Memory across trials in visual search

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In two experiments we evaluated whether memory for item locations across trials can improve visual search performance. Measuring both response times and eye movements we examined how visual search performance is influenced by a progressive change in item locations across successive search trials. The positions of items in the search displays were slightly shifted across successive displays and the degree of shift (trial-to-trial stability) was varied across participants. In addition, at the beginning of a trial we either presented only the current target (no-preview) or current and the next target (preview). This allowed us to evaluate performance under preview and under load, as participants on some trials held a future target in working memory. We found that search performance improved with increased stability. In addition, we demonstrate direct links between the accuracy with which an item is observed on one trial and the facility of search for that item during later trials, implicating a strong influence of trial-to-trial memory. Finally, we found that previewing a target improved performance particularly under load. Overall, our results support a model of search in which relatively slow top-down information guides and constrains the deployment of fast perceptual processes.

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Table of Contents

List of Figures

List of Tables

1.1 Introduction

Visual search is a crucial component in a large number of human activities. That the task is accomplished so easily, and so often without appreciable thought, is remarkable given the scope and complexity of the environments we typically search in. If the process of search as a whole were driven purely by bottom-up feature extraction, it would likely take prohibitively long to locate any given object in day-to-day situations. A natural intuition might be that we leverage environmental regularities and past experience to constrain where and how we query the environment during search. However, existing research on the use and utility of memory in visual search is in conflict, with strong support both for (e.g. Chun & Jiang, 1998; Kristjánsson, 2000; Gilchrist, & Harvey, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; Korner, & Gilchrist, 2007; Peterson, Beck, & Vomela, 2007; Maljkovic and Nakayama, 1994; Maljkovic & Nakayama, 1996; McPeek, Maljkovic, Nakayama, 1999; Hillstrom, 2000; Maljkovic & Nakayama, 2000; Kumada & Humphreys, 2002; Horowitz, 1995) and against (e.g. Horowitz & Wolfe, 1998; Horowitz & Wolfe, 2003; Olivia, Wolfe, & Arsenio, 2004; Wolfe, Klampen, & Dahlen, 2000) the hypothesis that visual search is influenced by memory, with conclusions varying depending on the timescale of memory being considered.

A task-based division of these times scales has been provided by Shore and Klein (2000), who propose a three level division of the influence of memory in search. The broadest level, perceptual learning, captures the learning that occurs over the course of many trials, associated with general improvements in performance over time. Perceptual learning has been studied extensively, and this type of gradual learning has been demonstrated for a wide range of task features. A notable instance of this form of memory can be found in the contextual cueing effect, first reported by Chun and Jiang (1998). In this paradigm, participants search through a mixture of new and repeated displays, and demonstrate considerable improvements in performance for repeated displays over time – despite a lack of either conscious awareness or forced-choice recognition of any repetition. This finding has been replicated numerous times, and shown to occur with exact repetitions of displays, exact repetition with 'jitter,' and partial repetition (Chun & Jiang, 1998; Endo & Takeda, 2005; Jiang & Leung, 2005). This work demonstrates that performance improvements in search can arise due to memory for specific displays, and not simply because of more general improvements due to familiarity with the task (e.g. Sireteanu & Rettenbach, 1995).

At the other end of Shore and Klein's (2000) spectrum, there is within-trial memory, a type of memory that has received considerable attention in studies of search, particularly in recent years. There is debate surrounding the issue of whether memory at this scale can be used in visual search, in particular to prevent attention from being redeployed to previously rejected distractors. Initial progress on this issue emerged from the randomized search paradigm (Horowitz & Wolfe, 1998; Horowitz & Wolfe, 2003). In this paradigm search efficiency, measured using response time by set size slopes, is compared between a typical visual search and a dynamic search in which the positions of the items are randomly changed roughly every 100 ms. The authors reasoned that if memory for previously rejected distractors was a critical component in search, then search should be much less efficient in the dynamic condition – where previously rejected distractors could not be kept track of – than in the static condition. Finding no slope differences between these conditions, they concluded that memory for distractors does not play a role in visual search, and instead that search is amnesic, operating by moment-to-moment selection of the most probable target location based on the levels of activation of relevant feature detectors.

Subsequently, Kristjánsson (2000) performed a similar experiment to that of Horowitz and Wolfe (1998), only instead of moving every item to a new random location, items were exchanged between the same set of locations. In addition, in the control condition items were rotated on each frame, providing a better perceptual match between conditions (i.e. in both conditions the displays changed every 100ms, but in the 'static' condition location information was preserved). Unlike

Horowitz and Wolfe (1998), Krisjánsson did find a significant slope difference between conditions, providing support for a mechanism that tracks rejected locations. In a second experiment, Krisjánsson replicated the original randomized search protocol (Horowitz & Wolfe, 1998), such that items were not restricted to the same set of locations in the dynamic conditions, but also expanded the range of set sizes tested. The results showed comparable slopes and response times at low set sizes, but a marked divergence at larger set sizes, with the dynamic condition both slower and less efficient than the control condition. Attempts by Horowitz and Wolfe (2003) to replicate this pattern of results were unsuccessful (though similar trends were observed, particularly in accuracy data), but methodological differences in display generation preclude a perfect comparison. One consistent aspect of these data is a significant or nearly significant intercept difference in mean response times between static and dynamic conditions, such that response times are reliably faster in the static conditions. Similar trends, at times significant, have also been found in error rates. Given the apparent lack of slope effects, the assumption is that these intercept differences must arise from some fixed cost in the dynamic conditions, presumably incurred either prior to initiating the search process, or else following location of the target but prior to response. These hypotheses however, have not been explicitly tested.

A complimentary approach for evaluating within-trial memory is to use eye-tracking to monitor the explicit sampling strategy during search, and to compare observed rates of distractor refixation to those predicted by perfect-memory and amnesic models of search. Though differing widely in the reported degree of memory influence in search, there is overwhelming convergence that previously inspected distractors are refixated less often than would be predicted by a purely amnesic model of visual search (Gilchrist, & Harvey, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Korner, & Gilchrist, 2007; Peterson, Beck, & Vomela, 2007).

The intermediate level of memory outlined by Shore and Klein (2000), and the focus of the present work, is trial-to-trial priming, which addresses the influence of memory from one trial on the next trial. In contrast to the two extremes of perceptual learning and within-trial memory, where there is clear evidence of a role for memory, to date only limited effects of trial-to-trial memory in visual search have been demonstrated. Some early work on this question examined the search benefits obtained with single-feature repetitions across successive trials. For instance, Maljkovic and Nakayama (1994) had participants report the orientation of a target defined as a color singleton. It was found that participants responded faster when the target-distractor color-mapping that defined the singleton was preserved across successive trials. In a follow-up experiment, it was shown that saccadic latencies and accuracies were better when the color-mapping was preserved, and that this effect increased with the length of the 'run' of trials with the same color-mapping (McPeek, Maljkovic, Nakayama, 1999). The repetition effect has further been shown to decay gradually with the number of non-matching trials following a run, although this decay was not present for less salient target-defining features (Hillstrom, 2000; Maljkovic & Nakayama, 2000; Goolsby & Suzuki, 2001).

It has also been shown that search is influenced by repetition of the spatial locations of targets and distractors across trials and that this influence can be manifested in both facilitation and inhibition effects. Search can be facilitated by repeating the location of the target in sequentially nearby displays, and can be impeded by presenting the target in a location recently occupied by a distractor (Maljkovic & Nakayama, 1996) with effects lasting upwards of 30 seconds. Similar results were reported by Kumada and Humphreys (2002), who showed that response times in an orientation singleton search were slowed when the target was presented at a location previously occupied by an irrelevant color singleton distractor. It has also been shown that this type of inhibition is cumulative, such that increasing the number of successive trials having a distractor in the same location increases the response time for a target subsequently presented at that location (Horowitz, 1995).

