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Adrian von Mühlenen, Hermann J. Müller and Dagmar Müller

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Research Article

SIT-AND-WAIT STRATEGIES IN DYNAMIC VISUAL SEARCH

Adrian von Mühlenen, Hermann J. Müller, and Dagmar Müller
Ludwig-Maximilians-University, Munich, Germany

Abstract—*The role of memory in visual search has lately become a controversial issue. Horowitz and Wolfe (1998) observed that performance in a visual search task was little affected by whether the stimuli were static or randomly relocated every 111 ms. Because a memory-based mechanism, such as inhibition of return, would be of no use in the dynamic condition, Horowitz and Wolfe concluded that memory is likewise not involved in the static condition. However, Horowitz and Wolfe could not effectively rule out the possibility that observers adopted a different strategy in the dynamic condition than in the static condition. That is, in the dynamic condition observers may have attended to a subregion of the display and waited for the target to appear there (sit-and-wait strategy). This hypothesis is supported by experimental data showing that performance in their dynamic condition does not differ from performance in another dynamic condition in which observers are forced to adopt a sit-and-wait strategy by being presented with a limited region of the display only.*

An important question for theories of serial visual search concerns how the serial scanning mechanism avoids redirecting focal attention to already examined stimuli, thereby improving search efficiency. One possible mechanism is the operation of inhibition of return (IOR) in serial search. Klein (1988) provided strong evidence for this mechanism in an analysis of reaction times (RTs) for the detection of a luminance probe presented after the observer had performed a serial or a parallel visual search task. He reported delayed detection RTs for probe stimuli placed at distractor locations, relative to probe stimuli at empty locations, following serial, relative to parallel, search (see also Klein & MacInnes, 1999; Müller & von Mühlenen, 2000; and Takeda & Yagi, 2000). He assumed that in serial search, an inhibitory tagging mechanism marks the locations or items previously scanned, excluding them from reexamination. This mechanism involves the implicit ability to remember where focal attention has been allocated previously. That is, serial visual search is memory based.

However, recently, Horowitz and Wolfe (1998) claimed that serial visual search works without memory. In their experiments, observers had to search displays for a *T* among *L*s in two experimental conditions. In one condition, the display was static; in the other, all letters were randomly relocated every 111 ms. If search involves a memory-based mechanism that keeps track of the previously examined locations, observers would be expected to have great difficulties searching the displays in the dynamic condition—because the scanned and nonscanned items constantly change their locations. Surprisingly, the target-present search rates (i.e., the slopes of the RT × Display Size functions) in the dynamic condition were statistically indistinguishable from those in the static condition. From this finding, Horowitz and Wolfe concluded that the same processes must operate in the dynamic and static conditions and that these processes cannot rely on memory for locations.

Shore and Klein (2000) reanalyzed the complete data set of Horowitz and Wolfe (1998), including the data from the target-absent trials. Whereas in the static condition the search rates for target-present and -absent trials exhibited a 1:2 ratio (as would be expected from serial self-terminating search), in the dynamic condition the ratio was nearly 1:1. Furthermore, the base RTs (i.e., the *y*-intercepts of the RT × Display Size functions) and the rate of false alarms were greatly increased in the dynamic condition. Shore and Klein took the dissimilarities in these other performance measures to indicate that the two search conditions involved different processes, and they concluded that Horowitz and Wolfe's findings provide no grounds to argue that visual search is memory-less.

The role of memory in visual search has subsequently become a controversial issue (e.g., pro memory: Gibson, Li, Skow, Brown, & Cooke, 2000; Kristjánsson, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2000; Shore & Klein, 2000; contra memory: Horowitz & Wolfe, 2001; Woodman, Vogel, & Luck, 2001). Some of these studies (Gibson et al., 2000; Kristjánsson, 2000) also used a dynamic search condition. Even though doubts have been raised concerning Horowitz and Wolfe's (1998) proposal that the same processes operate in the static and dynamic conditions (e.g., Shore & Klein, 2000), it remains a startling finding—at least for the memory advocates—that the rather drastic relocation manipulation in the dynamic condition did not more greatly affect search performance. Does this indicate that the role of memory in visual search has been overestimated? In this article, we put forward an alternative explanation to explain the good performance in the dynamic condition, and we present data to support this account.

