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What do eye movements reveal about the role of memory in visual search?

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Horowitz and Wolfe (1998, 2003) have challenged the view that serial visual search involves memory processes that keep track of already inspected locations. The present study used a search paradigm similar to Horowitz and Wolfe's (1998), comparing a standard static search condition with a dynamic condition in which display elements changed locations randomly every 111 ms. In addition to measuring search reaction times, observers' eye movements were recorded. For target-present trials, the search rates were near-identical in the two search conditions, replicating Horowitz and Wolfe's findings. However, the number of fixations and saccade amplitude were larger in the static than in the dynamic condition, whereas fixation duration and the latency of the first saccade were longer in the dynamic condition. These results indicate that an active, memory-guided search strategy was adopted in the static condition, and a passive "sit-and-wait" strategy in the dynamic condition.

Theories of serial visual search commonly assume that, while searching for a target amongst a set of distractors, it is important to know which distractors have already been inspected and rejected during the course of a trial. Retaining the locations of such elements in some sort of visual short-term, or working, memory could expedite target detection by avoiding unnecessary reinspections of already rejected distractors—that is, by biasing the scanning towards novel locations that potentially contain the target (for a recent review, see Klein & Dukewich, 2006).

However, according to Horowitz and Wolfe (1998, 2003), memory processes, such as inhibition of return (IOR; Klein, 1988; Posner & Cohen, 1984), do only play a minor, if any, role for the guidance of serial visual search. Horowitz and Wolfe's (1998) observers performed a difficult search task—search for a T amongst Ls—under a static and a dynamic search condition. In the *dynamic condition*, each trial consisted of a succession of display frames, each presented for 111 ms. The stimuli in each frame were identical; however, their locations were shuffled randomly from frame to frame. The target, if present, appeared in every frame. Horowitz and Wolfe assumed that under these circumstances the system is prevented from keeping track of already inspected distractor

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locations, because the location of a particular distractor in a given frame provided no information as to its location in any of the following frames. In contrast, in the standard *static search condition*, the locations of the search stimuli remained constant throughout a trial, permitting observers to use a memory of already inspected locations to improve target detection. With serial scanning of the stimuli, the slope of the function relating reaction time (RT) to the number of display elements (i.e., the search rate) would be expected to be twice as steep in the dynamic as in the static condition, given that elements are sampled with replacement in the dynamic (no-memory) and without replacement in the static (perfect-memory) condition. Yet, strikingly, Horowitz and Wolfe found no difference in search rates between the dynamic and static conditions. They took this to mean that there is no role for a memory system in visual search that prevents the reinspection of already-scanned locations.

In a follow-up study, Horowitz and Wolfe (2003) introduced a more difficult search task, which required scrutiny of individual search stimuli, with an extended frame duration of 445 ms in the dynamic condition. These measures were intended to take into account the possibility that the memory for already-scanned display locations may depend on overt eye movements. Again, Horowitz and Wolfe found no difference in search rates between the dynamic and static conditions, reaffirming their proposal that visual search is memory-less, whether it involves covert or overt shifts of attention.

The claim of memory-less search has stirred a great deal of interest (e.g., Kristjánsson, 2000; Shore & Klein, 2000; von Mühlenen, Müller, & Müller, 2003), since several studies had provided evidence of IOR operating in demanding serial search tasks (e.g., Klein, 1988; Müller & von Mühlenen, 2000; Snyder & Kingstone, 2000; Takeda & Yagi, 2000), in particular, tasks that require the execution of a series of eye movements (Klein & MacInnes, 1999; McCarley, Wang, Kramer, Irwin, & Peterson, 2003). To reconcile these findings with those of Horowitz and Wolfe (1998), Shore and Klein suggested that observers in Horowitz and Wolfe's paradigm employ a different search strategy in the dynamic condition from that in the static condition.[1]

Consistent with the differential-strategy argument, von Mühlenen et al. (2003) hypothesized that observers in Horowitz and Wolfe's (1998) dynamic condition may have used a *sit-and-wait strategy*. That is, observers may have kept attending to one or a few display locations, waiting for the target to appear there. Although Horowitz and Wolfe had taken measures designed to prevent observers from using such a strategy, von Mühlenen et al. argued that these were not very effective when observers at a given time deployed their focus of attention not to just one, but to several locations. To test this, von Mühlenen at al. introduced two types of dynamic search condition. In the first, observers were presented only with a fixed aperture view of 25% of the whole search display, forcing them to adopt a sit-and-wait strategy (dynamic aperture condition). In the second condition, the whole dynamic search display was visible (dynamic full-view condition). Von Mühlenen et al. reasoned that, if observers attend to only one or a few display locations in the dynamic full-view condition, performance in this condition should be similar to that in the dynamic aperture condition. This is exactly what they found: The target-present search rates were near-identical in the two conditions. Von Mühlenen et al. took this as evidence that, in the dynamic search condition of Horowitz and Wolfe, observers do indeed adopt a sit-and-wait strategy. Clearly, such a strategy makes sense only in the dynamic, but not in the

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[1] In a reanalysis of Horowitz and Wolfe's (1998) data set, Shore and Klein (2000) found fundamental differences between the static and dynamic conditions. In particular, when plotting target-absent RTs against display size, the slopes were steeper in the static than in the dynamic condition. In contrast, mean RT standard deviations and errors were overall larger in the dynamic than in the static condition. Shore and Klein concluded from this that different search strategies were at play in the two conditions. This conclusion receives further support from a recent meta-analysis of relevant studies by Klein and Dukewich (2006).

static, search task. Thus, von Mühlenen et al. concluded, it would be inappropriate to compare the dynamic with the static condition in order to argue that visual search is generally memoryless—that is, not guided by a memory of already-scanned distractor locations.

