays and with differing demands on the participants' attention while they performed the search. They successfully replicated Hooze and Erkelens's finding that fixation time was related to the difficulty of the discrimination task, with longer fixations being devoted to harder discriminations. However, in three experiments, they failed to find any relationship between the currently fixated item and the target of the next fixation. One major difference between these two studies was the type of array that was used. In Hooze and Erkelens's study, the stimuli were presented in rows, with an equal number of stimuli in each row, whereas in Shen et al.'s study, the stimuli were presented in a more traditional style for visual search—scattered randomly across the display. The former type of stimulus array may have encouraged the participants to scan the stimuli in an orderly manner that could maximize the contribution of parafoveal information.

Given the difference in the predictability of the location of the stimuli between Hooze and Erkelens (1999) and Shen et al. (2003), we attempted to use a display that would maximize our chances of predicting the participants' scanning patterns. That is, we arranged search stimuli so that they resembled words on a single line of text. By presenting the stimuli in a manner consistent with the presentation of words in a text, it seemed quite likely that the participants would (mentally) scan the array in a left-to-right fashion, despite the fact that we did not give them explicit scanning instructions. Our study is not the first to use text-like displays to study eye movements in search. Rayner and Fisher (1987) employed a visual search task in three experiments in which participants searched for a target letter in clusters (not resembling real words) that had two, four, six, or eight letters that either were similar in shape to the target letter or were not. Using a moving window technique (Bertera & Rayner, 2000; McConkie & Rayner, 1975; Rayner & Bertera, 1979), they manipulated how many clusters were visible to the right of the fixated cluster. Rayner and Fisher found that for clusters of more than two letters, search was faster when the window included the cluster to the right of the fixated cluster but was hardly any faster when the window was extended beyond that. In other words, it appeared that people did not extract information much beyond a region of eight letters. Moreover, for clusters of four or more characters, the difference between the two-cluster window condition (in which the window included the fixated cluster and the one to the right) and the one-cluster condition (in which the window contained only the fixated cluster) was not large. However, the difference between the one-cluster and the two-cluster search was more pronounced when the distractors were dissimilar from the target, suggesting that people extracted useful information from a region larger than the fixated cluster only when the target–distractor discrimination was easier. (These findings were based on conditions in which all the letters outside the window were Xs.)

The first finding is, in general outline, similar to what has been found for reading. That is, for reading, performance in a one-word condition is not that different from

performance when there is no window restriction (Rayner, Well, Pollatsek, & Bertera, 1982), and reading is still reasonably fluent when only the fixated word is visible (about 60% of normal reading speed). The findings in the visual search task suggest that most of the processing during a fixation consists of deciding whether the fixated cluster contains the target but that there is some processing of the next cluster, especially if discrimination is easy. This, in general outline, is reasonably consistent with the E-Z Reader model of reading (Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003), which posits the following sequence of events during a fixation. First, the reader attempts to identify the fixated word. When the identification process is near completion, a signal goes out to fixate the next word. When the identification process reaches completion, covert attention shifts to the next word, and processing of that word begins. Thus, typically, the beginning of the processing of a word starts when the prior word is fixated (this preview benefit presumably accounts for the difference between the zero-word window condition and the one-word window condition). Rayner and Fisher's data suggest that there may be a similar relationship between processing and eye movement control in their visual search paradigm, except that the cognitive event consists of deciding that a cluster does not contain the target, instead of identifying a word in reading (Rayner, 1995).

Rayner and Fisher's (1987) study provides important information, but there are some critical questions still unanswered. The first is the extent to which such a serial cluster-by-cluster processing assumption is tenable or, alternatively, the conditions under which it may be true. As we suggested above, Rayner and Fisher's data indicate that it may not be true when the clusters are only two letters. In that condition, information was extracted from at least two clusters beyond the fixated cluster. Another important question that Rayner and Fisher's study leaves unanswered is how the manipulated variables affect the moment-to-moment pattern of eye movements. Rayner and Fisher reported only more global measurements, such as the average fixation duration and the average length of a saccade. However, in current work on reading, one typically wants measures that more directly tap the immediacy of the effects of manipulated variables. Two important variables are *first-fixation duration* on a word and *gaze duration*, the sum of the fixation durations on a word prior to exiting the word. A third key measure is the probability that a word will be skipped. In reading, for example, the fact that the frequency of a word influences gaze duration on a word and the probability that it will be skipped indicates that the cognitive processing involved in identifying a word has quite immediate consequences on eye movements (Rayner, 1998). Analogously, we wanted to examine whether the difficulty of processing a cluster would influence the measures of ongoing processing of the cluster, such as the gaze duration on it and the probability that it would be skipped.

The present study is an attempt to bridge the gap between a realistic visual search task and one that either prevents or ignores eye movements by employing a paradigm in which

one is reasonably confident of how the participant intends to search the array. Admittedly, text-like displays do not closely resemble typical real-world searches (such as finding a car key one has dropped), but they have the virtue of allowing one to make sense of the pattern of eye movements during the search. Furthermore, having word-like “clumps” of stimuli does resemble real-world environments in one important way: The environment is typically not a random array but, instead, contains objects made of sub-components. Thus, although our stimuli may not look like real-world scenes, the present study can help in the understanding of eye movement patterns and processing in more realistic and important visual search tasks. Finally, the present design can lead to a better understanding of the aspects of eye movement control that are shared by language and nonlanguage tasks and those that are unique to reading.