Recently, this issue has been addressed more directly by Wolfe, Klampen, and Dahlen (2000), who introduced the repeated search paradigm, wherein participants searched through an identical display for several successive trials (ranging from five to several hundred repetitions). Comparing search slopes for repeated versus unrepeated searches, the authors found no indication that repetitive exposure to an unchanging search display improved search efficiency. The implication, that memory for previous trials is either absent entirely or else is simply not used, is counterintuitive. Not only do these results seem to go against common experience, but more critically they pose a theoretical concern regarding the perceptual learning scale of memory in search. It is difficult to reconcile the established observation of learning across many trials with the observation that there appears to be little if any integration of information across successive trials. This apparent difficulty may be resolved by noting several important features of the experiments described in Wolfe et al. (2000). First, we note that only relatively small set sizes (8 items at the most) were tested. Second, the search arrays in these experiments were constructed in such a way that search could in principle be performed with a single central fixation, though fixation was not actually constrained. These two factors suggest that the lack of trial-to-trial influence may reflect the fact that visual processing is more efficient at these scales than memory is, but leave open the possibility that trial-to-trial memory may yet play a role in larger visual fields, with more items, and where there are greater memory demands. A third point of note is that, in parallel to findings for within-trial memory, considerable main effects of response time were reported, with repeated search much faster than typical random search. Despite the absence of slope effects, it is clear that performance is improved in repeated search as compared to random search, and the source of this effect is unknown.

We have seen already, in the context of within-trial learning, that there is precedent for suggesting that effects not present at small set sizes might be present at larger set sizes (Kristjánsson, 2000), and also that effects not seen in manual response data may still be found by assessing search behaviour more directly – for instance by monitoring eye-movements (Gilchrist, & Harvey, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Korner, & Gilchrist, 2007; Peterson, Beck, & Vomela, 2007). Critically, we also see some support for trial-to-trial memory effects in studies using exclusively manual responses, and specifically evaluating trial-to-trial repetition. Olivia, Wolfe, and Arsenio (2004) investigated trial-to-trial memory using another novel paradigm – the panoramic search. In these experiments, participants observed several different viewpoints of a single 3D scene, as though viewing the scene from a stationary rotating perspective. When the view was not rotating, participants searched for various target objects, divided into three categories: 1) visible targets, which could be seen from the immediate viewpoint, 2) absent targets, which were not present anywhere within the scene, and, critically, 3) hidden targets, which were present within the scene, but not visible at the probe viewpoint. The critical contrast addressed two response conditions. In one, participants responded ‘present’ only if the target was visible, and ‘absent’ if it was either not in the scene at all, or merely hidden. The contrasting instructions required that the participant respond ‘present’ if the target occurred anywhere within the scene, regardless of whether it was visible or hidden, and ‘absent’ only if the target did not occur at all. While in the former condition, in which the task could be completed relying solely on vision, search efficiency did not improve over repeated trials, the latter condition did provide indications that memory was used. In this condition, search slopes for even visible items became nearly flat as the experiment progressed, indicating a switch to the use of memory instead of vision (or at least a much stronger bias in that direction). While this is unlikely to represent an improvement in the efficiency of the perceptual component of search, it does provide a clear indication that memory can be used in search when necessary, and suggests the possibility that when search is extended to the scale and complexity of natural environments, memory influences might become increasingly prevalent.

Our aim in this study is to further explore the subject of trial-to-trial memory in search. We make several departures from the existing literature to provide a novel perspective on the question. First, we have used a larger set size and a larger viewing area than are typical. While it has been demonstrated that visual processing is favoured over memory for small set sizes, there is reason to believe that this may not be the case for larger set sizes and larger displays (e.g. Kristjánsson, 2000), and where eye-movements are necessary to identify all of the items (e.g. Peterson, Beck, & Vomela, 2007). These conditions amplify the cost of sampling the wrong (e.g. target-absent) regions of space, and therefore should promote the use of mechanisms such as memory that might be able to inform sampling behaviour. Second, instead of examining the extremes of completely random display sequences, or completely fixed repeated display sequences, we examine a gradation of stability, providing access to a more complete sampling of the changes which might occur in search behaviour across the spectrum of stability. Third, we focus our assessment of search behaviour on eye-movement data as opposed to traditional manual-response based measures of efficiency such as RT by set size slope functions. Using eye-movement data, we provide a complementary perspective to traditional efficiency measures by directly measuring the sampling behaviour during visual search – factors which are only indirectly accessible by response times. Finally, we introduce an additional variable, target preview, which we expect to interact with any effects of trial-to-trial memory that do exist. Target preview is a manipulation wherein the participant is informed of the target identity for a given trial during the preceding trial. By providing a preview of future targets, we may bias participants to use a memory strategy where they otherwise might not have, and where this is the case, we may also examine whether and how the use of such a strategy might influence performance. In addition to its explicit role as preview, this manipulation also imposes a load on trials where the preview item is presented, as use of the preview would require participants to keep both targets (the target of current search and the previewed target for the next search display) in working memory.

This type of memory load has previously been shown to interact with visual search, increasing overall RTs and in some cases influencing search slopes (e.g. Woodman, Vogel, & Luck, 2001; Oh & Kim, 2005; Woodman & Luck, 2004). Evaluating the relation between these two conflicting roles for target previewing allows us to make more refined conclusions regarding how information on one trial might be used in subsequent trials.

We collected data from four levels of stability across two experiments. In Experiment 1, we compared a moderate level of stability to a random condition. In Experiment 2, we extended these findings, comparing a higher level of stability and a lower level of stability to a random condition. Since all aspects other than the levels of stability were exactly replicated across the two experiments, the data were analyzed together. T-tests confirmed that the two sets of data from the random conditions did not differ on any measures, and they were therefore combined to improve power. Analyses were first conducted to assess the impact of the stability manipulation on search accuracy, response times, and eye guidance measures. Next, analyses were conducted to specifically evaluate trial-to-trial and sequential effects. Finally, the competing effects of the target preview manipulation and their potential interactions with stability were assessed.

1.2 Methods

Participants. Ninety-six undergraduate students from the University of Waterloo participated in these experiments for course credit, thirty-six in the first experiment and sixty in the second. All participants reported normal or corrected-to-normal visual acuity, and normal color vision. Two participants from the first experiment and one participant from the second experiment with response times more than four standard deviations from the remaining participants were removed from the analyses, and two additional participants from the first experiment were removed due to poor eye-tracking data. The remaining subjects included 59 females and 32 males. The final dataset included 19, 15, and 20 participants in the three stability conditions, and 37 participants in the aggregated random condition.

Displays. Each trial included a target display, and a search display. Target displays consisted of two square boxes, each subtending 2.5 degrees of visual angle (d.v.a. – the angle a stimulus subtends at the viewer's eye), on a black background, one bright green and the other dark grey. The target for the immediate trial was always presented in the green box. The previewed target, when present, appeared in the grey box, and otherwise the grey box remained empty. The target letter was selected randomly for each trial, with half of the 24 letters used as possible targets. We chose to use half of the items as targets as a compromise between, on the one hand, placing high demands on the memory requirements necessary for ideal performance, and on the other hand ensuring sufficient target repetition to enable an analysis of sequential effects. Preview and no-preview target displays were randomly intermixed throughout the experiment. This effectively produced four different preview conditions, resulting from the absence or presence of previewing in two different roles. On the one hand, if the current trial's target was previewed during the *preceding* trial, this preview might provide a benefit to search on the current trial. This role conforms to the intuitive notion of the effects of preview. From the complementary perspective, when the current trial included a preview for the *upcoming* trial, this preview might act as a load on the current trial – as knowledge of the upcoming target might result not only in a small memory load for target identity, but also might explicitly disrupt search for the immediate target. The four conditions are illustrated in Figure 1.