However, the observers of von Mühlenen et al. (2003) were forced to adopt a sit-and-wait strategy in the dynamic aperture condition. Thus, the mere similarity of performance in this and the dynamic full-view condition does not conclusively show that observers were indeed adopting such a strategy in the dynamic full-view condition as well (when they were free to choose one among several alternative strategies). More direct evidence for the hypothesis that observers operate a sit-and-wait strategy in the dynamic full-view search task would be provided by a differential oculomotor scanning behaviour between the dynamic and static conditions. In the static condition, observers would be expected to search through the display making a number of saccades and avoiding refixations of already-scanned locations. This would be indicative of serial shifts of visuo-spatial attention across the display and inhibitory tagging of rejected distractor locations. In contrast, if observers adopt a sit-and-wait strategy in the dynamic condition, one would expect this to be revealed in terms of a tendency for the eyes to remain fixed at one position, indicative of attentional processing of only the subset of elements appearing in the vicinity of this position.[2] To examine for such differences in strategic oculomotor behaviour, the present experiment recorded observers' eye movements while they performed the static and dynamic (full-view) search tasks.

EXPERIMENT

The purpose of the present experiment was twofold: first, with respect to search RTs, to replicate Horowitz and Wolfe's (1998) findings; and second, by examining overt gaze shifts, to provide more conclusive evidence that observers adopt an active, memory-guided strategy in the static condition and a passive sit-and-wait strategy in the dynamic search condition.[3]

With reference to eye movement behaviour, it was hypothesized that, if observers employ a sit-and-wait strategy in the dynamic condition, the number of fixations would be reduced relative to a static condition, while fixation duration and the latency of the first saccade (postsearch display onset) should be prolonged. The latency prediction was predicated on the assumption that, in the dynamic task, the central fixation point (presented prior to the search display) marks a convenient starting point for the sit-and-wait behaviour.

In the static condition, observers were expected to show an active, memory-guided scanning behaviour. To look for evidence of memory-guided scanning in the eye movement data, observers' refixations of previously inspected stimulus locations were analysed along the lines of Peterson et al. (2001). They had found such refixations to be rare overall: 5.7% of all fixations (with 2.0% being redirected to the target location), which compares with 26.1% refixations predicted by a Monte Carlo simulation of a memory-less search model. Furthermore, when they examined refixations as a function of the number of intervening fixations, the greatest proportion of refixations (3.7% of all fixations) was found for lag 2—that is,

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[2] A deliberately adopted sit-and-wait strategy would be but one of several reasons why observers may make fewer eye movements in the dynamic than in the static search condition. Another reason may be that the rapid and unpredictable changes of stimulus locations have an inhibitory effect on the oculomotor system, resulting in fewer saccades and longer saccadic latencies (Pannasch, Dornhoefer, Unema, & Velichkovsky, 2001; Reingold & Stampe, 2002). However, in effect, oculomotor inhibition may be just regarded as a variation of sit-and-wait behaviour.

[3] The aim of the experiment was to examine for differential oculomotor strategies in the two search conditions, rather than to produce further evidence of memory processes operating in visual search. There is already ample evidence for the latter (see Klein & Dukewich, 2006, and Shore & Klein, 2000, for reviews), though memory capacity estimates vary dependent on whether RT (e.g., Jiang & Wang, 2004) or oculomotor measures (e.g., Gilchrist & Harvey, 2000, 2006; Hooge & Frens, 2001; Peterson, Kramer, Wang, Irwin, & McCarley, 2001) are taken into account.

with one intervening fixation. Based on further model simulations, Peterson et al. argued that refixations occurred because the stimuli at reinspected locations had not been adequately processed. Peterson et al. concluded that there are memory mechanisms keeping track of already-inspected stimulus locations and stimuli that were insufficiently processed. A similar pattern of refixations, indicative of a memory-guided search strategy, was expected in the static condition of the present experiment.

Method

Participants

A total of 10 observers participated in the experiment (6 females; ages ranging from 20 to 32 years; all reported normal or corrected-to-normal visual acuity). All observers were naïve as to the purpose of the study and gave informed consent prior to their participation. They were paid at a rate of €8.00 per session.

Apparatus

The experiments were conducted in a dimly lit laboratory to minimize reflections on the monitor. Stimulus presentation and RT measurement was controlled by a PC (a 266-MHz Pentium II). Stimuli were presented on a 17-inch colour monitor (at a frame rate of 85 Hz), with a resolution of 1,024 × 768 pixels. Observers viewed the monitor from a distance of 60 cm, controlled by a chin rest. They responded target-present and target-absent by pressing, respectively, the left and right buttons of a response box connected via the serial port to the PC. Eye movements were recorded using an SMI Eyelink system (SR Research Ltd., Version 2.01), with 250-Hz temporal and 0.2° spatial resolution.