In the present study (as in Hooge & Erkelens, 1999), participants searched for an O in a background of Landolt Cs (i.e., Os with a gap in them), allowing for a manipulation of the similarity of the target to the distractors that was more precise than that in Rayner and Fisher (1987). The size of the gap was manipulated, and it varied from cluster to cluster, allowing us to control how difficult it was to detect the absence of a target O in each cluster. This allowed us to examine not only how the processing difficulty of the currently fixated cluster (n) affected processing time, but also how the difficulty of clusters $n+1$ and $n-1$ affected processing time on cluster n . This is of interest because, if only the difficulty of the fixated cluster affects gaze duration on that cluster, that would be evidence that processing of the cluster to the right of fixation has not progressed far enough to control the decision to move from one cluster to the next. However, the processing time on cluster $n+1$ might be affected by the difficulty of the discrimination on cluster n . For example, difficult discriminations on cluster n could lead to reduced parafoveal processing of cluster $n+1$ (as in Henderson & Ferreira's [1990] work on reading). Conversely (as in Hooge & Erkelens, 1999), as more time is spent on cluster n (due to a difficult discrimination), more parafoveal information may be extracted from cluster $n+1$, and thus, less time would be spent on it. It is also possible that unlike reading, the difficulty of the cluster to the right of the fixated cluster (cluster $n+1$) affects processing time on cluster n , indicating that clusters in this visual search task are unlikely to be processed serially.

METHOD

Participants

Eight participants were recruited from the University of Massachusetts community. All were naive as to the purpose of the experiment but had participated in other eye-tracking experiments.

Apparatus

Eye movements were monitored using an Eyelink 2 system operating at 250 Hz. This system is accurate to less than 0.5° of visual angle. The stimuli were displayed on a 19-in. monitor at a distance of 77 cm. A chinrest was used to minimize head movements and maintain a consistent distance from the monitor.

Materials and Design

Extended search experiment. As was indicated earlier, the materials were designed so as to appear similar to words on a page (see Figure 1). There were eight clusters of four Landolt Cs presented in a single horizontal line. Each element subtended 30 pixels (0.48°) horizontally, so that each cluster subtended 120 pixels (1.92°). Since the clusters were separated by 30-pixel gaps, the entire display subtended 18.24° horizontally. The Landolt Cs had a line weight of 6 pixels (0.064°) with varying sizes of gaps: 2-, 4-, 6-, or 8-pixel-wide gaps (0.032° , 0.064° , 0.096° , and 0.128° gaps, respectively) that were intended to manipulate the similarity of the distractor Cs to the target O. All of the distractors in a cluster had the same gap size, and the position of each gap was oriented to the top, left, right, or bottom. Within each cluster, the gap of each C was randomly assigned to one of these four orientations. The target, if present, would replace one randomly selected element of the cluster. The target was present on 52% of the trials (136 of the 264 trials). For 256 of the trials, the target appeared on half the trials in the critical clusters that were analyzed (2–7) and was absent on the other half of the trials. The other 8 trials were trials on which the target appeared in either Cluster 1 or 8, to ensure that these clusters were also processed. The target appeared 21 times in Clusters 2, 3, 6, and 7 and 22 times in Clusters 4 and 5, and it appeared as the first element 33 times, the second element 34 times, the third element 31 times, and the fourth element 30 times.

In order to examine the effects of the processing of the previous cluster on the fixation time on the current cluster and to examine the effects on processing of the current cluster on the next cluster, all possible combinations of gap sizes were present for Clusters 2–7. This meant that the gap size in cluster n was completely crossed with the gap sizes in clusters $n-1$ and $n+1$ for Clusters 3–6. Clusters 1 and 8 were not included in the counterbalancing scheme, since they were excluded from the eye movement analyses. Cluster 1 was excluded because the eyes were likely to be already on it before the trial began, and Cluster 8 was excluded because the manual responses on target-absent trials would likely interfere with eye movements. (As will be seen, eye movement measures for the cluster containing the target appear to have been somewhat compromised.)

Single-cluster search experiment. In addition to the reading-like search described above, we also presented the participants with a search task in which they were presented with a single cluster of four Landolt Cs in the center of the screen. The single clusters were identical to the individual clusters of the reading-like search task described above, and the target was again an O. There were an equal number of target-present and target-absent trials, and all gap sizes and target positions within a cluster were used.

Procedure

The experiment was conducted in two 1-h sessions. The participants were given instructions and an informed consent form prior to participation. They were informed that they were to search for an O in a field of Cs with varying gaps. They were told to start on the left side of the screen and were told that to ensure that they were

Figure 1. An example display of a target-present trial. The target is the first element of the seventh cluster from the left. The background was a neutral gray (RGB = 120).

looking at the left hand side of the screen prior to the beginning of each trial, an eye-movement-contingent box would control the onset of the array. However, the participants were not given any specific instructions on how to search the display. A button box was used for their present/absent responses, with the left button indicating that the target was present and the right button indicating that the target was absent. Before the start of the experiment, the participant went through a calibration sequence. On each trial, the calibration was checked, and a recalibration was performed when necessary. In between the trials, a drift correction was performed. There was a total of 264 trials in this portion of the search task.

At the end of the second session, the participants performed the single-cluster search portion of the experiment. These trials proceeded as in the main search task, except that all the events took place in the center of the screen. The gaze-contingent onset box subtended the same width as that for the central two elements of the single cluster. There were 64 target-present trials and 64 target-absent trials. The target position was counterbalanced so that it was equally likely to be each of the four elements on the screen.

RESULTS

Extended Search Task

As was indicated above, this experiment was conducted to determine whether moment-to-moment decisions about where to fixate are influenced by the ongoing processing of a display, rather than by a predetermined strategy of fixation. There are various levels at which this question can be asked, but as was indicated above, the one that we thought would be the most diagnostic was the cluster level, which is roughly analogous to a word in reading. That is, it is unlikely that eye movement targeting is accurate enough that the character fixated is usually the intended target of a fixation (if, indeed, specific characters are targeted), whereas if the cluster is the level of analysis, one can safely assume that if a cluster is targeted, it will be fixated with a fairly high probability.