Search displays consisted of 24 capital letters (‘M’ and ‘W’ were excluded on the basis of width), presented in light grey on a black background. Each display was segmented into a 20 by 12 grid of possible locations, with a centre-to-centre distance between adjacent cells of 1.85 d.v.a. Each item measured approximately 1.2 by 1.2 d.v.a., and the minimum distance between stimuli was 0.6 d.v.a. The assignment of individual item locations varied depending on the stability condition. In the random condition, the locations of the target and distractor items were generated randomly and independently on each trial. In the stable conditions, an initial seed trial was generated randomly and subsequent trials were produced iteratively, such that each successive display was generated on the basis of the preceding trial. Production of a trial on the basis of its predecessor consisted of translating each item by a one-, two- or three-step random walk over the grid (see Figure 2). Each step consisted of a movement to an adjacent cell on the grid (diagonals included). In multiple step conditions, it was possible for an item to return to its starting location, and therefore to appear stationary from one trial to the next. The number of drift steps in this display-production algorithm provides an intuitive metric for the level of stability, with the random condition equivalent to the limit case in the number of steps. Mean item displacements at each stability level are provided in Table 1.

Display configurations were generated offline using a command line tool written by the author in C. The experiment was created using Experiment Builder (SR Research, version 1.4.36), and run on a Dell Precision 390, with a 1.86GHz Intel Core 2 processor. The stimulus displays were presented on a 24” Dell 2407WFP monitor at a resolution of 1920 by 1200, with participants seated approximately 80 cm from the screen. In this configuration, the screen subtended 32.9 d.v.a. horizontally, and 22 d.v.a. vertically.

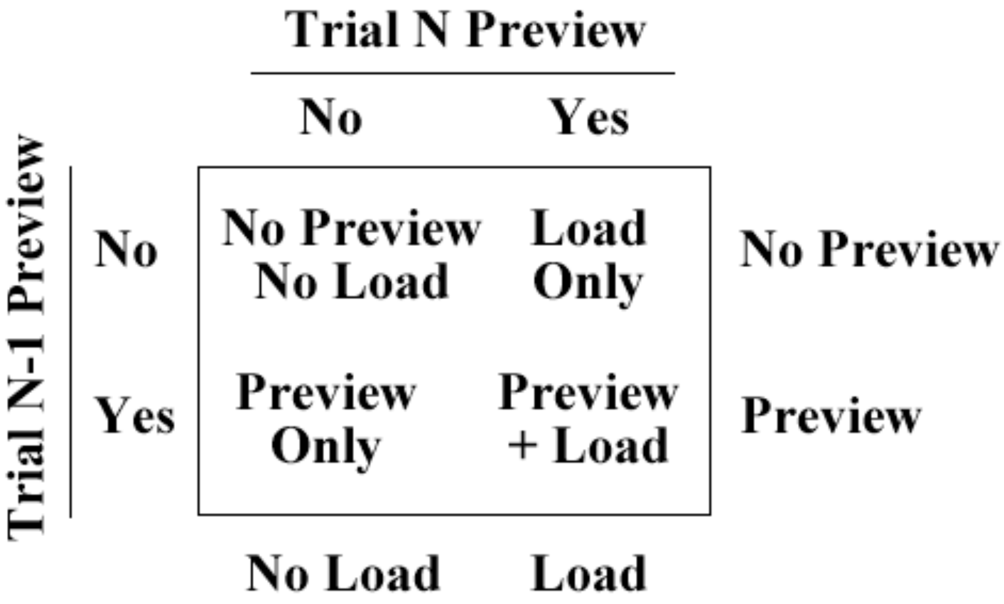

Figure 1. Trial conditions resulting from the target preview manipulation.

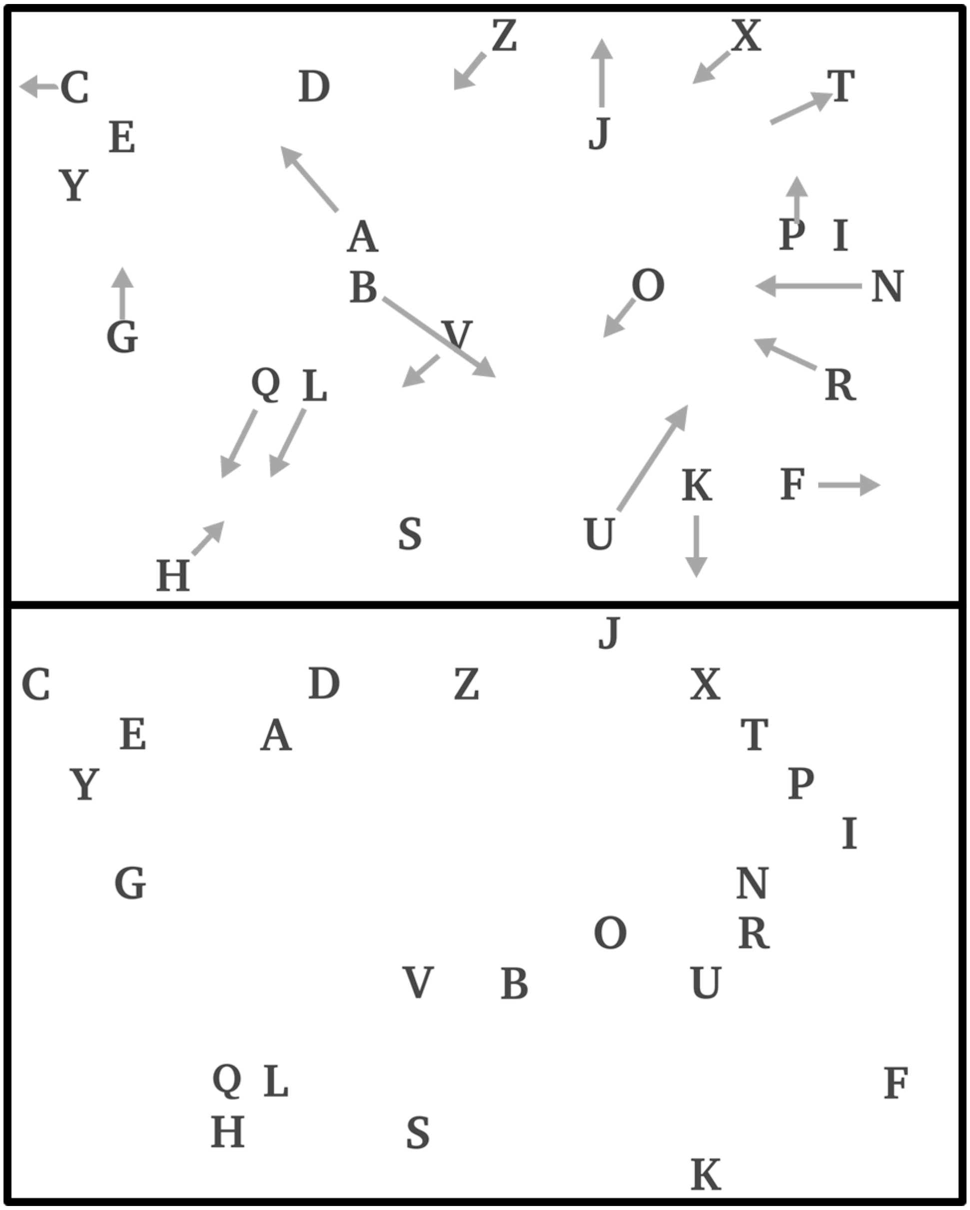

Figure 2. An example of two successive displays in the three-step stability search context. In the upper panel, light grey arrows indicate the trajectory of each item that will produce the subsequent display. Items without arrows are those that will remain in place. The lower panel shows the new locations of the items. Note that the displays are shown in reversed contrast; the actual stimuli were light grey on a black background.

Table 1. Mean trial-to-trial displacement of each item (degrees of visual angle) for each of the four stability conditions.

Condition	Mean item displacement (D.V.A.)
1 Step Drift	2.193
2 Step Drift	2.701
3 Step Drift	3.343
Random	15.702

Procedure. Each participant completed 240 search trials, the first 20 of which were designated as practice trials. A short break was given after the first 120 trials. An example trial sequence is shown in Figure 3. Each trial began with a 1200 ms target display, followed immediately by the search display. Participants were instructed to press the space bar when they had located the target letter (response time), at which point each letter in the display was replaced with an identical mask and the participant was instructed to use the mouse to indicate the location of the target letter (accuracy). The search display self-terminated if the participant did not respond within 20 seconds and participants had unlimited time to enter the location of the target in the masked display. The next trial began immediately following selection of the target location.