"SIT-AND-WAIT" STRATEGIES

We suggest that performance in the dynamic condition can be explained in terms of a sit-and-wait strategy, that is, a strategy of attending to one or several locations and waiting for the target to appear there.

Horowitz and Wolfe (1998) took measures to prevent sit-and-wait strategies in their dynamic condition. They restricted the number of possible target locations, permitting the target to appear only at a few, randomly selected locations (rather than at all locations). For example, in their Experiment 1, Horowitz and Wolfe used a four-frame sequence (i.e., the same four display frames were continuously repeated), so that the target could appear at only 4 randomly chosen stimulus locations. In their Experiment 2, stimulus locations were arranged in four concentric circles, and the target changed location but remained at the same eccentricity. Horowitz and Wolfe argued that these measures effectively thwarted a strategy of focusing attention on one location, because the likelihood of the target appearing at this location was significantly reduced. For example, with 64 possible stimulus locations (in their Experiment 1), restricting the target to only 4 locations reduced the probability of the target appearing at a selected location at least once during the course of a trial to 15% (from only 28% without restriction). However, as we show, sit-and-wait strategies can become much more efficient when focal attention is allocated not to one, but to several stimulus locations.

Address correspondence to Adrian von Mühlenen, Department of Psychology, Ludwig-Maximilians-University Munich, Leopoldstrasse 13, 80802 Munich, Germany; e-mail: vonmuehlenen@psy.uni-muenchen.de.

Extended Sit-and-Wait Account

An extended sit-and-wait account assumes that the attentional focus can be flexibly expanded from one to several stimulus locations (*focus-expansion account*; e.g., Eriksen & St. James, 1986). Increasing the size of the focus would considerably increase the probability *P* that the target appears at least once inside it. For example, in the dynamic condition with 64 locations (and 21 frames), expanding the focus from 1 to 4, 9, or 16 locations would increase *P* from 28 to 74, 96, or 99.8%, respectively. And even with the 4-location restriction, focus expansion would increase *P* from 15 to 30, 52, or 72%, respectively.

A further extension assumes that, rather than being maintained at the same area throughout a trial, attention may pause at a given area only for a brief time before being shifted to another area (*focus-shifting account*). This would provide an effective means to circumvent Horowitz and Wolfe's (1998, Experiment 1) sit-and-wait prevention with 4 target locations. Because *P* drops to zero if no target has appeared within the focus after four frames, the best strategy would be to shift the focus to new locations every four frames until either the target is detected or the last frame (or some threshold for search termination) is reached. For example, under the conditions of Horowitz and Wolfe's Experiment 1, shifting the attentional focus every four frames to new locations (that do not overlap with the old locations) would increase *P* from 15, 30, 52, or 72% without focus shifting to 33, 81, 98, or 100% with focus shifting (for focus sizes of 1, 4, 9, or 16 locations, respectively). Note that an empirical hit rate of 80% is not unrealistic, as it means that the target will be detected, on average, in the 11th display frame or after 1,300 ms; in the remaining 20% of the trials, on which a target is present but does not appear within the focus, observers might respond that the target is absent or might guess, as is suggested by the relatively high miss and false alarm rates in Horowitz and Wolfe's data.

With Horowitz and Wolfe's (1998, Experiment 2) other sit-and-wait prevention measure using a constant target eccentricity, the optimum waiting duration before shifting the attention focus would increase linearly with the number of potential target locations. That is, with more target locations, it would take more time or frames to ascertain whether or not the currently focused locations encompass a possible target location. Consequently, one would expect fewer focus shifts with this second sit-and-wait prevention.

Plausibility of the Sit-and-Wait Extensions

In the display conditions we have described, on average, only an eighth to a fourth of the display matrix locations are occupied by stimuli (Horowitz & Wolfe, 1998, Experiment 1). There are no grounds to assume that observers have to restrict focal attention to one single location at a time. Rather, it seems reasonable that the focus can be expanded to encompass several locations—for example, to contain, on average, one stimulus (e.g., the focus would encompass four to eight locations). Another factor likely to determine the adjustment of the focus size is target-distractor discriminability: It is plausible to assume that the focus size can be expanded when target discrimination becomes easier (e.g., Lavie, 1995). Thus, for each task, there should be an optimal focus size, depending mainly on display density (i.e., stimuli/locations proportion) and target-distractor discriminability.