The analyses below of the search data mimic the standard analyses of eye movement data in reading. This seems appropriate, since the patterns of eye movements looked very much like those in reading. That is, even though the participants were given no instructions about how to search the arrays, their pattern of eye movements was predominantly left to right, fixating each cluster in turn and only occasionally skipping a cluster. There were some *regressive* (i.e., right-to-left) saccades, but these were a small percentage of the total. In order to be as consistent with reading studies as possible, we included as a fixation on a cluster any fixation that fell on the space that preceded the cluster. (As was mentioned earlier, the width of the space was the same as that of a single element in the cluster.) Thus, a cluster region extended from one character width to the left of the cluster to the right boundary of the last element in the cluster. In addition, any fixation that was shorter than 90 msec or longer than 4,000 msec was eliminated from the analysis. Finally, 1 participant had a hit rate of under 50% on target-present trials and was eliminated from all the analyses reported here. All the other participants had hit rates of at least 80%; their average hit rate was 90.6%, and their false alarm rate was 0.4%. There was virtually no difference among the hit rates for Clusters 2–7 [$F(5,30) = 1.19$, $MS_e = 0.16$, $p > .20$], and although the

hit rate was about 4% lower for gap size of 2 pixels than for the other three gap sizes, the difference was far from significant [$F(3,18) = 1.50$, $MS_e = 0.10$, $p > .20$].

Most of the analyses reported below focused on Clusters 2–7 in which the target was not present, because these were the purest measures of eye behavior, since there was no manual motor program being planned and/or executed that would disrupt the eye movement record (see Fischer, 1999; Loschky, McConkie, Yang, & Miller, 2005; Zelinsky, 1996). At the end, we will briefly discuss the target present trials.

Gaze duration. Plausibly, the single best measure of the time spent processing a cluster (except for double-checking) is *gaze duration*, the total fixation time on the cluster on the *first pass*, conditional on fixating the cluster during the first pass. As can be seen in Table 1, the gaze durations on nontarget clusters were heavily influenced by the difficulty of the ongoing processing, since the gaze duration on a cluster was close to 275 msec longer when the elements had a gap size of 2 pixels than when the elements had a gap size of 8 pixels. The overall effect of gap size was significant [$F(3,18) = 25.40$, $MS_e = 25,498$, $p < .001$], as were paired comparisons between all of the conditions (all $ps < .01$). There was no main effect of the ordinal position of the cluster on the gaze duration on that cluster [$F(5,30) = 1.05$, $MS_e = 2,446$, $p > .20$]. However, there was a significant interaction between the cluster order and the gap size [$F(15,90) = 2.81$, $MS_e = 1,211$, $p = .001$], which indicated that for clusters of gap size 2, the farther into the search display the eyes went, the longer the gaze durations tended to be. This pattern was not found for gap size 4 and was actually reversed for the largest gap sizes, with clusters of gap sizes 6 and 8 having shorter gaze durations on later clusters. Thus, the farther into the display one looks, the more quickly one rejects dissimilar distractors and the more slowly one examines the similar distractors.

To summarize, how long one fixates a cluster before going on to the next cluster appears to be influenced largely by the time spent deciding that the cluster does not contain a target. (The data from the single-cluster experiment, reported below, strongly support this conclusion.) There was a slight indication that a more global strategy was operating, however, since the participants seemed to be increasingly cautious about leaving clusters with the smallest gap size as they went through the array.

Table 1
Gaze Durations (in Milliseconds) on a Cluster as a Function of Gap Size and Cluster Position During Target-Absent Trials

Cluster Position	Gap Size				Mean
	2	4	6	8	
2	727	606	528	522	596
3	785	577	567	505	609
4	785	597	551	515	612
5	798	616	552	513	620
6	799	593	533	499	606
7	806	597	500	476	595
Mean	783	598	539	505	606

Finer measures of first-pass processing. An even earlier measure of processing on a cluster is the *first-fixation duration*, the mean duration of the first fixation on a cluster on the first pass through the cluster, conditional on there being a fixation on the cluster. As can be seen in Table 2, the pattern for the first-fixation duration was similar to that for gaze duration, although the effect of gap size on first-fixation duration [$F(3,18) = 32.89$, $MS_e = 2,317$, $p < .001$] was less than half the effect of gap size on gaze duration. The 1-msec difference between the two largest gap sizes was not significant, but all other pairwise comparisons between gap sizes were significant ($ps < .013$). The effect of cluster position was also significant [$F(5,30) = 4.17$, $MS_e = 926$, $p < .01$]. The first-fixation duration appeared to get larger for later clusters, the linear trend was significant [$F(1,6) = 10.02$, $MS_e = 1,195$, $p = .02$] and the effect of cluster appears to have been negatively accelerated, as evidenced by a significant quadratic trend [$F(1,6) = 7.93$, $MS_e = 582$, $p = .03$]. There was no interaction between the two variables ($F < 1$).

These data indicate that the duration of the first fixation on each cluster reflects the difficulty of processing the cluster (i.e., determining that there was no O in the cluster). They also reveal that somewhat less than half of the effect in gaze duration was due to a lengthened first fixation and, thus, that the other half of the gaze duration effect was due either to an increase in the number of refixations or the durations of subsequent fixations on the cluster before the eyes moved on. In fact, the number of fixations on a cluster decreased significantly with increasing gap size [$F(3,18) = 23.28$, $MS_e = 0.047$, $p < .001$]. There were 1.82, 1.60, 1.52, and 1.45 fixations per cluster for gap sizes 2, 4, 6, and 8, respectively, and all paired comparisons between the means were significant ($ps < .025$). Although there was a slight suggestion that the number of fixations per cluster decreased as the fixation location went from left to right, neither the main effect of cluster location nor the linear trend was significant [$F(5,30) = 1.01$, $MS_e = 0.031$, $p > .20$, and $F(1,6) = 2.87$, $MS_e = 0.041$, $p > .10$, respectively]. However, as in the gaze duration data, there was an interaction of gap size and cluster, in that the number of fixations increased slightly for the clusters of distractors that were most similar to the target (gap size 2) and decreased for the clusters less similar to the target (gaps 4, 6, and 8) [$F(15,90) = 1.88$, $MS_e = 0.014$, $p = .035$].