Each participant was assigned to either the random (low stability) or one of the stable conditions. Because we were interested in the impact of trial-to-trial memory, and not in whether participants would learn the stability over time, participants were informed as to the general characteristics of the condition to which they were assigned. Participants in the stable conditions were told: *The displays have been created in such a way that each of the items will be in a similar location from one trial to the next.* Participants in the random conditions were told: *Each display has been generated randomly, so the location of an item on one trial will have no consistent relation to its location on the next trial.*

Response time and accuracy measures were collected for the search performance. Participants' eye movements were recorded using an EyeLink 1000 (SR Research), with participants' heads stabilized by a padded chin-rest and forehead band.

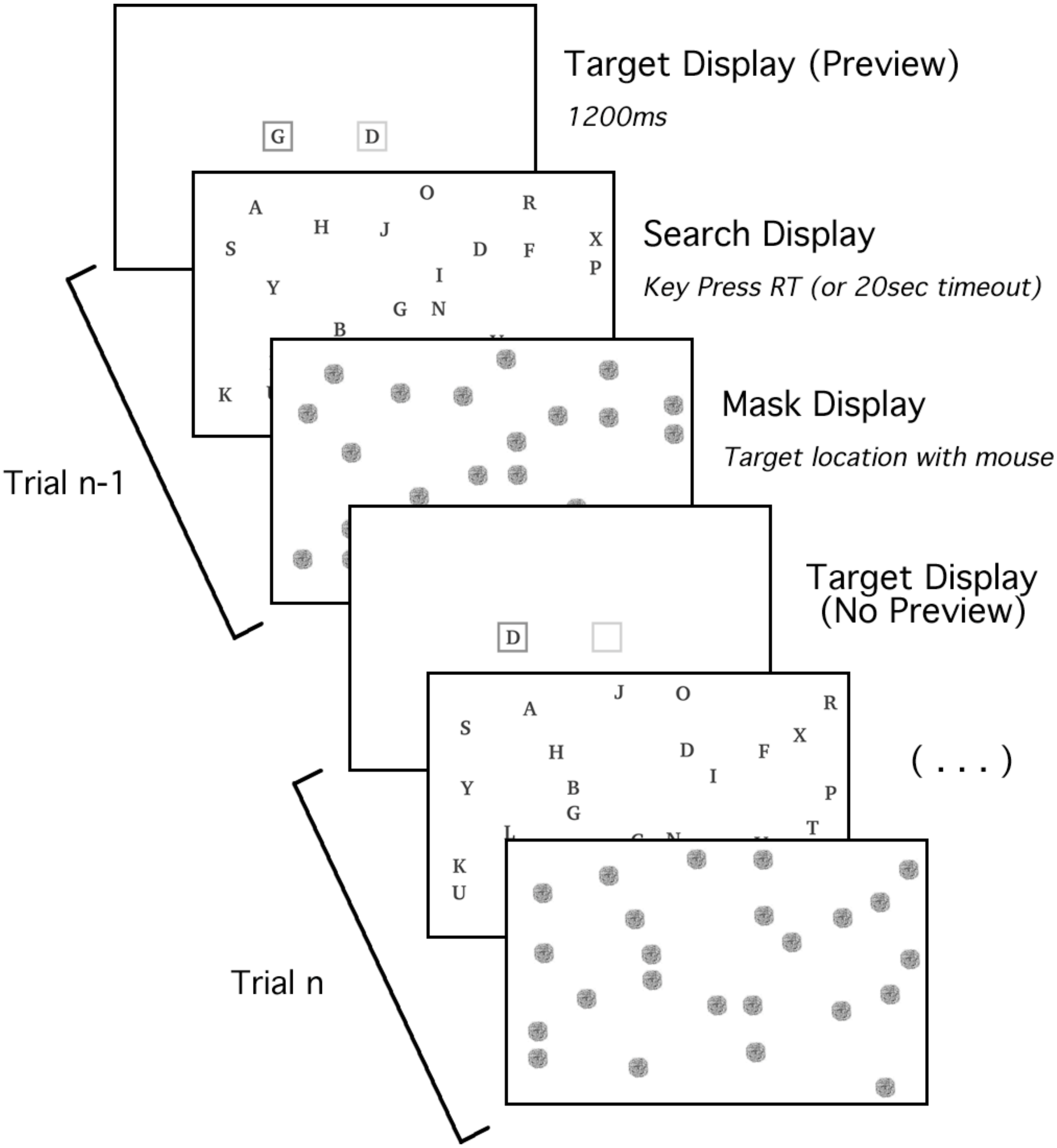

Figure 3. An example of the sequence of displays on two trials of the experiment. The displays are shown in reversed contrast.

1.3 Analysis

Outliers. With the exception of accuracy measures, trials associated with errors were excluded from all analyses. Outlier trials were then removed on the basis of manual response times (RTs), using a recursive technique: RTs more than 3 standard deviations away from the mean of the condition were removed, then statistics were recomputed. The process was repeated until no further RTs could be removed. The process was applied for each subject, split by both levels of preview (i.e. present on the prior trial and acting as preview for the current trial, or present on the current trial and acting as load on the current trial). In total, the procedure removed 3.0% of the correct RTs in experiment 1, and 2.8% of the correct RTs in experiment 2.

1.3.1 Stability Effects

We first evaluated the between-subjects factor of stability to assess the hypothesis that search performance should vary as a graded function of display stability, with increasing stability leading to increasing improvement in search performance. To test this, we ran a one-way analysis of variance (ANOVA) for each of our dependent variables (errors, RT, fixation data), evaluating in particular the linear contrast[1]. To provide a pure measure of the stability effect alone, in the absence of previewing effects, we restricted this analysis to those trials in the no preview / no load category (recall Figure 1).

Errors. We considered as errors those trials where the participant clicked more than an item's width away from the target's location. Means and standard deviations are reported in Table 2. There was no effect of Stability on errors ($F < 1$, $p > .8$), precluding the need to adjust for error rates in subsequent measures. Overall, accuracy was very high, with participants having on average error rates lower than one percent.

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[1] Strictly speaking, we hypothesize only that behavioural measures should be strictly increasing with stability, and not that this function should necessarily be rectilinear. The linear contrast is used as the simplest test of this pattern.

Table 2. Average percent error, with standard deviations in brackets, as a function of preview and load, as well as overall rates for each stability condition.

		1 Step	2 Step	3 Step	Random
No Load	No Preview	0.8% (1.5)	1.1% (1.3)	0.8% (1.0)	0.8% (1.1)
	Preview	1.2% (1.6)	0.5% (1.1)	0.5% (1.3)	1.1% (1.4)
Load	No Preview	1.1% (1.5)	1.6% (1.8)	1.3% (1.7)	1.3% (2.0)
	Preview	0.9% (1.5)	0.2% (0.7)	1.2% (1.6)	1.2% (2.0)
Overall		0.8% (1.2)	0.7% (0.8)	0.8% (1.2)	1.1% (1.2)

Response Times. In addition to assessing overall Response Times (RTs), we also used the eye-tracking data to dissociate RT into three distinct components, reflecting the time prior to initiating search, the time taken to generate a response, and the remaining time not accounted for by the other two factors, representing the search process itself. The three components were operationalized as the latency to the first saccade, the time between first fixating the target and generating a response, and the remaining time when these two components were subtracted from overall RT. The main effects observed in RTs in previous studies of trial-to-trial stability (e.g. Wolfe, Klempen, & Dahlen, 2000) may reflect a number of possible factors including time prior to initiating search and time taken to generate a response once the target has been located. By using the eye-tracking data to decompose RT, we can evaluate each of these components independently.