The second extension assumes that observers shift their attentional focus to a new area after sitting and waiting for a certain number of frames. It is very likely that observers would quickly discover that target detection is improved when attention is occasionally moved about (rather than sitting and waiting on the spot). Although they might not discover the optimal strategy (e.g., shifting the focus every four frames), they will nevertheless be able to perform the task satisfactorily using a nonoptimal strategy.

THE APERTURE CONDITION

We conducted the present experiment to examine the hypothesis that observers in Horowitz and Wolfe's (1998) dynamic condition used some form of the sit-and-wait strategy. To do so, we introduced a third display condition in addition to the static and dynamic conditions. This condition, which we refer to as the *aperture* condition, was the same as the dynamic condition with one exception: Observers viewed the display through an "aperture" making only a limited region of the display visible. That is, the aperture manipulation forced observers to adopt a sit-and-wait strategy. Thus, if observers adopt a sit-and-wait strategy in the dynamic condition, performance in the dynamic condition should differ little from that in the aperture condition.

According to Horowitz and Wolfe's (1998) account, performance in the aperture condition would be expected to be inferior to performance in the static and dynamic conditions, because target information can be sampled only in display frames in which the target appears within the aperture. A serial search model without memory[1] would predict that the likelihood of rapid target detection would be reduced in the aperture condition simply because the target would not be available for sampling in every frame (i.e., it would not be available in those frames in which the target lay outside the aperture). The same would hold for a parallel search model assuming that target information is accumulated over time (e.g., Ratcliff, Van Zandt, & McKoon, 1999). Little difference would be expected between the static and dynamic conditions, as target information is available in all frames.

METHOD

Observers

Twelve observers, 3 male and 9 female, took part in the experiment. Their ages ranged from 19 to 31 years. They all had normal or corrected-to-normal visual acuity and were paid 10 German marks for taking part in one 45-min session.

Apparatus

The stimuli were presented on a Dell 17-in. Trinitron monitor, controlled by a Pentium-II computer. Observers viewed the monitor from a distance of 57 cm, maintained using a chin rest. Their responses were recorded using the right and left buttons of a serial Microsoft mouse, with the track ball removed to improve timing accuracy (Segalowitz & Graves, 1990).

Stimuli

The search displays contained 8, 12, or 16 stimuli (display-size variable). The stimuli were white letters, *T* for the target and *L*s for the

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[1] In this model, display items are sampled in parallel for evidence of the target in each frame until the target summons focal attention. Distractors that happen to summon attention in earlier frames are rejected with replacement; that is, they reenter the competition for selection.

distractors, presented on a black background. The size of the letters was 1.2° of visual angle, and the thickness of the strokes 0.15°. The stimuli were randomly rotated by 0°, 90°, 180°, or 270° and randomly placed within the cells of an imaginary 8 × 8 matrix (cell size = 2.4°).

The experiment comprised three display conditions: In the *static condition*, all stimuli remained at their initial positions until a response was made or the maximum presentation time of 2,450 ms had elapsed (see Fig. 1a). This condition corresponds to the standard visual search condition.

In the *dynamic condition*, the display consisted of a sequence of up to 21 frames, each lasting 116.6 ms (see Fig. 1b). Exactly the same stimuli as in the first frame were presented in each of the subsequent frames; however, they were placed at different, randomly chosen positions. This sequence of frames was presented until a response was made or the end of the 21st frame had been reached. If a target was present, its position in the first frame was chosen at random (with equal probability for all cells). However, in the subsequent frames, it was restricted to positions of the same eccentricity; that is, its distance from the matrix center was held constant at one, two, three, or four cells. A very similar procedure was used by Horowitz and Wolfe (1998, Experiment 2) in order to prevent a sit-and-wait strategy.

The *aperture condition* was essentially the same as the dynamic condition, except that stimuli were visible only within a restricted area of the display (the aperture); that is, the stimuli outside the aperture were blanked out throughout the course of a trial (see Fig. 1c). The aperture had a constant size of 4 × 4 cells and was positioned at one of the four quadrants of the display matrix, chosen at random at the beginning of a trial.