Stimuli

The stimuli consisted of black Ts and Ls (luminance: 0.44 cd/m^2), presented against a white background (luminance: 31.9 cd/m^2). Targets were upright Ts, and distractors Ls rotated 0°, 90°, 180°, or 270° from the vertical. Each search display consisted of 8, 12, or 16 search stimuli (the display size), which were randomly scattered across the cells of an invisible 8 × 8 matrix (matrix size: 19.8° × 19.8° of visual angle; stimulus size: 1.1° × 1.1°). The placement of the stimuli within the display matrix was slightly jittered, with the horizontal and vertical distances between adjacent stimuli varying randomly between 0° and 0.7°. The diameter of the black fixation circle, presented in the display centre at the start of a trial, was 0.9°. Error feedback was provided visually by the presentation of the word "Error" in red letters in the screen centre.

Design and procedure

The experiment consisted of 600 trials, with 50 trials for each Search Task (dynamic, static) × Target (present, absent) × Display Size (8, 12, 16 elements) condition. In the dynamic task, a trial consisted of 21 frames, with the search stimuli relocated every 116.6 ms; in the static task, a trial consisted of only a single frame. In both tasks, the maximum trial duration was 2,450 ms. In the first frame of the dynamic condition, the target was equally likely to appear at any of the 64 positions within the 8 × 8 matrix. In subsequent frames, the target was presented at the same eccentricity (i.e., the same distance from the display centre) as in the first frame to thwart the sit-and-wait strategy.[4]

At the beginning of a trial, a fixation circle was presented in the centre of the monitor. Observers were instructed to first fixate the circle and then to initiate the trial by pressing the central button of the response box. This button press was followed by a blank interval of 1,000 ms. Thereafter, the search display was presented for maximally 2,450 ms or until observers responded target present/absent (observers were instructed to respond as fast and accurately as possible).

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[4] Thus, if observers were to focus attention on only one, constant, display location, a sit-and-wait strategy would fail in approximately 72% of the trials. However, if attention is spread across a display region of, say, 4 × 4 locations (the size of the aperture used by von Mühlenen et al., 2003), then a sit-and-wait strategy would hardly ever fail (in only 0.23% of the trials).

An incorrect response was followed by presentation of the word "Error" for 1,000 ms on the screen. The intertrial interval was 1,000 ms following correct-response trials, and 2,000 ms after error trials.

The experiment was run in four sessions, separated by a break of at least 1 hour (but not more than 2 days). Two consecutive sessions were devoted to the static search condition and two to the dynamic condition, with condition order counterbalanced across the observers. Each session consisted of three blocks with 5 (unrecorded) warm-up plus 45 experimental trials. At the beginning of each of the consecutive sessions, observers practised the respective task in one block of 50 trials (data not recorded). Target-present and target-absent trials and trials with 8-, 12-, and 16-element displays were presented in randomized order.

Results and discussion

Trials on which a response error was made (7.0%) and time-out trials with RTs exceeding 2,450 ms (overall 1.2% of the trials) were eliminated prior to RT analysis. Furthermore, for each observer and experimental condition, RTs 2.5 standard deviations above or below the mean were discarded as outliers (overall, 2.7% of the trials). Following McCarley et al. (2003), eye movements were classified as saccades if their speed exceeded $35^\circ/\mathrm{s}$ and their acceleration $9{,}500^\circ/\mathrm{s}^2$. The first saccade was defined as the first eye movement landing outside the diameter of the fixation circle (0.9°). Furthermore, when observers made a manual (i.e., a target-present/absent) response during a fixation, the duration of this fixation was calculated as the time between the end of the previous saccade and the manual response. This led to a slight underestimation of the average fixation duration.

Reaction time

Figure 1 presents the group mean correct RTs, along with the error rates, as a function of display size, separately for target-present and target-absent trials. RTs were examined by a repeated measures analysis of variance (ANOVA) with three factors: search task (static, dynamic), target (present, absent), and display size (8, 12, 16 elements). The ANOVA revealed all main effects and interactions to be significant. The most interesting effects were the main effect of search task, $F(1, 9) = 5.38$, $p < .05$, $MSE = 46{,}562$, due to overall faster RTs in the static than in the dynamic condition (833 vs. 925 ms, respectively), and the Search Task × Display Size interaction, $F(2, 18) = 6.75$, $p < .01$, $MSE = 2{,}782$, due to overall slower search rates in the static than in the dynamic condition (28 vs. 17 ms/item). However, the latter effect was due only to target-absent trials (37, static, vs. 17 ms/item, dynamic), but not target-present trials (19 vs. 17 ms/item), as confirmed by the significant three-way interaction, $F(2, 18) = 4.96$, $p < .05$, $MSE = 2{,}454$. This RT pattern of results is very similar to that reported by Horowitz and Wolfe (1998) and von Mühlenen et al. (2003).