A one-way ANOVA was performed for each of the four RT variables: overall RT, latency to first saccade, residual search time, and time post target fixation (Figure 4). A significant effect of Stability was found for overall RT, $F(3, 87) = 6.96$, $p < .001$, and this effect was dominated by the linear term, $F(1, 87) = 19.81$, $p < .001$, without significant deviation ($F < 1$, $p > .5$). This result provides initial support for our primary hypothesis that search performance should improve with increasing trial-to-trial stability.

To further localize this effect, we considered the three components of overall RT separately. Neither first saccade latency ($F = 1.72$, $p > .15$; Figure 4, panel B), nor time post target ($F = 2.62$, $p = .056$; Figure 4, panel D) showed a significant effect of Stability in the overall ANOVA, though the latter effect was close. In contrast, the effect of Stability on residual search time (Figure 4, panel C), was highly significant, $F(3, 87) = 5.43$, $p < .005$, and again was dominated by the linear term, $F(1, 87) = 14.15$, $p < .001$, without significant deviation ($F < 1.1$, $p > .3$). This pattern of results provides a strong case that the observed improvements in overall RT are not simply a result of differences in the onset of search, or in the time taken to generate a response, but instead reflect primarily an

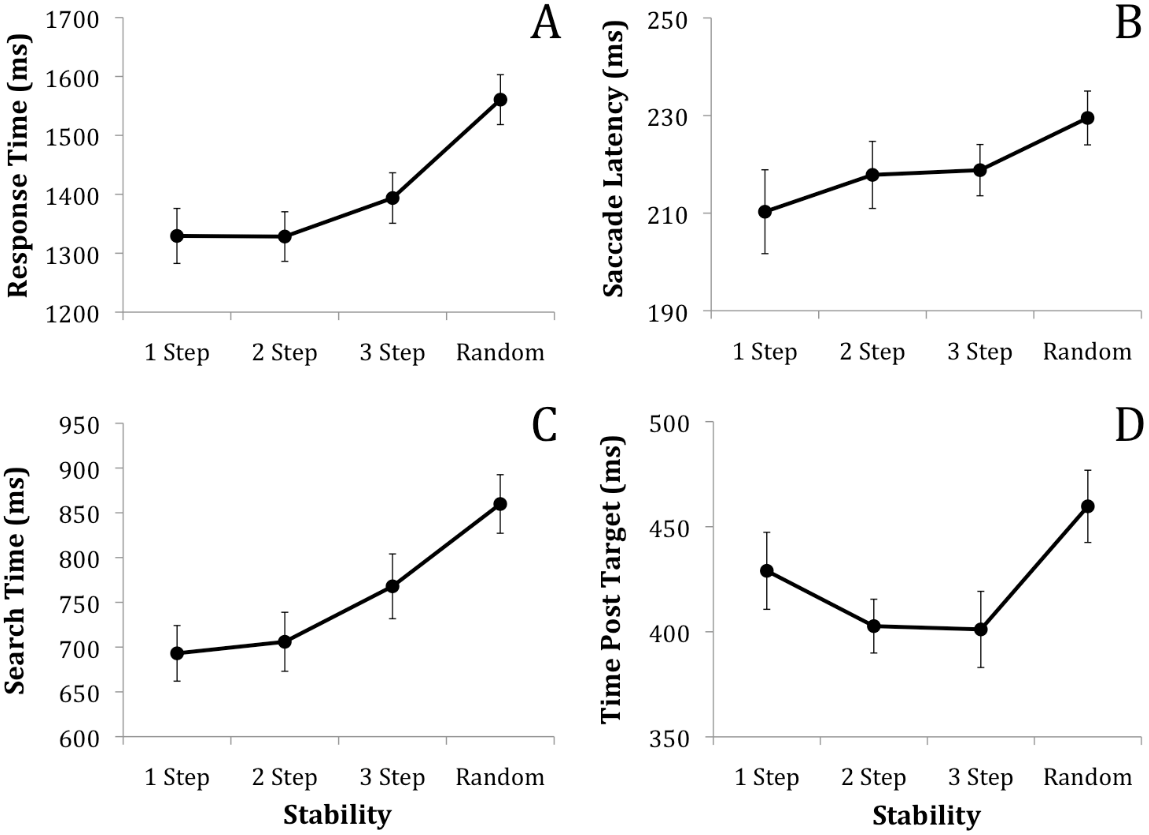

Figure 4. Response times and response time components determined using eye tracking measures. **(A)** Overall response times (ms). **(B)** First saccade latency (ms): the time between search display onset and initiation of the first saccade. **(C)** Search time (ms): the component of overall response time not accounted for by saccade latency or time after first fixation of the target. **(D)** Time post target (ms): the time between first fixation of the target and the manual response. Error bars depict one standard error of the mean.

improvement in the search process itself. As trial-to-trial stability increases, the search process becomes faster.

Guidance Effects. Our hypothesis is that stability should improve search by means of memory for a target's location during previous trials. If this is the case, we should expect that early fixation guidance during search would be improved as stability increases. To test this, we measured the accuracy of the first saccade during search, defined as the radial angle difference between the observed saccade and an ideal saccade directed perfectly to the location of the target (Figure 5). If search can be directed by memory for the locations of items in previous trials, first saccades should be more accurate in high stability conditions than in low stability conditions.

The distribution of first saccade accuracies was found to be highly non-normal, characterized by a prominent positive skew with a uniform tail. Because of this, we used the median as our measure of central tendency for this variable. Median accuracy for the first saccade is plotted across Stability in Figure 6. As with previous measures, first saccade accuracy was tested with a one-way ANOVA, revealing a significant effect of Stability, $F(3, 87) = 4.67$, $p < .005$. As expected, this effect had a strong linear component, $F(1, 87) = 7.74$, $p < .01$, though unlike previous measures the data deviated significantly from linearity $F(2, 87) = 3.13$, $p < .05$, owing to an additional quadratic component ($F(1, 87) = 6.24$, $p < .05$. Inspection of the figure suggests that the second-order term arises because of a slight flattening at the lower stability levels, but critically the data remains monotonic with Stability.

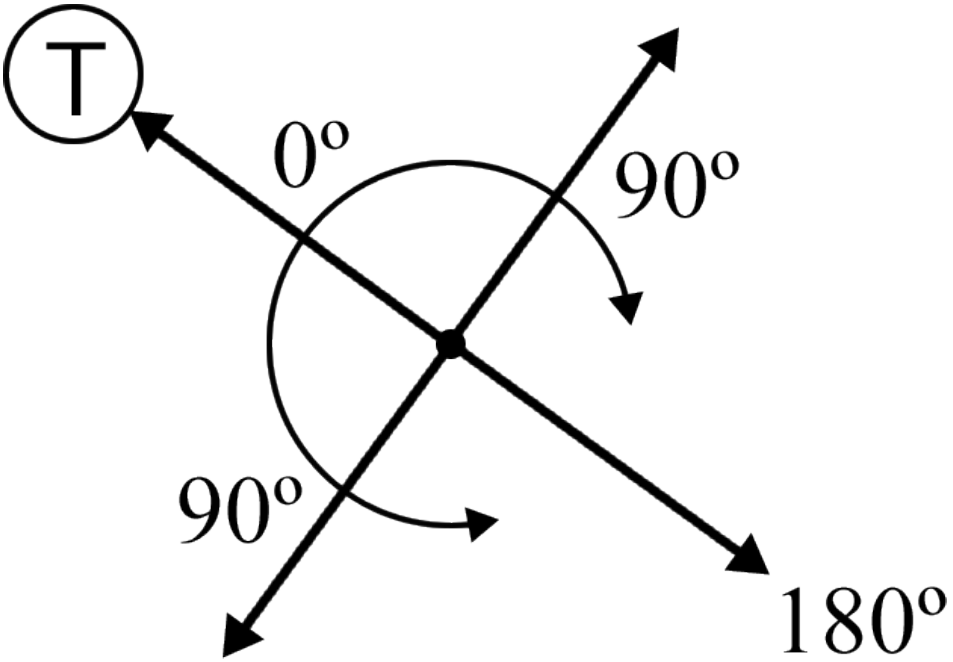

Figure 5. Definition of saccade accuracy measure. A saccade made directly towards the location of the target, shown here as the circled ‘T’, defines the ideal saccade angle. The angle of an observed saccade is compared against the ideal, and assigned a score in degrees of radial angle from the ideal. A saccade with an accuracy of 0° is one made directly to the target, and a saccade with an accuracy of 180° is one made directly away from the target.