Design and Procedure

There was a total of 450 experimental trials, 25 trials for each combination of target condition (present or absent), display size (8, 12, or 16 items), and display condition (static, dynamic, or aperture). The

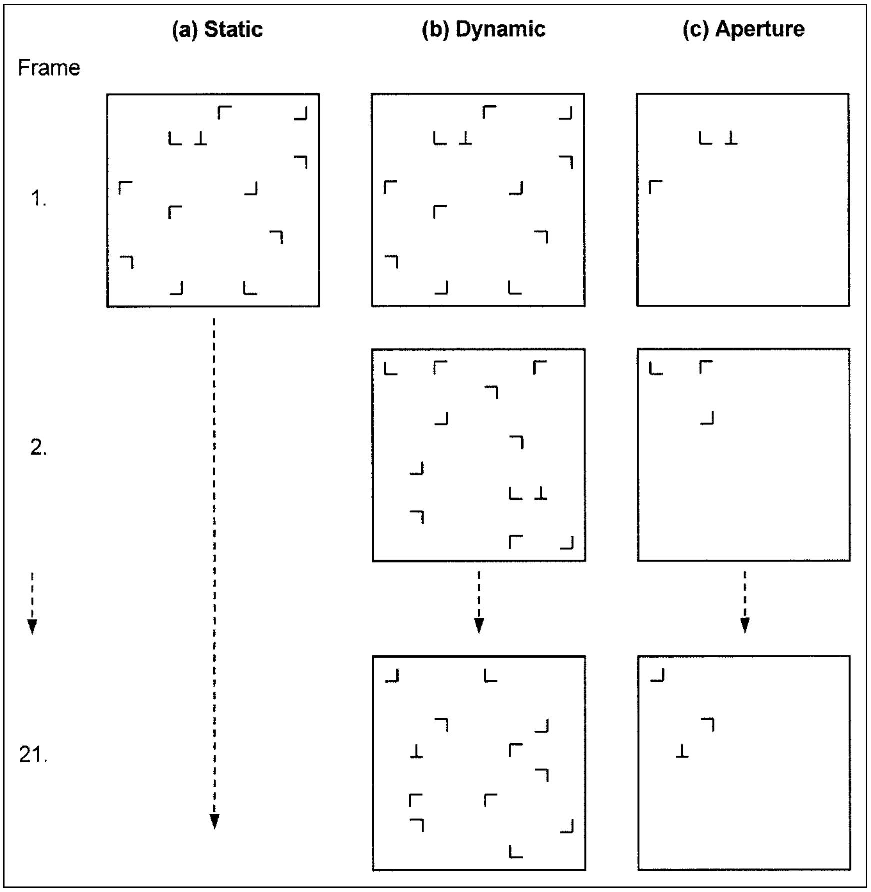

Fig. 1. Example displays illustrating the sequence of frames in the three display conditions. Stimuli were randomly rotated *T*s (target) and *L*s (distractors). In the static condition (a), the same display was shown without interruption until a response was given or the maximum duration of 2,450 ms was reached. In the dynamic condition (b), a sequence of up to 21 frames, each lasting 116.6 ms, was presented. Each frame contained exactly the same stimuli, but replotted at new positions chosen randomly for every frame. The aperture condition (c) was identical to the random condition in all but one respect—only one quadrant of the display was shown.

450 trials were divided into nine blocks. Target condition and display size were varied randomly within trial blocks, whereas display condition was kept constant throughout a block. The various display-condition blocks were presented in randomized order. At the beginning of the experiment, observers performed a block of 50 practice trials in each display condition.

Each trial started with a fixation cross presented for 500 ms, followed by a blank interval of 200 ms. The display was then presented for a maximum of 2,450 ms, unless terminated by the observer's response. Observers were instructed to indicate whether the target was present or absent as quickly and accurately as possible. Acoustic error feedback was provided after incorrect responses. The intertrial interval was 1,000 ms after a correct response and 2,000 ms after an incorrect response.

RESULTS

Figure 2 presents the mean percentage of errors (bars) and the mean correct RTs (lines) as a function of display size, separately for the target-present and -absent trials.