Table 2
First-Fixation Durations (in Milliseconds) on a Cluster as a
Function of Gap Size and Cluster Position

Cluster Position	Gap Size				Mean
	2	4	6	8	
2	430	373	354	352	377
3	466	383	374	377	400
4	455	398	359	360	393
5	476	398	373	381	407
6	467	403	389	380	410
7	463	408	372	361	401
Mean	460	394	370	369	398

Probability of fixating a cluster. The analyses above indicate that the decision of whether or not to move on to the next cluster is affected by the difficulty of deciding whether a target is present in the fixated cluster. Another question of interest is whether the decision to fixate or to skip a cluster is also dependent on the difficulty of deciding that the cluster does not contain a target. In fact, there was little skipping of clusters, and the differences among the gap size conditions were not significant. The probabilities of skipping a cluster for gap sizes 2, 4, 6, and 8 were .025, .036, .038, and .035, respectively [$F(3,18) = 1.34$, $MS_e = 0.001$, $p > .20$]. There was no suggestion of an effect of cluster location or of an interaction between the two variables ($Fs < 1$).

Total time. Another index of interest is the *total time* spent on a cluster (see Table 3). Total time is the sum of all fixation times on a cluster during the trial, conditional on fixating the cluster at any time during the trial. Perhaps the most interesting feature of the data is that the values are not much greater than the gaze duration values (the difference in the overall means was only 34 msec), which means that people did not regress back to clusters very often once they had initially fixated them. As was the case for gaze duration, there was a large, significant effect of gap size [$F(3,18) = 29.43$, $MS_e = 25,098$, $p < .001$] with all the gap sizes differing significantly from all the other gap sizes in paired comparisons ($ps < .03$), and as was the case for the gaze duration, the effect of cluster location was not close to significant [$F(5,30) = 1.55$, $MS_e = 1,891$, $p > .20$]. As was the case for the gaze duration and number of fixation measures, there was a significant interaction of cluster position and gap size [$F(15,90) = 2.60$, $MS_e = 1,581$, $p = .003$].

Tests of indirect influences on eye movements. The analyses above are consistent with a model of eye movement control in which the decision to move the eyes is controlled almost completely by the difficulty of processing the current string. However, the present design also allows two tests of "almost immediate" influences on eye movements.

The first is whether the difficulty of processing an entity *spills over* onto the time to process the next entity. In the reading literature, it has often been found that there is such a spillover effect. For example, if a word is infrequent, not only are gaze durations on that word longer, but gaze durations and first-fixation durations on the next word are often longer; however, the size of these frequency effects on spillover is usually quite a bit smaller than the size of the frequency effect on the word itself; on average, spillover is about 25% the size of the gaze duration effect on the target word (Staub & Rayner, 2007). Because the gap size in cluster n was independent of the gap size in cluster $n - 1$, one can examine this effect using a factorial design, where the fixation duration measure is examined as a function of the gap size of cluster n (i.e., the fixated cluster) and the gap size of cluster $n - 1$ (i.e., the cluster just fixated). The effect of the gap size of cluster n in these analyses was highly significant, but since this is just a replication of the earlier analyses above, we will not

Table 3
Total Time (in Milliseconds) on a Cluster as a Function of
Gap Size and Cluster Position

Cluster Position	Gap Size				Mean
	2	4	6	8	
2	771	643	560	555	632
3	849	608	593	538	647
4	843	624	583	528	645
5	842	648	575	551	654
6	823	615	553	539	633
7	852	633	519	508	629
Mean	830	628	564	536	640

repeat them. In contrast, there was little effect of the gap size of cluster $n-1$, the mean gaze durations on cluster n for gap sizes 2, 4, 6, and 8 of cluster $n-1$ were 598, 614, 600, and 620 msec, respectively [$F(3,18) = 2.19$, $MS_e = 1,471$, $p = .13$]. We think it is safe to conclude that there is no spillover effect in this task, both because the effect is not significant and because it is not clear what would produce such a “zig-zag” pattern. In addition, the general trend was, if anything, the opposite of the usual spillover effect, since processing a difficult cluster previously appears, if anything, to have a slight facilitative effect on processing the next cluster. We also examined the first-fixation duration on a cluster, using an analysis parallel to the one above. The first-fixation durations on cluster n for gap sizes 2, 4, 6, and 8 of cluster $n-1$ were 403, 399, 398, and 408 msec, respectively ($F < 1$).

The opposite test is to determine whether fixation duration measures on a cluster are influenced by the cluster that is about to be fixated. Accordingly, we examined fixation times on cluster n as a function of the gap size of cluster n and the gap size of cluster $n+1$. The pattern again was not what one might expect, since the gaze durations on cluster n for gap sizes 2, 4, 6, and 8 of cluster $n+1$ were 590, 611, 611, and 623 msec, respectively. That is, when the cluster to the right of fixation was harder to process, gaze durations on the fixated cluster were actually shorter. The main effect of gap size of cluster $n+1$ was not significant [$F(3,18) = 2.36$, $MS_e = 2,195$, $p = .11$]; however, the linear trend was marginally significant [$F(1,6) = 5.57$, $MS_e = 2,411$, $p = .056$], and the difference between gap size 8 and gap size 2 was significant ($p < .05$). The pattern of results was similar for first-fixation duration. The first-fixation durations on cluster n for gap sizes 2, 4, 6, and 8 of cluster $n+1$ were 388, 401, 398, and 402 msec [$F(3,18) = 2.51$, $MS_e = 449$, $p = .09$], but there was no evidence of a linear trend across gap sizes [$F(1,6) = 3.46$, $MS_e = 583$, $p = .11$].