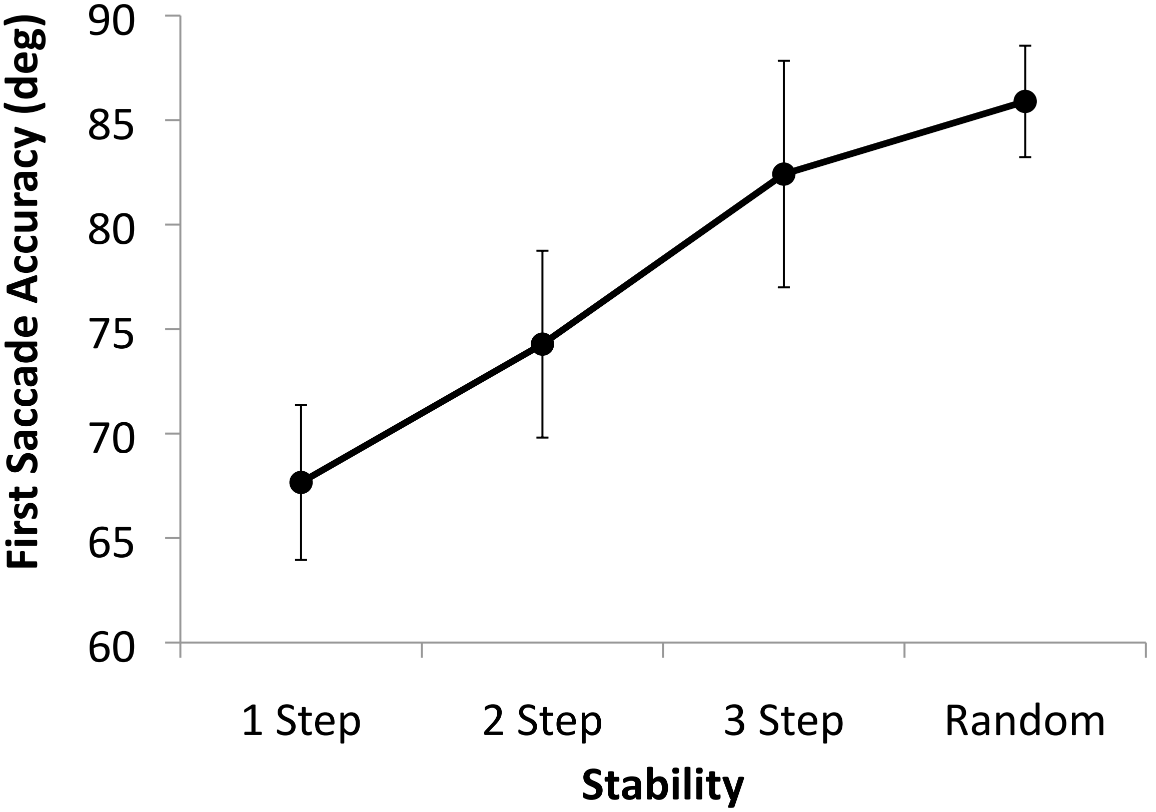

Figure 6. Median accuracy of the first saccade during search (in degrees of radial difference; see Figure 5 and text). Error bars depict one standard error of the mean.

Although these median first saccade accuracies conform to our hypothesis of graded effects of Stability, the values are nonetheless higher than we might expect – presumably due to the heavy tail in the distribution. For this reason, we conducted a more targeted analysis, by specifically evaluating the proportion of trials with very high accuracy first saccades. We reasoned that a memory-driven effect in guidance should manifest in an all-or-none fashion, such that memory for the target location results in a first saccade directly towards the target, while the absence of memory for the target results in an arbitrarily directed saccade, with equal probability across accuracy. Figure 7 shows the proportion of trials at each level of Stability for which the first saccade was less than 15° from the ideal saccade, between 15° and 30° from the ideal saccade, and between 30° and 45° from the ideal saccade. The figure clearly shows that the difference across Stability occurs only for the most accurate saccades, falling off sharply thereafter.

This pattern of data was tested by conducting a mixed-factors repeated measures ANOVA, with Stability (1 Step, 2 Step, 3 Step, Random) as a between subjects factor, and accuracy (0° – 15°, 15° – 30°, 30° – 45°) as a within subjects factor, with the proportion of trials as the dependent measure. The analysis confirmed that more trials had high-accuracy first saccades than low-accuracy saccades, $F(2, 174) = 40.53$, $MSE = .002$, $p < .001$, and that the more stable conditions had a higher proportion of trials at these accuracy levels than did the less stable condition, $F(3, 87) = 2.80$, $MSE = .002$, $p < .05$. Critically, the interaction also reached significance, reflecting the selective effect of Stability at the highest accuracy, $F(6, 174) = 2.22$, $MSE = .002$, $p < .05$. To confirm this interpretation of the interaction, a separate one-way ANOVA was conducted at each of the three accuracy levels. As expected, an effect of Stability was found only for the 0° – 15° first saccade accuracy level, $F(3, 87) = 3.82$, $p < .05$, driven by the linear component, $F(1, 87) = 7.53$, $p < .01$. Stability effects at the other accuracy levels did not approach significance ($Fs < 1.1$, $ps > .35$).

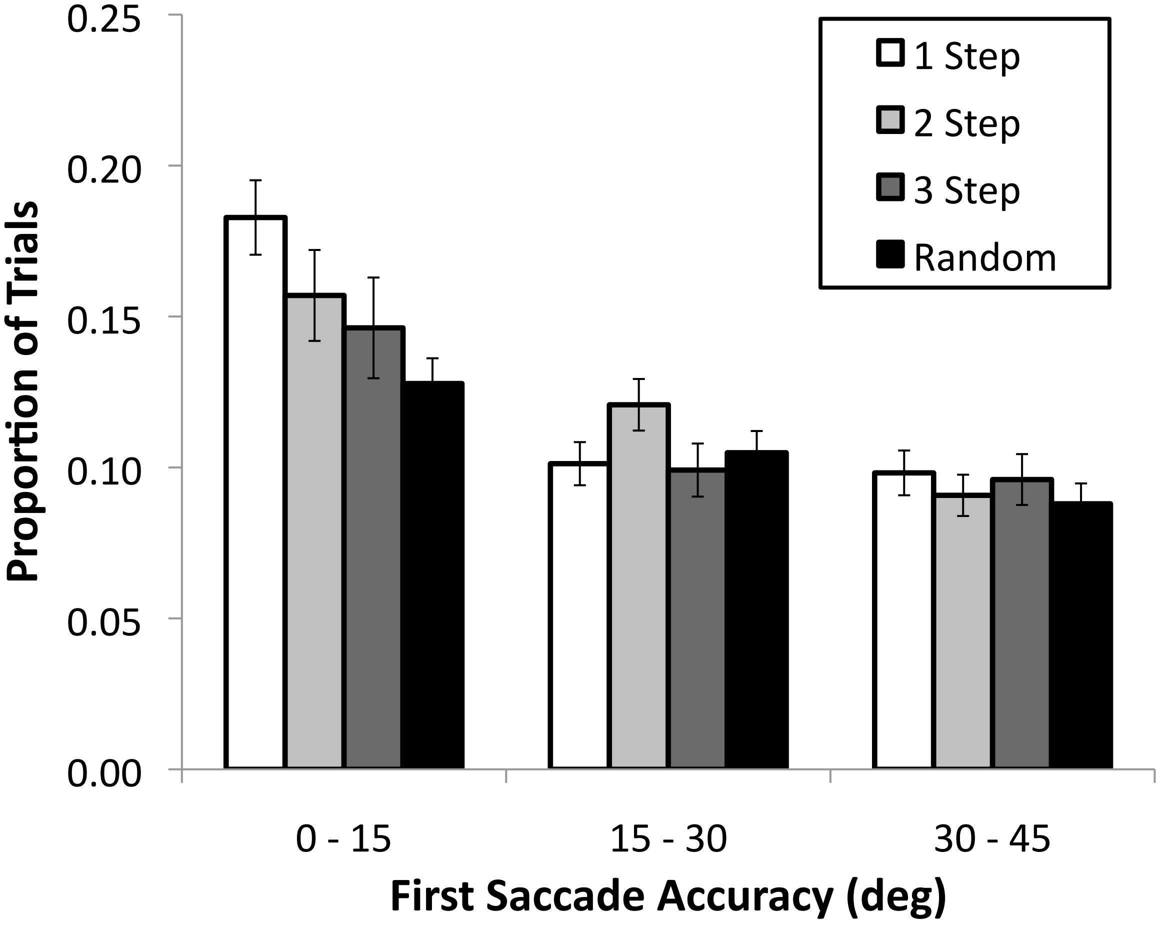

Figure 7. Proportion of trials having highly accurate first saccades. Error bars depict one standard error of the mean.