RT Analysis

As can be seen from Figure 2, RTs were faster in the static than in the dynamic and aperture conditions, and there was little difference between the dynamic and aperture conditions. The RT data were analyzed by a repeated measures analysis of variance (ANOVA) with main terms for display condition (static, dynamic, aperture), target condition (present, absent), and display size (8, 12, 16 items). All three main effects and all interactions involving display condition were significant, including the three-way interaction of display condition, target condition, and display size, $F(4, 44) = 12.85, p < .001$.

Two separate follow-up ANOVAs were conducted to further explore the differences among the three display conditions. The first ANOVA, with main terms for display condition (static, dynamic), target condition, and display size, compared the static and dynamic conditions. All main effects and interactions were significant. Most interesting are the effects involving display condition: RTs were faster overall in the static than in the dynamic condition (936 vs. 1,359 ms), as reflected in the significant main effect of display condition, $F(1, 11) = 27.89$, $p < .001$. Search rates, however, were overall slower in the static than in the dynamic condition (20.2 vs. 38.3 ms/item), as indicated by the significant Display Condition × Display Size interaction, $F(2, 22) = 6.18, p < .01$. This effect was due only to target-absent trials (57.4 vs. 18.4 ms/item), not target-present trials (19.1 vs. 22.3 ms/item), as shown by the significant Display Condition × Target Condition × Display Size interaction, $F(2, 22) = 10.18, p < .001$. Separate analyses of the target-present and -absent RTs confirmed this interpretation. The second ANOVA, with main terms for display condition (dynamic, aperture), target condition, and display size, compared the dynamic and aperture conditions. Only the main effects of target condition, $F(1, 11) = 32.97$, $p < .001$, and display size, $F(2, 22) = 11.95$, $p < .001$, were significant.

In summary, the separate ANOVAs confirm that performance in the dynamic condition was much closer to that in the aperture condition (mean RT difference: 14 ms), $t(11) = 0.26$, n.s., than to that in the static condition (mean RT difference: 423 ms), $t(11) = 4.81, p < .001$.