One possible explanation for this small effect of the parafoveal cluster (cluster $n+1$) on the fixation time on the prior cluster is that some saccades that were intended to land on cluster $n+1$ were mistargeted and landed short of it (i.e., the participant intended to direct his or her eyes to cluster $n+1$ and simply landed short of the intended target). On such presumably mistargeted fixations (which would affect the gaze duration on cluster n), cluster $n+1$ is attended initially, and the decision of when to *refixate* cluster $n+1$ would be the major determinant of the length of these fixations. Given that the actual fixation point

(which is not on cluster $n+1$) is a bad vantage point for processing that cluster, a refixation may be programmed fairly rapidly. Moreover, for smaller gap sizes, it may be close to impossible to discriminate the O from the Cs from this vantage point, so that the decision to refixate may be even more immediate than it would be if some significant processing of cluster $n+1$ could actually occur. If so, these “extra” fixations would add more time to the gaze duration on cluster n , as the gap size of cluster $n+1$ increased. (See Nuthmann, Engbert, & Kliegl, 2005, and Rayner, Warren, Juhasz, & Liversedge, 2004, for explanations of phenomena in reading involving mislocated fixations.)

In an attempt to investigate this possibility, we eliminated all trials on which the last element of the cluster was fixated and recomputed the analyses above. The results indicate that the parafoveal effect above was primarily the result of fixations that landed on the final element in the cluster [$F(3,18) = 1.22$, $MS_e = 2,781$, $p > .20$; linear trend $F(1,6) = 2.21$, $MS_e = 4,251$, $p = .19$]. Thus, it appears that the trend for a parafoveal effect on the gaze duration on a cluster is dependent on fixations that are very near the boundary of the cluster and is not a general trend of the fixation patterns. Although not conclusive, these data are consistent with the explanation above that this *parafoveal on foveal effect* is due to mistargeting of saccades, rather than indicating that two clusters are processed in parallel.

Target clusters. As was indicated above, we were less confident about the eye movement measures on target clusters, because they would likely be contaminated by the requirement of making the response while fixating the cluster. Nonetheless, we thought it would be of interest to examine them. As can be seen in Table 4, the gaze durations and first-fixation durations on the target cluster were substantially longer than those for the target-absent clusters, presumably because the cluster was usually fixated until the response was made. Nonetheless, somewhat surprisingly, the effect of gap size on the duration measures was quite similar to that on the target-absent clusters and was significant for both gaze duration and first-fixation duration for correct responses [$F(3,18) = 14.55$, $MS_e = 7,896$, $p < .001$, and $F(3,18) = 12.75$, $MS_e = 1,152$, $p < .001$, respectively]. [The pattern was the same for all responses: $F(3,18) = 14.12$, $MS_e = 7,410$, $p < .001$ and $F(3,18) = 7.84$, $MS_e = 1,214$, $p = .001$, for gaze duration and first-fixation duration, respectively]. In paired comparisons for gaze duration, gap sizes 2 and 4 were marginally different from each other ($p = .083$), and each was significantly different than the other gap sizes ($p < .02$); gap sizes 6 and 8 did not differ. In paired comparisons for first-fixation duration, gap size 2 was significantly different from all other gap sizes ($p < .05$), and gap size 4 was significantly different from gap size 6 ($p < .01$) but was not different from gap size 8 ($p > .10$). The largest gap sizes again did not differ.

We found the target cluster data somewhat surprising, since we expected the nontarget elements to have a substantially smaller effect on processing time because not all the nontarget elements of the string needed to be processed to find the target. (In addition, there were only

Table 4
Selected Fixation Duration Measures (in Milliseconds) on Target Clusters

Gap Size	All Responses		Correct Responses	
	Gaze	First-Fixation	Gaze	First-Fixation
2	1,026	581	1,056	606
4	894	525	925	542
6	776	499	797	504
8	764	507	781	514
Mean	852	529	890	542

three nontarget elements in these strings, rather than four.) Nonetheless, the pattern of differences between the gap sizes was remarkably similar (e.g., about a 275-msec difference in gaze duration and a 90-msec difference in first-fixation duration between the biggest and the smallest gap sizes). This finding would seem to go against a model in which the elements within a cluster were interrogated serially, since such a model would predict a gap size effect for target-present clusters that was about half the size of that for target-absent clusters. For example, in a serial, self-terminating search, all four elements of a four-element cluster would have to be examined in target-absent clusters, as compared with, on average, only 2.5 elements in target-present clusters, of which only 1.5 would be nontarget elements.

Single-Cluster Search Task

As was indicated above, the participants also performed a task in which they fixated the center of the screen; a single cluster then appeared centered around the fixation point, and they had to decide whether it contained an O. The principal motivation for this task was to determine the length of time it would take to make a decision for a cluster and, perhaps more important, to determine how the differences in the time to make this decision between nontarget clusters having different gap sizes would relate to the gaze durations in the extended search task. Because the responses likely perturbed the measurement of individual eye movements, we will not report eye movement measures for this task.

The first analyses included gap size (of the nontarget elements) and target present versus target absent as the two factors. As can be seen in Table 5, there was a large effect of gap size [$F(3,18) = 18.45$, $MS_e = 7,446$, $p < .001$]. The main effect of target present versus target absent was not significant [$F(1,6) = 2.48$, $MS_e = 19,785$, $p > .10$], but there was a significant interaction between the two variables [$F(3,18) = 3.78$, $MS_e = 3,009$, $p = .029$], since there was almost twice as large an effect of gap size for the target-absent trials. When the response times to the target-absent items were analyzed separately, the effect of gap size on these trials was significant [$F(3,18) = 12.97$, $MS_e = 8,767$, $p < .001$], and all pairwise comparisons between gap sizes were significant, except for the difference between the two largest gap sizes ($ps < .05$). The target-present data had a similar pattern, with a main effect of gap size [$F(3,18) = 20.77$, $MS_e = 1,689$, $p < .001$], and gap size 2 was significantly different from the other gap sizes ($p < .01$). Gap size 4 was not significantly different

from gap size 6 ($p = .11$) but was significantly longer than gap size 8 ($p = .014$). There was no significant difference between the largest gap sizes.