Response accuracy

Observers' individual error rates ranged between 2.4% and 14.5% on target-present trials (misses), and between 1.1% and 16.6% on target-absent trials (false alarms). The individual miss and false alarm rates were analysed separately by two ANOVAs, with the factors search task and display size. Both ANOVAs revealed a significant and a marginally significant main effect for search task, due to higher miss rates (10.3% vs. 7.0%), $F(1, 9) = 3.86$, $.10 < p > .05$, $MSE = 44$, and false-alarm rates (8.2% vs. 2.3%), $F(1, 9) = 9.74$, $p < .05$, $MSE = 53$, in the dynamic than in the static condition. Thus, the accuracy data were again very similar to those reported by Horowitz and Wolfe (1998) and von Mühlenen et al. (2003).

Comparison of eye movements between the static and dynamic search tasks

Figure 2 presents the average number of fixations as well as fixation duration as a function of display size, separately for target-present and target-absent trials. The eye movement parameters—number of fixations, saccade amplitude, fixation duration, and latency of first saccade—were examined in four separate ANOVAs, each

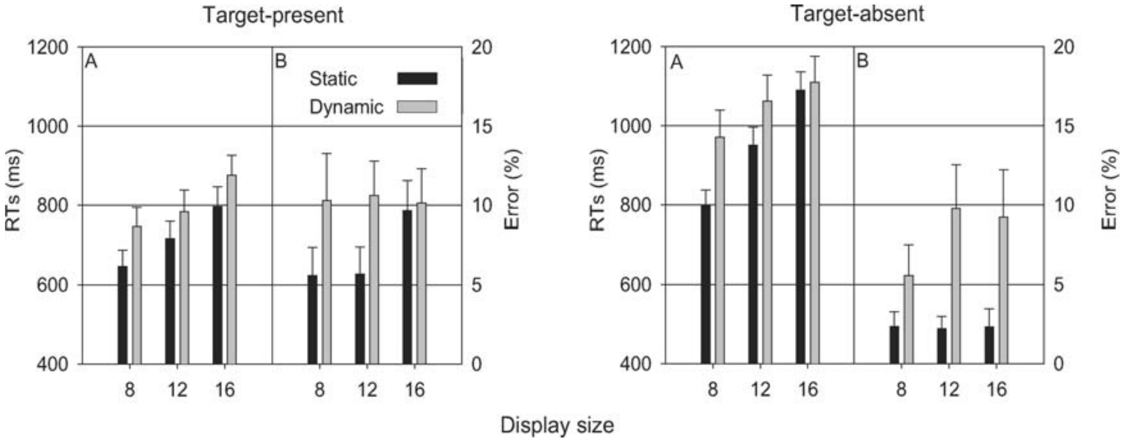

Figure 1. *Mean correct RTs (A) and mean associated percentage of errors (B) with associated standard errors, respectively, for the static (black bars) and the dynamic search task (grey bars) as a function of display size, separately for target-present (left panel) and target-absent trials (right panel).*

with factors search task, target, and display size. All four ANOVAs revealed a main effect of search task. The number of fixations was larger in the static than in the dynamic task: 2.3 versus 0.4, $F(1, 9) = 107.82$, $p < .01$, $MSE = 0.92$, as was saccade amplitude: 7.6° versus 2.7°, $F(1, 9) = 99.48$, $p < .01$, $MSE = 7.16$. In contrast, fixation duration was reduced in the static as compared to the dynamic task: 156 versus 315 ms, $F(1, 9) = 114.24$, $p < .01$, $MSE = 6{,}638$, as was the latency of the first saccade: 364 versus 780 ms, $F(1, 9) = 62.02$, $p < .01$, $MSE = 83{,}962$.

With regard to the number of fixations, more fixations were made on target-absent than on target-present trials (1.73 vs. 0.98), main effect of target: $F(1, 9) = 40.83$, $p < .01$, $MSE = 0.41$, mainly due to the static condition (2.90 vs. 1.63); dynamic condition: 0.55 versus 0.33; Search Task × Target interaction: $F(1, 9) = 79.89$, $p < .01$, $MSE = 0.11$. Also, the number

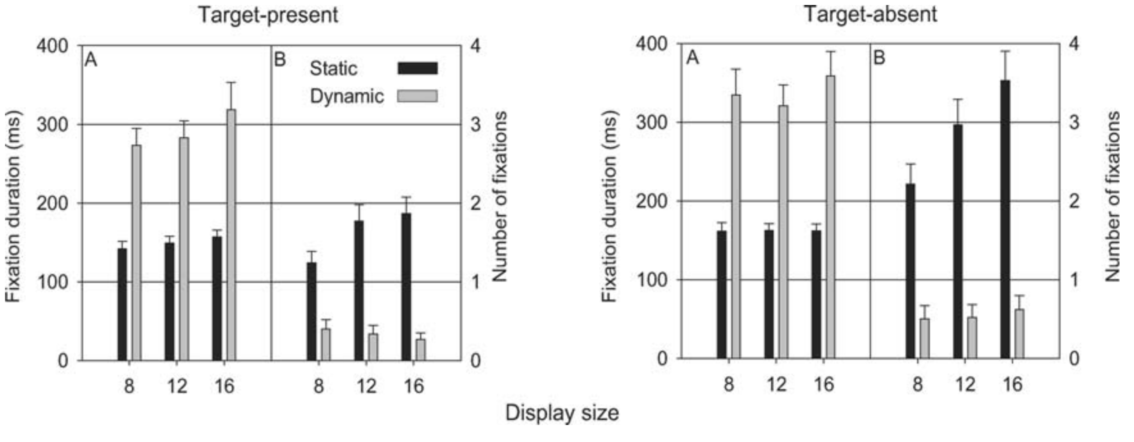

Figure 2. *Mean fixation duration (A) and mean number of fixations (B) with associated standard errors, respectively, for the static (black bars) and the dynamic search task (grey bars) as a function of display size, separately for target-present (left) and target-absent trials (right).*