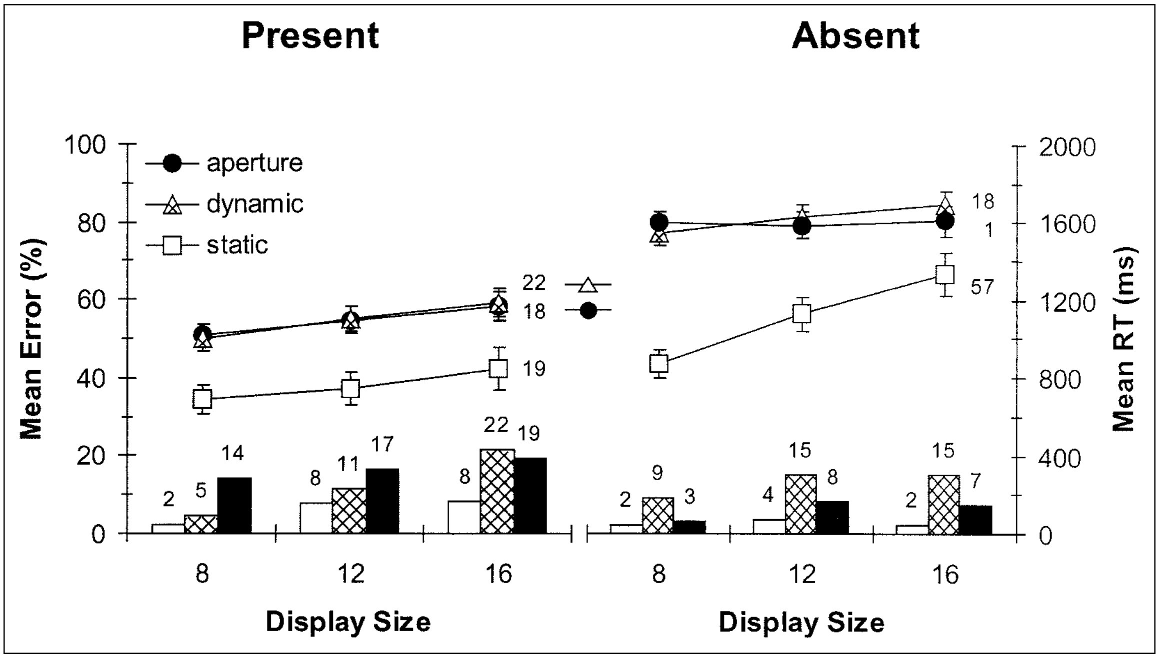

Fig. 2. Mean percentage of errors (bars) and mean correct reaction times (RTs) in milliseconds (lines), with associated standard errors, as a function of display size, separately for target-present (left) and target-absent (right) trials. The white squares and bars represent the static condition, the crosshatched triangles and bars represent the dynamic condition, and the black circles and bars represent the aperture condition. The number above each bar represents the exact error value, and the number to the right of each line gives the search rate (in milliseconds/item).

Table 1. *Mean search rates (in milliseconds/item) and percentage errors in the present experiment and in Horowitz and Wolfe's (1998) Experiment 1*

	Present experiment				Horowitz and Wolfe (1998)			
	Search rate		Errors		Search rate		Errors	
Condition	Target present	Target absent	Misses	False alarms	Target present	Target absent	Misses	False alarms
Static	19	57	6	3	19	50	8	4
Dynamic	22	18	12	13	18	24	11	15
Aperture	18	1	18	6	—	—	—	—

Error Analysis

The overall error rates were 11.8% on target-present trials (misses) and 7.4% on target-absent trials (false alarms). Miss and false alarm rates were arcsine-transformed and analyzed separately by two-way ANOVAs with main terms for display condition and display size. The miss rate ANOVA revealed significant main effects of display condition, $F(2, 22) = 7.36$, $p < .005$, and display size, $F(2, 22) = 20.26$, $p < .001$. The display-size effect was due to an overall rise in misses with increasing display size. Follow-up ANOVAs comparing pairs of display conditions revealed significantly fewer misses in the static condition (6.1%) than in the dynamic and aperture conditions (12.7% and 17.6%), $F(1, 11) = 5.22$, $p < .05$, and $F(1, 11) = 14.34$, $p < .005$, respectively; the difference between the dynamic and aperture conditions was not significant, $F(1, 11) = 2.23$, n.s. The false alarm rate ANOVA revealed only a significant main effect of condition, $F(2, 22) = 17.03$, $p < .001$. Follow-up ANOVAs comparing pairs of conditions revealed that the false alarm rate for each condition (2.8, 13.0, and 6.3% for the static, dynamic, and aperture conditions, respectively) differed significantly from the false alarm rate for the other two conditions.

Speed-Accuracy Trade-Offs

Because the ANOVAs for misses and false alarms revealed significant effects of display condition, the RT differences between conditions might be confounded by differential speed-accuracy trade-offs (i.e., faster RTs at the expense of higher error rates). However, the higher error rate in the dynamic than in the static condition reinforces the corresponding RT pattern (i.e., if errors had been about equal in these two conditions, RTs in the dynamic condition would have been even longer). In contrast, the higher error rate in the dynamic than in the aperture condition might hide an effect in the corresponding RT pattern (i.e., if errors had been about equal in these two conditions, the RTs would have been slower in the dynamic condition than in the aperture condition). This possibility cannot be entirely ruled out.[2] However, as long as performance is not worse in the aperture condition than in the dynamic condition (as predicted by Horowitz & Wolfe's, 1998, account), this does not pose a problem to our line of argument.

DISCUSSION

Dynamic Versus Static Condition

The patterns of RTs and error rates in the static and dynamic conditions are very similar to those reported by Horowitz and Wolfe (1998, Experiment 1). RTs were in a similar range, and there was little difference in search rates and errors (see Table 1). Overall, our findings represent an astonishingly close replication of Horowitz and Wolfe's results, providing no indication that our observers performed the task in a different way than their observers did.

Despite this remarkable resemblance, we do not agree with Horowitz and Wolfe's (1998) interpretation that the same search processes underlie performance in the static and dynamic conditions. Clear differences between the two conditions emerge when the full pattern of data is taken into consideration (see also Shore & Klein, 2000). These differences provide strong evidence that performance in the static and dynamic conditions is based on different search processes. Further support for this alternative interpretation comes from our third, aperture, condition.