The pattern in the error data was similar to that in the data for the extended search task (see Table 5), since most errors involved missing target items when they were present, rather than making false alarms [$F(1,6) = 5.89$, $MS_e = 0.005$, $p = .051$]. Although there was a suggestion that increasing gap size decreased errors for target-present trials and had little or no consistent effect on errors for target-absent trials, neither the main effect of gap size nor the interaction with target present versus absent was significant [$F(3,18) = 1.95$, $MS_e = 0.002$, $p > .10$, and $F(3,18) = 1.19$, $MS_e = 0.002$, $p > .10$, respectively]. In addition, even when the target-present trials were analyzed separately, the effect of gap size on errors was not close to significant [$F(3,18) = 1.64$, $MS_e = 0.003$, $p > .10$].

What is most striking is how closely the pattern of differences in response times in the target-absent condition mirrors those in the gaze duration data (see Figure 2). The difference in times between gap sizes 2 and 4 was 185 msec in the gaze duration data and 205 msec in the response time data, and for gap size 4 versus 6, the difference was 59 msec for gaze duration and 60 msec for response times. For gap size 6 versus 8, there is a bit of a disconnect between the measures, since the differences were 34 and 7 msec in the gaze duration and response time data, respectively. Although the effect of gap size in the response times for the target-present clusters was only about half that for the target-absent clusters in the response time data (except for the largest gap sizes), there were some striking consistencies between the pattern of response times in the target-present data and the pattern of gaze durations for target-present clusters in the extended

Table 5
Response Times (RTs, in Milliseconds) and Percentages of Errors in the Single-Cluster Condition as a Function of Whether a Target Was Present and the Gap Size of the Nontarget Elements in the Cluster

Gap Size	Target				Mean	
	Present		Absent			
	RT	%E	RT	%E	RT	%E
2	813	8.9	954	0.9	884	4.9
4	697	6.2	749	0.9	723	3.6
6	672	3.6	689	0.0	680	1.8
8	657	2.7	682	0.9	670	1.8
Mean	710	5.3	769	0.7	740	3.0

Figure 2. A comparison of the average gaze durations for the different gap conditions in the extended search task (closed symbols) and the response times in the single-cluster response task (open symbols). Squares represent target-present clusters/trials, and triangles represent the target-absent clusters/trials.

search task. Notably, the difference of 130 msec between gap sizes 2 and 4 for the gaze duration measure was similar to the 116-msec difference for the response time measure, and the differences between the gap size 6 and the gap size 8 conditions were similar (10 and 15 msec for the gaze duration and response time measures, respectively). The chief mismatch was that the difference between gap sizes 4 and 6 was 121 msec for gaze duration and only 25 msec for the response time for the single cluster. The reason for this one deviation from the pattern in the gaze duration data is far from clear.

Although the patterns are similar overall, we are at a loss to explain the slightly different pattern for the target-present clusters in the response time task, as compared with the gaze duration measure. The difference in pattern cannot be explained by incomplete processing of the target during the single-cluster response task. Although a majority of the errors in the response time data involved missing a target when it was present, incomplete processing of a target-present stimulus would result in an error and would not be counted in the response time analysis for the single-cluster task. Thus, the difference in the pattern between the two target-present data sets is not the result of participants responding quickly but inaccurately in the gap size 4 condition during the single-cluster response task. Moreover, similar “cheating” when there was no target present (which would yield a correct response) should have depressed the size of the gap size effect for target-absent trials at least as much.

DISCUSSION

In the present study, we examined the role of eye movements in a search task similar to reading, in that the array was linear and punctuated by spaces. This design of the displays in the present experiment permitted us to manipulate (1) the information that was available to the

participant at fixation, (2) the information that he or she was likely to fixate next, and (3) the information that had previously been fixated. It also enabled us to use the total first-pass fixation time (gaze duration) on a cluster as a meaningful index of search. We found that first-fixation durations and gaze durations appeared to have been driven by the discriminability of the Cs in the fixated cluster from the target O (i.e., the size of the gaps in the cluster). This was true for both nontarget clusters containing all Cs and the target cluster containing three Cs and the target.

We also found that there was an interaction between the ordinal position of the cluster being examined and the size of the gap: The gaze duration for the smallest gap increased the farther into the display the search proceeded, whereas gaze duration in the other gap conditions was either unaffected or got slightly shorter. (However, it should be kept in mind that there are large gap size effects at all cluster locations.) One interpretation of this pattern is that as the number of clusters that have been examined increases, participants’ “tuning” for decisions changes, and they become more cautious about rejecting the most similar distractors and more willing to reject dissimilar distractors. Overall, though, their ability to detect a target does not change, since the miss rate was essentially constant for Clusters 2–7.

In an examination of the possible effects of the processing of one cluster on that of another cluster, there was no significant effect of the difficulty of the prior cluster on the fixation time on a cluster (i.e., no *spillover effect*), but there was a suggestion of an effect of the difficulty of the cluster about to be fixated. However, the pattern was difficult to interpret, since it was in the “wrong direction”: Clusters that were about to be fixated that had larger gaps lengthened gaze duration on the prior cluster, relative to clusters that had smaller gaps. Furthermore, most of this effect came when the last letter of the prior cluster was fixated and, thus, was plausibly due to mistargeted fixations. Our failure to find an impact of preceding or following clusters fails to replicate the previous finding of Hooze and Erkelens (1999), who found that the likelihood of fixating a similar distractor was influenced by the item examined previously. However, our finding that the fixation time on a cluster was almost completely dependent on the difficulty of the discrimination of the current cluster is similar to the findings in Shen et al. (2003).