of fixations increased with increasing display size: 1.09, 1.40, and 1.57 for 8-, 12-, and 16-element displays, respectively, $F(2, 18) = 28.37$, $p < .01$, $MSE = 0.08$, though again this was due to the static condition (1.73, 2.37, and 2.70), not the dynamic condition (0.45, 0.43, and 0.44); Search Task × Display Size interaction: $F(2, 18) = 29.74$, $p < .01$, $MSE = 0.08$. Finally, the three-way interaction was significant, $F(2, 18) = 5.56$, $p < .05$, $MSE = 0.02$, indicating a steeper increase in fixation number for target-absent than for target-present trials, but again only for the static condition.

With regard to saccade amplitude, there was a main effect of target, $F(1, 9) = 43.15$, $p < .01$, $MSE = 0.27$: Saccades were slightly larger on target-absent than on target-present trials (5.5° vs. 4.9°). For the latency of the first saccade, there was also a main effect of target, $F(1, 9) = 58.13$, $p < .01$, $MSE = 83{,}448$: Latencies were longer on target-absent than on target-present trials (597 vs. 544 ms). Furthermore, latencies increased with increasing display size: 544, 577, and 594 ms for 8-, 12-, and 16-element displays, respectively: main effect of display size, $F(2, 18) = 13.70$, $p < .01$, $MSE = 2{,}162$, more markedly in the dynamic than in the static condition: 721, 804, and 789 ms versus 360, 351, and 397 ms: Search Task × Display Size interaction, $F(2, 18) = 9.51$, $p < .01$, $MSE = 2{,}327$. Finally, for fixation duration, besides the main effect of search task, the main of target was significant, $F(1, 9) = 5.84$, $p < .05$, $MSE = 4{,}566$, with longer fixation durations on target-absent than on target-present trials (250 vs. 220 ms).

In summary, for each of the four parameters, a main effect of search task was obtained. In addition, the number of fixations was larger on target-absent than on target-present trials and increased as a function of display size, more markedly on target-absent than on target-present trials. However, the latter effects were evident only in the static task. In contrast, the latency of the first saccade increased more markedly as a function of display size in the dynamic task. This pattern of results is consistent with different search strategies being at play in the two conditions: a passive sit-and-wait strategy in the dynamic task and an active, serial-search strategy in the static task.

Refixations in the static search task

Evidence that the serial scanning of display elements in the static search condition was guided by a memory of already inspected locations was provided by an additional analysis of observers' refixations. As can be seen from Figure 3, which presents the proportion of refixations as a function of the number of intervening fixations (lag), refixations were rare overall: only 6.4% of the fixations. This proportion of refixations is much smaller than that predicted by a memory-less model of visual search (see Peterson et al., 2001), suggesting that observers had almost perfect memory for previously inspected stimulus locations, in particular, distractor locations (only 5.5% of all fixations were redirected to previously inspected distractors, 0.9% to a previously inspected target). In addition, the proportion of refixations was largest at lag 2 (3.7%) and decreased asymptotically as the lag increased. This pattern replicates that reported by Peterson et al. (2001). It can be interpreted as evidence for the operation of inhibitory tagging of already-inspected locations (e.g., Klein & Dukewich, 2006) in the static search condition.

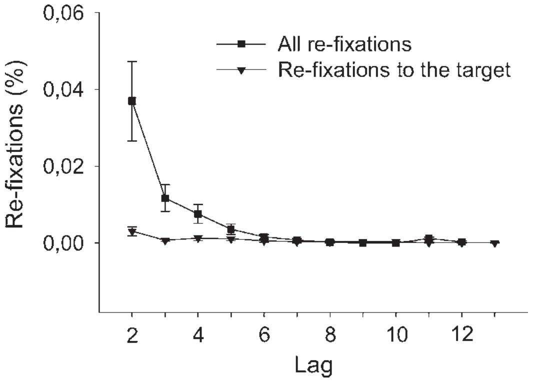

Figure 3. *Static condition: Mean proportion of refixations and associated standard errors as a function of the number of intervening fixations ("lag"; e.g., lag 2 means 1 intervening fixation; refixations with lag > 13 were included in the lag 13 condition). The upper graph (squares) represents all refixations, the lower graph (triangles) only refixations to the target.*

Sit-and-wait behaviour in the dynamic search task: Stimulus imposed or strategic?