Summary. It is clear from these analyses that trial-to-trial stability in this experiment resulted in considerable improvements in search performance. Overall RTs were considerably faster with increasing stability, with no observable differences in accuracy. Additionally, by dividing the overall RT into separate components, we have demonstrated that the majority of this effect is found not in fixed effects prior to the onset of search or following fixation of the target, but rather during the process of search itself.

We were also able to directly evaluate early guidance by measuring the accuracy of the first saccade during search, again finding improvements in performance as stability increases. Furthermore, we determined that this improvement arises specifically from differences in the proportion of trials where the first saccade is made almost directly towards the target, providing a strong case that these benefits are driven by memory for the target location. Although early attentional deployment effects such as these may, in some instances, reflect perceptually-driven guidance, and not any form of memory or expectation, there are several reasons to believe that this is not the case in the present experiment. First, letter items are complex feature conjunctions, which are unlikely to be readily identified without being fixated (Rayner & Fisher, 1987). Second, arrays of unique items are featurally heterogeneous, which typically reduces efficiency (Duncan & Humphreys, 1989), precluding pop-out effects or other rapid forms of perceptually-driven target detection. Third, because targets in this experiment were also (and usually) distractors, it is difficult to argue that by chance salient features of the targets might be responsible for preferentially capturing attention. Finally, from a standpoint of parsimony, we are unaware of any simple explanation for how trial-to-trial stability in item locations would produce facilitation in bottom-up guidance, whereas it is trivial to see how memory for the location of an item might be used to guide vision back to that location, and that the benefit from this type of memory-driven effect should be a function of the degree of stability.

1.3.2 Sequential Effects

Having demonstrated improvements in both RTs and guidance measures as stability increases, we next attempt to more explicitly assess the hypothesis that these effects are driven by memory for previous trials. First, we evaluate whether performance on a given trial is impacted by how closely that trial's target was fixated during the previous trial. Second, we assess the duration and rate of decline of memory for previous trials, by examining search performance as a function of the number of trials that have elapsed since the last instance of the current target. Data from all target preview conditions were included for these analyses to improve power.

An obvious prediction from a memory-driven search hypothesis is that search performance should be best when memory for the location of the target in previous displays is most accurate. There is ample evidence that attending an object promotes memory for that object, and likewise that overt eye-movements are closely tied to attention when participants are not explicitly instructed to use a covert strategy (Findlay & Gilchrist, 2003). Consequently, we would anticipate that accurately fixating an item should improve the likelihood that that item's location could be accurately recalled on a subsequent trial. In the present context we expect that having accurately fixated a trial's target during the preceding trial (where it appeared as a distractor) should be associated with improved search performance on the current trial. To evaluate this, we determined for each trial the accuracy[2] of the fixation landing closest to that trial's target during search on the preceding trial, then binned this variable using 20% intervals, collapsing across subjects and conditions. Both first saccade accuracy

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[2] Accuracy was quantified in terms of acuity, by the following formula: acuity = $(1 + \text{eccentricity}/2.5)^{-1}$ with eccentricity measured in degrees of visual angle from the point of fixation (Findlay & Gilchrist, 2003). Acuity has a maximum value of 1 corresponding to an eccentricity of 0, and tends toward a value of 0 as eccentricity increases. This function was used in place of Euclidean distance because it more accurately reflects the non-linear decline of visual acuity with eccentricity from the fovea.

and response time were then calculated in each of these bins[3]. The results are plotted in figure 8, with first saccade accuracy in panel A, and response time in panel B.

As expected, search performance improves as a function of how accurately the current trial's target was fixated on the preceding trial, but does so only for the stable conditions, and not in the random condition. This pattern is seen in both first saccade accuracy and in response times, and was tested for each measure with a Stability (1 Step, 2 Step, 3 Step, Random) by Previous Trial Accuracy Bin (5 levels) repeated-measures ANOVA, with Stability entered as a between subjects factor. For both measures, all effects were highly significant (all Fs > 5, all ps < .005). To confirm the nature of the interaction, the repeated-measures ANOVA was repeated with only the three stable conditions (1 Step, 2 Step, 3 Step), and a separate one-way ANOVA was conducted for the Random condition. Having excluded the Random condition, the three stable conditions continued to show a significant effect of Previous Trial Accuracy, having both more accurate first saccades, F(4, 204) = 16.42, MSE = 305.4, p < .001, and faster response times, F(4, 204) = 25.62, MSE = 19,131, p < .001, as Previous Trial Accuracy increased. However, neither the main effect of Stability nor the interaction reached significance for either measure (Fs < 1.1, ps > .4). Results for the one-way ANOVA also conformed to expectations, showing that in the Random condition, neither first saccade accuracy nor response time were affected by Previous Trial Accuracy (Fs < 1, ps > .5). These results clearly indicate that having attended to the location of an upcoming target during a preceding trial facilitates guidance to that target in the subsequent trial, and that this facilitation is observed only under conditions of trial-to-trial stability, and not in the random condition.

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[3] Because bins were computed by collapsing across subjects and conditions, the number of data points contributing to each cell in the final analysis differed a small amount between subjects. These differences were small compared to the total in each cell, and were ignored.