Dynamic Versus Aperture Condition

In contrast to the clear differences between the static and dynamic conditions, no real differences were revealed between the dynamic and aperture conditions (see Fig. 2). This remarkable similarity is a strong indication that similar processes were used in these two conditions.[3] We suggest that a different strategy was used in the dynamic condition than in the static condition and that the strategy in the dynamic condition was more similar to that used (or, rather, imposed) in the aperture condition. Because only a restricted area of the display could be processed in the latter condition, any common strategy in the dynamic condition would likewise be based on the processing of only part of the display. The efficient search performance in the aperture condition indicates that there was no need to inspect all display areas for search to be successful overall, because there was a good chance for the target to appear within the externally determined (restricted) display area sooner or later. Similarly, there was a good chance for the

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[2] Even when we used Townsend and Ashby's (1983) method of dividing RT by accuracy to correct for speed-accuracy trade-offs, the resulting pattern looked much the same as the RT pattern shown in Figure 2.

[3] Of course, the similarity of results obtained with two different procedures is no guarantee that the same mental processes are responsible for these results. However, this problem is a rather general one in this debate, and it lies at the heart of the original claim made by Horowitz and Wolfe (1998).

target to eventually appear within a self-selected area of attention in the dynamic condition. Such a partial-display inspection strategy constitutes a sit-and-wait strategy, with focal attention "sitting" at a display area "waiting" for the target to appear.

Target-Absent Decisions

Such a sit-and-wait strategy could also explain the target-absent data, in particular, the shallow slope in the dynamic condition (as well as the flat slope in the aperture condition). Even though search was more difficult (i.e., overall slower) in the dynamic condition than in the static condition, the target-absent RT × Display Size function exhibited a shallow slope: 18 ms/item, as compared with 57 ms/item in the static condition. This likely reflects the fact that in the dynamic condition, in contrast to the static condition, target-absent responses cannot be based on an exhaustive serial scanning process. Rather, the search is terminated when a certain time threshold is reached and no target has been detected by that time (Chun & Wolfe, 1996). The threshold is set primarily according to the size of the attentional focus (which is determined by the target-distractor discriminability), rather than according to the display size, although it may be adjusted between trials depending on the error feedback.

Role of Eye Movements

Recording eye movements might have provided another way to examine the sit-and-wait account: Because the sit-and-wait strategy does not require active searching, this account predicts that there might be no eye movements in the dynamic condition, or at least fewer eye movements than in the static condition. However, there are several reasons why eye movement data might not have provided the ultimate answer to the question. First, strategic eye movements would in fact be expected in the dynamic condition when a sit-and-wait prevention is used, for reasons elaborated in the introduction. Second, the stimuli used in our, and Horowitz and Wolfe's (1998), experiment were relatively large and easy to discriminate even in peripheral vision, so that there might have been no need for eye movements in either condition (i.e., the movements of the eye might not reflect the movements of attention in a 1:1 manner). And third, in the dynamic condition, the continuous relocation of the stimuli might make observers suppress eye movements actively, to maximize the time available for information intake. In fact, using a sit-and-wait strategy is only one of several reasons why observers might make fewer eye movements in the dynamic condition than in the static condition.

Conclusions

We believe that the performance difference between the static and dynamic conditions can be best explained by assuming that observers adopt different search strategies in the two conditions. In the static condition, observers use a serial and memory-guided scanning process, directing focal attention to the various potential target locations (or sets of locations) until the target is found or all items are searched. In the dynamic condition (as well as the aperture condition), observers use an extended sit-and-wait strategy, directing focal attention to a whole group of locations and waiting there for the target to appear.

If sit-and-wait preventions are used in the dynamic condition, observers probably learn that performance may be improved by shifting the attentional focus from time to time to other locations. When the attentional focus is shifted, an explicit memory (e.g., for the scan path) or an implicit memory (e.g., IOR) might help, as well, to optimize performance. Whether or not this is the same memory as that used in the static condition cannot be answered on the basis of the present experiment.

At the very least, the present findings seriously call into question Horowitz and Wolfe's (1998) assumption that the dynamic condition provides an "analytical" counterpart to the static condition that indicates how search is performed with normal, static displays. Therefore, the present results cast doubt on an interpretation of Horowitz and Wolfe's findings as evidence against the view that serial visual search is memory based.

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