While observers display sit-and-wait behaviour in the dynamic search task, the question arises whether this behaviour is imposed by the stimulus display or is strategic in nature. One possibility is that observers suppressed eye movements strategically, because they realized that they were missing too many targets when moving the eyes (see, e.g., Findlay, 1997; Inhoff & Radach, 1998; recall that a more successful strategy would be to attentionally monitor a fixed display region for the appearance of the target within this region). Alternatively, the sit-and-wait strategy could be due to the disruption of normal saccadic scanning behaviour by the constant and unpredictable changes in stimulus locations, resulting in fewer saccades and longer fixation duration (e.g., see Pannasch et al., 2001). If the latter is correct, the percentage of fixations in the dynamic condition should be similar across the 2 (sessions) $\times$ 3 = 6 blocks in the dynamic condition, because the same disruptive effects would be expected to be at work in all blocks. In contrast, if observers suppressed eye movements strategically, one would expect that they acquired this strategy over the course of the 6 blocks, after they realized that normal saccadic scanning behaviour is detrimental to performance. Consequently, the number of fixations should be larger in the first few blocks than in the later blocks.

It is also possible that strategic suppression of eye movements is established more rapidly during the course of a block of 50 trials (e.g., the first block), rather than slowly across blocks. That is, the sit-and-wait strategy may become evident not only in later experimental blocks (reflecting longer term learning of the active suppression of eye movements), but also on later trials within a block (reflecting short-term learning). Importantly, there would be no evidence of such effects in the static condition.

The two alternative accounts (strategic vs. stimulus-imposed suppression) would also make differential predictions with regard to performance accuracy. If observers were prevented from making eye movements by the disturbance of normal saccadic scanning, the error rates should be similar for trials within blocks and across blocks of trials. In contrast, if observers came to adopt a sit-and-wait strategy only after becoming aware of their poor performance when attempting to scan the display actively, then a higher rate of errors should be manifest in, say, the first third of trials within a block than in the later trials (i.e., short-term learning of sit-and-wait behaviour) as well as in blocks at the beginning than in those towards the end of the experiment (i.e., longer term learning).

Figure 4 presents the number of fixations, along with the rates of erroneous responses, in the dynamic search condition as a function of experimental block and trial, separately for Sessions 1 and 2. The number of fixations and the error rates were analysed in separate ANOVAs, both with the factors target (absent, present), session (1, 2), experimental block (1, 2, 3), and trials within blocks (Trials 1–15, Trials 16–50). The ANOVA for number of fixations revealed significant effects of target, $F(1, 9) = 7.16$, $p < .05$, $MSE = 0.39$, block, $F(2, 18) = 11.70$, $p < .01$, $MSE = 0.14$, and trial, $F(1, 9) = 11.30$, $p < .01$, $MSE = 0.49$. The main effect of target was due to more fixations being made on target-absent than on target-present trials (0.55 vs. 0.33). The main effect of block was examined further by LSD post hoc tests, which revealed that more fixations were made in Block 1 than in Blocks 2 and 3 (0.60 vs. 0.44 and 0.31, respectively). The main effect of trial was due to observers making more fixations in the first 15 than in the later trials within experimental blocks (0.60 vs. 0.30). Furthermore, the Block $\times$ Trial interaction was significant, $F(2, 18) = 7.78$, $p < .01$, $MSE = 0.02$, due to the difference in the number of fixations between the first 15 and the later trials being larger in Block 1 (0.80 vs. 0.41) and Block 2 (0.58 vs. 0.29) than in Block 3 (0.42 vs. 0.22)—an effect that was more pronounced in Session 1 than in Session 2: interaction Session $\times$ Block $\times$ Trial, $F(2, 18) = 6.11$, $p < .01$, $MSE = 0.04$. Finally the four-way interaction was significant, $F(2, 18) = 5.16$, $p < .05$, $MSE = 0.01$, due to a more marked decrease in the number of fixations

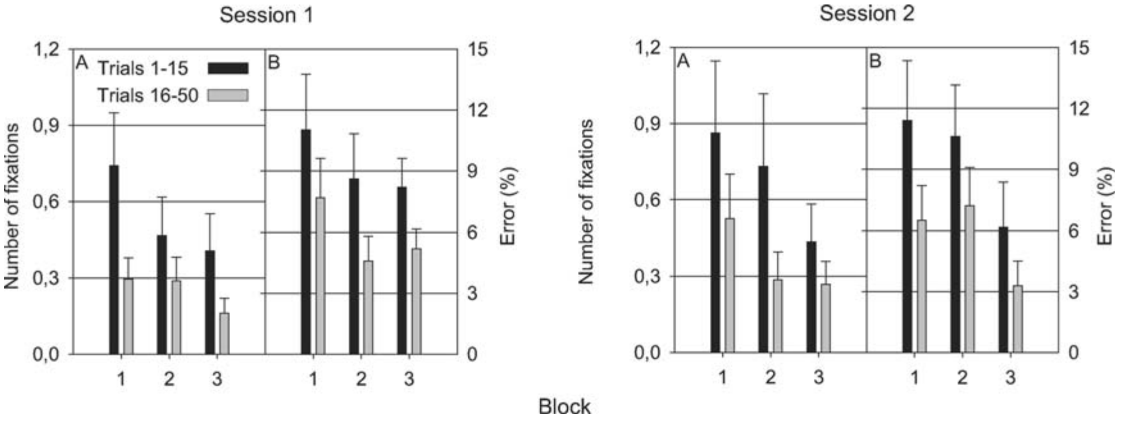

Figure 4. *Dynamic condition: Mean number of fixations (A) and mean percentage of errors (B) with associated standard errors for Trials 1–15 (black bars) and Trials 16–50 (grey bars) as a function of block, separately for the first and the second sessions (left- and right-hand panel, respectively). The data are combined across target-present and target-absent trials.*

within blocks, across blocks, and across sessions for target-present than for target-absent trials.