In addition to finding that the *difficulty* of the current cluster appeared to predict the gaze duration on a cluster, we found that the pattern of gaze durations was similar to the pattern of response times in a task in which a single cluster was presented, with the initial fixation on the center of the cluster. This was especially true for target-absent clusters. There, the differences in response times almost perfectly mirrored the differences in gaze durations on a cluster in the search task. The absolute times were longer for the absent trials in the response time task, undoubtedly reflecting the programming and execution of a manual response that was not immediately required when Clusters 2–7 were encountered during the extended search task. The correspondence was admittedly a bit less good for the target-present clusters (since the difference between

the gap size 4 and 6 conditions for the gaze durations was larger than that for the response times). However, the close correspondence is striking, given that people universally start out on what is likely to be the optimal spot to process the cluster in the response time task (the center of the cluster), whereas the initial fixation on the cluster in the extended search task is likely to be more variable. In an attempt to determine whether initial landing position was the primary reason for this difference between the pattern in the gaze duration and the pattern in the response time data, we limited the analysis of the gaze duration to only those trials in the extended search task in which the initial fixation landed on either the second or the third element in the target cluster (closely simulating the initial viewpoint of the single-cluster search). The gaze durations on the target cluster under these circumstances were 1,008, 875, 748, and 737 msec for the 2, 4, 6, and 8-pixel gaps, respectively. The critical difference between the gap size 4 and gap size 6 conditions under these restrictions for initial landing position actually increased to 127 msec (from a difference of 121 msec when all the initial landing positions are analyzed). Thus, it appears that initial landing position (or starting position, in the case of the single cluster) is not a sufficient explanation for the differences between the two searches. For completeness, we also performed the same analysis for the target-absent clusters and found a pattern of gaze durations when the initial landing position was near the center of the cluster that was almost identical to the pattern when all landing positions were included (754, 565, 507, and 476 msec for gap sizes 2, 4, 6, and 8, respectively). We are still unclear why there are these differences in the patterns of gaze durations and response times, but these should be considered small deviations in patterns of differences that are strikingly similar.

These data indicate that the gaze duration on a cluster for clusters that do not contain the target is almost a perfect measure of processing time: The differences in the gaze duration on the cluster for the different gap sizes is virtually equal to the differences in the time that it takes to decide that a cluster does not contain the target. At first, that may seem unlikely, since it takes time to decide to move the eyes on and off a target. However, a variation of a model of reading that has been developed, the E-Z Reader model (Pollatsek et al., 2006, Reichle et al., 1998) can easily explain our present data. In the E-Z Reader model, attention is assumed to be allocated serially to one word at a time, with attention shifting to the word to the right when processing of the prior word is complete. However, partly to account for spillover effects (which were not observed in the present study), shifting of attention is decoupled from eye movement programming in the E-Z Reader model. Instead, an incomplete stage of word identification (called *L1* in the model) is the trigger for an eye movement, whereas complete identification of the word (called *L2* in the model) is the trigger for an attention shift to actually begin processing the next word. (*L1* can be viewed as a “cheat” that helps reading to proceed more rapidly.) To explain the present data, however, a simpler model suffices, mirroring an earlier model proposed by Morrison (1984). In this model, a single signal, complete

processing of the currently fixated stimulus, is the signal both to shift attention and to program an eye movement to the next word.

Thus, in this adaptation of Morrison’s (1984) model, the following sequence of events occurs for all but the first and last clusters. First, the processing of the prior cluster is completed. This causes (1) an essentially instantaneous shift of attention to the next cluster and (2) a signal to the eye movement system to make a saccade to the next cluster. (In reading, the presumed target of the next saccade is the center of the succeeding word, although there is both systematic and random error in where the saccade actually lands.) However, it takes some time (on the order of 125–150 msec) for the saccade to be programmed and executed, so that processing of a cluster begins before it is fixated. The cluster is fixated and then continues to be processed (on more than one fixation if necessary) until a decision is made that it does not have the target, which triggers an attention shift to the next cluster and an eye movement program to fixate the next cluster. (Refixations are viewed as mostly being programmed to reach the optimal spot on a word or cluster—presumably, the center.)

This model thus predicts that fixation time on a cluster is equal to the time required to decide that the cluster does not contain the target. That is, according to the model, processing of the cluster starts when an eye movement is programmed to fixate it (say, 125 msec before it is actually fixated) and stops when the eye movement is programmed to fixate the next cluster (125 msec before it is left). Those two times obviously cancel. This would not necessarily predict an exact equality between the processing time in the extended search task and the single-cluster task, however, because the first 125 msec of processing is from the prior cluster and, thus, the processing for this first 125 msec should proceed more slowly as the cluster is farther from fixation, where visual acuity is worse. As a result, one could predict that processing times of a cluster (i.e., the time required to make the decision but not necessarily execute a response) should be somewhat longer in the extended search task, because the initial processing time is spent in a less than optimal viewing position, and, probably, also could predict that differences between the difficulty conditions would be somewhat exaggerated. However, we found almost exactly the same pattern, which indicates that the negative impact of processing the cluster before fixating it is not too detrimental.

In conclusion, the data in this task indicate that the time spent fixating a cluster is, to a good approximation, the time actually spent processing it. Two pieces of data point in that direction. First, the differences between gap sizes for gaze duration for the target-absent clusters were virtually the same as those for response times in the single-cluster task. Second, in contrast to reading, there was virtually no spillover effect (i.e., that a word that is difficult to encode not only increases fixation time on that word, but also increases fixation time on the next word). This lack of a spillover effect is furthermore not likely due to a power problem. That is, if spillover effects in this task were comparable to those in reading (where spillover effects are about 25% of the effect on the target word), we

should have observed spillover differences of something like 70 msec between gap sizes 2 and 8. These data thus indicate that eye movements in this visual search task, in fact, reflect immediate processing difficulty and that the basic results for reading (that fixation time on a word reliably reflects the difficulty of processing a word) is not a finding unique to language processing but, instead, may generalize to a wide variety of tasks. It is an open question what the range of search tasks is for which eye movement measures are such a reliable estimate of processing time.