The ANOVA of the error rates revealed a similar pattern of results: The effects of block, $F(2, 18) = 4.30$, $p < .05$, $MSE = 55.78$, and trial, $F(1, 9) = 21.50$, $p < .01$, $MSE = 35.79$, were significant. LSD post hoc tests revealed that more errors were made in Blocks 1 and 2 than in Block 3 (9.2% and 7.8% vs. 5.7%). In addition, more errors were made in the first 15 trials than in the later trials of an experimental block (9.3% vs. 5.7%; main effect of trial). Finally, the Session × Block × Trial interaction was significant, $F(2, 18) = 4.54$, $p < .05$, $MSE = 1.41$, due to the difference in the error rates between Trials 1–15 and Trials 16–50 being largest in Block 1 of the first experimental session.

Note that, in contrast to the dynamic condition, no effects of experimental block and trials within blocks were revealed for the static condition (compare Figure 5 with Figure 4).

The pattern of effects revealed in the above ANOVAs is consistent with observers learning to (strategically) suppress eye movements in the dynamic condition. Moreover, it demonstrates that the sit-and-wait behaviour consists of (at least) two components: one that becomes established rapidly, over the first third of trials within a block, and the other taking some additional time, developing over the first trial block within a session. These two components of the acquisition of sit-and-wait behaviour are unlikely to be independent. Rather, learning takes place within a block of trials (say, trial *n*), and further learning in the next block $n + 1$ commences at a level somewhat worse than that achieved in block *n* (i.e., there is a great deal of carry-over of learning from one block to the next). (Based on Session × Block × Trial interactions revealed in the above ANOVAs, one could distinguish a third component in the acquisition of sit-and-wait behaviour: one that operates across experimental sessions, permitting the sit-and-wait strategy to be reinstated faster over the course of the first block of trials in Session 2.)

However, note that, although the number of fixations was halved over the course of three consecutive blocks within a session in the dynamic condition (first vs. third block: 0.60 vs. 0.32), the number of fixations was much less than that in the static condition, even in the first 15 trials of the first block, when observers had little opportunity to acquire a sit-and-wait strategy (dynamic vs. static condition: 0.60 vs. 2.24). [Note that an ANOVA with the factors search task (static, dynamic), block (1, 2, 3), and trial (Trials 1

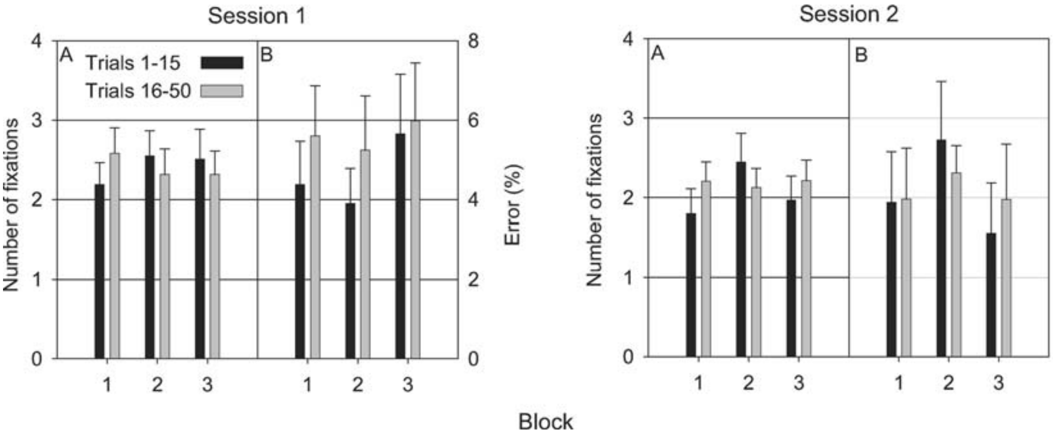

Figure 5. *Static condition: Mean number of fixations (A) and mean percentage of errors (B) with associated standard errors for Trials 1–15 (black bars) and Trials 16–50 (grey bars) as a function of block, separately for the first and second sessions (left- and right-hand panel, respectively). The data are combined across target-present and target-absent trials.*

through 15, Trials 11 through 60) revealed the two-way interaction of Search Task × Trial to be significant: $F(1, 9) = 7.88$, $p < .05$, $MSE = 0.12$; data combined across the Sessions 1 and 2.]

In summary, the concomitant reduction in the number of fixations and response errors across trials and blocks (sessions) is consistent with observers having acquired a strategy to suppress eye movements. However, the fact that the number of fixations was immediately reduced in the dynamic compared to the static condition suggests that observers were compelled to suppress eye movements due to the constant and unpredictable movement of the stimuli. Given that the first-trials difference between the static and dynamic conditions was larger than the learning effect within the dynamic condition, one may conclude that strategic effects only modulate an underlying stimulus-imposed sit-and-wait behaviour.