AUTHOR NOTE

This research was supported by Grant HD26765 from the National Institutes of Health. C.C.W. was supported as a postdoctoral fellow on Grant MH16745 while at the University of Massachusetts, Amherst. We thank Keith Rayner for his helpful comments on earlier drafts of the manuscript. Correspondence concerning the article should be addressed to C. C. Williams, Department of Psychology, Mississippi State University, P.O. Box 6161, Mississippi State, MS 39762 (e-mail: cwilliams@psychology.msstate.edu).

REFERENCES

- BERTERA, J. H., & RAYNER, K. (2000). Eye movements and the span of the effective stimulus in visual search. *Perception & Psychophysics*, **62**, 576-585.
- CAVE, K. R., & ZIMMERMAN, J. M. (1997). Flexibility in spatial attention before and after practice. *Psychological Science*, **8**, 399-403.
- DUNCAN, J., & HUMPHREYS, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, **96**, 433-458.
- FINDLAY, J. M. (1995). Visual search: Eye movements and peripheral vision. *Optometry & Vision Science*, **72**, 461-466.
- FINDLAY, J. M. (1997). Saccade target selection during visual search. *Vision Research*, **37**, 617-631.
- FINDLAY, J. M., BROWN, V., & GILCHRIST, I. D. (2001). Saccade target selection in visual search: The effect of information from the previous fixation. *Vision Research*, **41**, 87-95.
- FINDLAY, J. M., & GILCHRIST, I. D. (1998). Eye guidance and visual search. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 295-312). Oxford: Elsevier.
- FISCHER, M. H. (1999). An investigation of attention allocation during sequential eye movement tasks. *Quarterly Journal of Experimental Psychology*, **52A**, 649-677.
- GREENE, H. H., & RAYNER, K. (2001a). Eye-movement control in direction-coded visual search. *Perception*, **30**, 147-157.
- GREENE, H. H., & RAYNER, K. (2001b). Eye movements and familiarity effects in visual search. *Vision Research*, **41**, 3763-3773.
- HENDERSON, J. M., & FERREIRA, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **16**, 417-429.
- HOOGE, I. T. C., & ERKELENS, C. J. (1999). Peripheral vision and oculomotor control during visual search. *Vision Research*, **39**, 1567-1575.
- KIM, M., & CAVE, K. R. (1995). Spatial attention in visual search for features and feature conjunctions. *Psychological Science*, **6**, 376-380.
- LOSCHKY, L. C., MCCONKIE, G. W., YANG, J., & MILLER, M. E. (2005). The limits of visual resolution in natural scene viewing. *Visual Cognition*, **12**, 1057-1092.
- MCCONKIE, G. W., & RAYNER, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, **17**, 578-586.
- MORRISON, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 667-682.
- MOTTER, B. C., & BELKY, E. J. (1998). The guidance of eye movements during active visual search. *Vision Research*, **38**, 1805-1815.
- NUTHMANN, A., ENGBERT, R., & KIEGL, R. (2005). Mislocated fixations during reading and the inverted optimal viewing position effect. *Vision Research*, **45**, 2201-2217.
- POLLATSEK, A., REICHLER, E. D., & RAYNER, K. (2006). Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology*, **52**, 1-56.
- RAYNER, K. (1995). Eye movements and cognitive processes in reading, visual search, and scene perception. In J. M. Findlay, R. Walker, & R. W. Kentridge (Eds.), *Eye movement research: Mechanisms, processes and applications* (pp. 3-22). Amsterdam: North-Holland.
- RAYNER, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, **124**, 372-422.
- RAYNER, K., & BERTERA, J. H. (1979). Reading without a fovea. *Science*, **206**, 468-469.
- RAYNER, K., & FISHER, D. L. (1987). Letter processing during eye fixations in visual search. *Perception & Psychophysics*, **42**, 87-100.
- RAYNER, K., WARREN, T., JUHASZ, B. J., & LIVERSEDGE, S. P. (2004). The effect of plausibility on eye movements in reading. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **30**, 1290-1301.
- RAYNER, K., WELL, A. D., POLLATSEK, A., & BERTERA, J. H. (1982). The availability of useful information to the right of fixation during reading. *Perception & Psychophysics*, **31**, 537-550.
- REICHLER, E. D., POLLATSEK, A., FISHER, D. L., & RAYNER, K. (1998). Towards a model of eye movement control in reading. *Psychological Review*, **105**, 125-157.
- REICHLER, E. D., RAYNER, K., & POLLATSEK, A. (2003). The E-Z Reader model of eye-movement control in reading: Comparisons to other models. *Behavioral & Brain Sciences*, **26**, 445-526.
- SCHNEIDER, W., & SHIFFRIN, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, **84**, 1-66.
- SCIALFA, C. T., & JOFFE, K. M. (1998). Response times and eye movements in feature and conjunction search as a function of target eccentricity. *Perception & Psychophysics*, **60**, 1067-1082.
- SHEN, J., REINGOLD, E. M., POMPLUN, M., & WILLIAMS, D. E. (2003). Saccadic selectivity during visual search: The influence of central processing difficulty. In J. Hyönä, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 65-88). Amsterdam: Elsevier.
- STAUB, A., & RAYNER, K. (2007). Eye movements and on-line comprehension processes. In G. Gaskell (Ed.), *Oxford handbook of psycholinguistics* (pp. 327-342). Oxford: Oxford University Press.
- TREISMAN, A. M., & GELADE, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.
- WOLFE, J. M. (1998). Visual search. In H. Pashler (Ed.), *Attention* (pp. 13-73). Hove, U.K.: Psychology Press.
- WOLFE, J. M., CAVE, K. R., & FRANZEL, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 419-433.
- ZELINSKY, G. J. (1996). Using eye saccades to assess the selectivity of search movements. *Vision Research*, **36**, 2177-2187.

(Manuscript received January 5, 2006;
revision accepted for publication July 27, 2006.)