GENERAL DISCUSSION

The present experiment compared response and eye movement parameters between two search tasks: a static task, in which the locations of the display elements remained constant throughout a trial, and a dynamic task, in which the elements changed their locations randomly every 116.6 ms. The aims of the experiment were, first, to replicate the basic pattern of search RT effects reported by Horowitz and Wolfe (1998, 2003) and others and, second, to provide more direct eye movement evidence in favour of the idea that observers use differential strategies in the two search conditions.

On target-present trials, the slopes of the RT/display size functions were almost identical in the static and dynamic search tasks, in agreement with Horowitz and Wolfe (1998, 2003; see also Kristjánsson, 2000; and von Mühlenen et al., 2003). However, analysis of the eye movement data indicated that it would be a mistake to interpret the similarity in search rates in terms of similar strategies being employed in the two tasks. The number of fixations was six times larger, and the saccade amplitude three times larger, in the static than in the dynamic task, while the average fixation duration and the latency of the first saccade were only about half as long in the static as in the dynamic condition.

In particular, in the dynamic condition, observers made a saccade on only about every second trial; that is, essentially, they maintained fixation in the centre of the display (at the location of the fixation marker presented prior to the search display). This pattern of oculomotor effects is consistent with the hypothesis, proposed by von Mühlenen et al. (2003), that observers adopt a passive, sit-and-wait-strategy when performing the dynamic search task.[5] In contrast, in the static search task, observers actively search through the elements in the display, in serial fashion: They move their eyes from one element to another, until they either find the target or terminate the scanning after having inspected most of the elements. Importantly, the scan-paths in this task exhibit far fewer refixations of already-inspected elements than would be expected on the basis of random selection (of the next element to be fixated) from amongst all elements, consistent with the scanning being guided by visual working memory of already-scanned locations.

Interestingly, in the dynamic condition, both the number of fixations and the error rates decreased from Trials 1–15 of an experimental block to Trials 16–50 as well as from Block 1 to Blocks 2 and 3. This indicates that observers started out to search for the target more actively by moving their eyes in the dynamic condition, but then gradually came to suppress eye movements, perhaps because they realized that they could improve their response accuracy by keeping their eyes still. That is, the sit-and-wait strategy results, at least in part, from the strategic avoidance of eye movements.

Surprisingly, the changes in fixation number and response accuracy within and across blocks were generally similar in the two sessions (though there was progressive learning across trial blocks within sessions, and there was faster learning in the first trial block of Session 2 than in the first block of Session 1). That is, observers did not simply carry over the suppression strategy from one block to the next and from the first to the second session; rather, observers took time to reinstate avoidance of eye movements in each new block and session. It is likely that observers quickly reestablished their normal scanning behaviour during the short breaks between the three blocks and the long break between the two sessions, so that they had to reinstate an active eye movement suppression strategy in each block and session. Alternatively, the sudden changes of item locations in the dynamic condition may have prevented observers from developing a longer lasting sit-and-wait-strategy that could be maintained across blocks and sessions. Nevertheless, given that the number of fixations was markedly reduced already in the first third of the trials in the dynamic condition, compared to the static condition, it is likely that strategic adjustments only modulate stimulus-imposed effects that are detrimental to normal oculomotor scanning behaviour (Pannasch et al., 2001).

For comparing static and dynamic conditions in terms of oculomotor strategies, it would have been potentially interesting to include a dynamic condition in which the frame duration was longer, say, 300–400 ms, as the minimum time to make voluntary shifts of attention within dynamic displays is of the order of 300 ms (Horowitz & Wolfe, 2000; Reeves & Sperling, 1986). Longer frame durations might have decreased automatic (i.e., stimulus-dependent) effects on oculomotor behaviour, while providing a longer period for information accrual, so that observers' eye movement behaviour might have been more similar to those in the normal, static condition. However, although this is likely to be true (with the static condition representing one extreme with

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[5] The robust effects of display size on RTs may be taken to suggest that some kind of serial search process was at play even in the dynamic condition. However, these effects are better explained in terms of a sit-and-wait strategy when taking into account the differences in the number of fixations and fixation duration between the dynamic and static tasks. In the dynamic condition, while the number of fixations on target-absent trials was near-equivalent with 8-, 12-, and 16-element displays (0.51, 0.52, and 0.62, respectively), fixation duration increased as a function of display size (335, 321, and 359 ms). This pattern was reversed in the static condition, with the number of fixations increasing across display size (2.21, 2.97, and 3.53 for 8-, 12-, and 16-element displays, respectively) and fixation duration being equivalent in the three display size conditions (162, 163, and 162 ms).

unlimited frame duration), a key finding of the present study was that strategic avoidance of eye movements was manifest even when the frame duration was only 117 ms, over and above any stimulus-driven effects suppressing normal oculomotor behaviour.

In summary, there are fundamental differences in oculomotor scanning behaviour between the static and dynamic search tasks. Thus, caution is advised in attempting to compare the dynamic against the static condition in order to infer that search in the latter condition task proceeds in a memory-less fashion. More generally, the present findings demonstrate that RT and eye movement measures can lead to very different conclusions regarding the operation of memory in visual search.

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