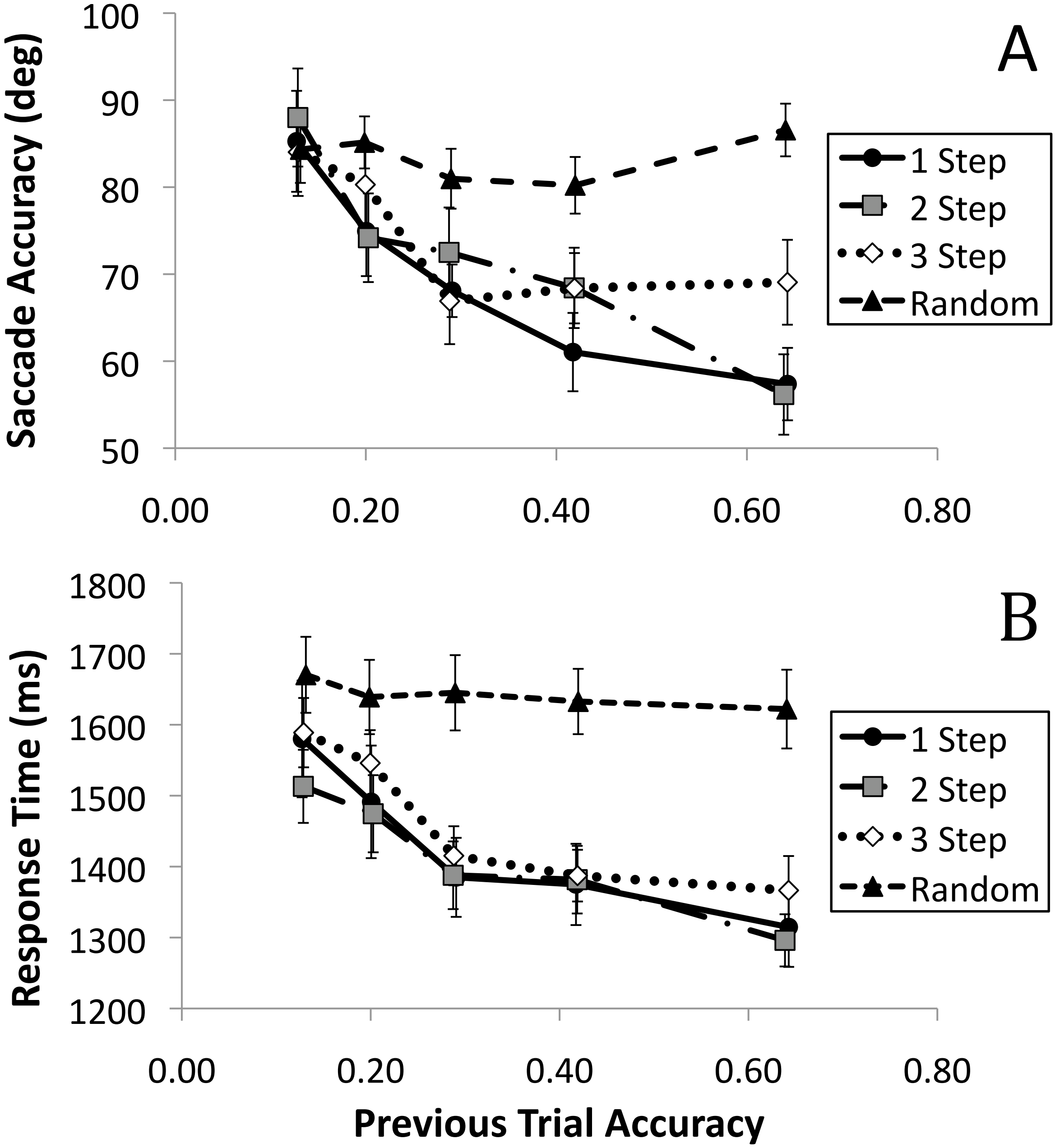

Figure 8. First saccade accuracy (degrees of radial difference) **(A)** and response time (ms) **(B)** as a function of how closely the current trial's target item was fixated while it was a distractor during the preceding trial. Previous Trial Accuracy ranges from 0.0 for the least accurate fixations, to 1.0 for the most accurate fixations (see footnote 2), and was sampled in 20% bins. Error bars depict one standard error of the mean.

Having provided a clear link between attending an item on one trial and locating it on the following trial, we next evaluate whether these effects can persist across multiple trials. To do this, we determined for each trial how many trials had intervened between that trial and the last trial having the same target. Back-to-back repetitions of the same target were excluded during the generation of target sequences, so the minimum number of intervening trials was 1, which is already a longer delay than was considered in the above associations between previous acuity and performance on the immediate trial. Because the number of trials contributing to each lag value decreased as the lag value increased, we considered only lags 1 through 5. We then calculated the mean response time at each of these lags, and compared those values to the overall means for each level of stability. The results are plotted in Figure 9. It is clear from inspection that search for a given item is facilitated when that item has recently been a target, but only when the search context is relatively stable. To test this, we performed a two-way mixed factors analysis of variance (ANOVA) for RT, with stability (1 Step, 2 Step, 3 Step, Random) as a between-subjects factor, and lag (1-5 intervening trials) as a within-subjects factor.

A significant effect of lag was found, reflecting a general increase in RT as the number of intervening trials increased, F(4, 348) = 6.75, MSE = 46,921, $p < .001$, as well as a significant effect of Stability, with stable conditions faster than the Random condition, F(3, 87) = 11.07, MSE = 283,535, $p < .001$. The interaction however, did not reach significance ($F < 1.5$, $p > .2$). Inspection of the figure suggests that the failure to detect an interaction in RTs was likely due to the fact that RT appears to have stabilized at the overall mean levels by lag 3. To confirm this, we ran two new ANOVAs for RT, comparing separately lags 1-3, and lags 3-5. Early lags showed both a significant effect of lag, F(2, 174) = 11.87, MSE = 46,704, $p < .001$, and a marginal lag by stability interaction, F(6, 174) = 2.04, MSE = 46,704, $p = .062$, while the later lags showed only a marginal effect of lag, F(2, 174) = 2.76, MSE = 48,287, $p = .066$, and no interaction ($F < 1$, $p > .9$). Both lag groups retained

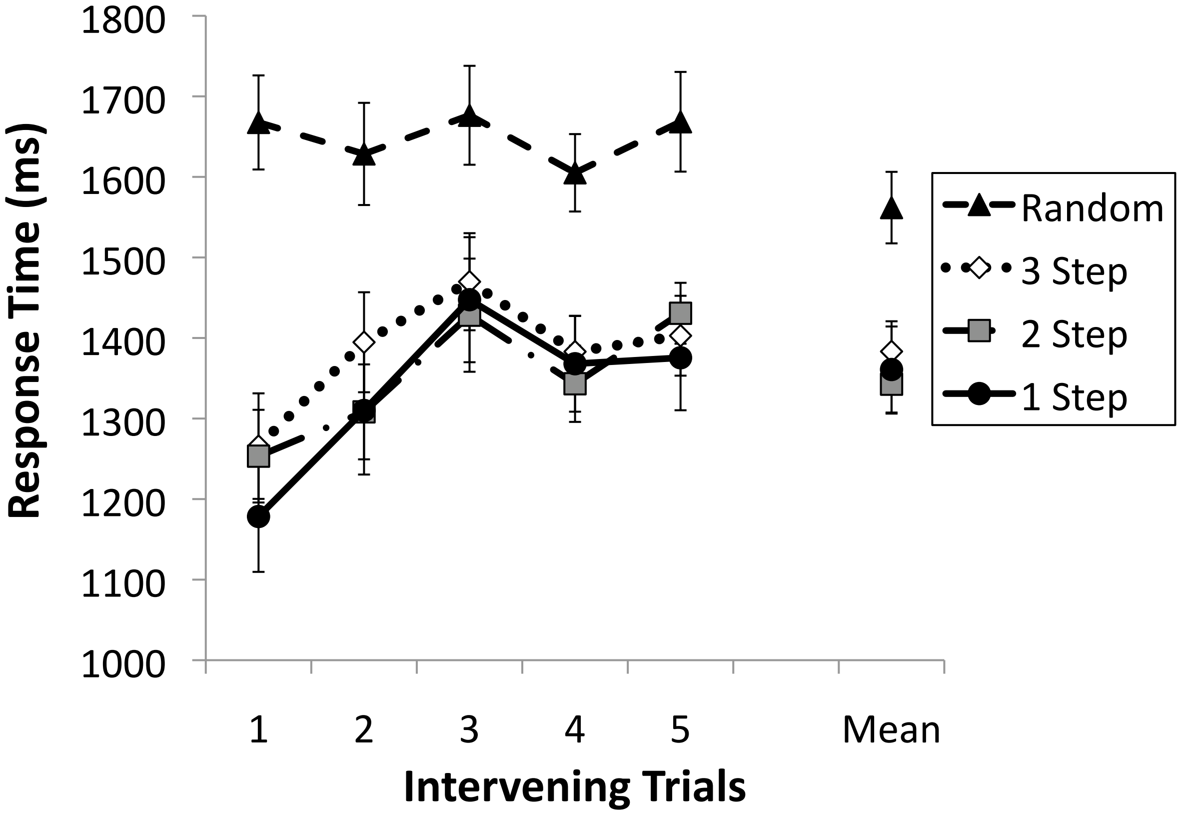

Figure 9. Response time (ms) as a function of the number of trials that have intervened since the last trial with the same target. Overall mean levels for each stability condition are also plotted for reference. Error bars depict one standard error of the mean.

a significant effect of stability (early lags: F(3, 87) = 9.97, MSE = 225,004, p < .001; late lags: F(3, 87) = 7.93, MSE = 165,414, p < .001).

We can draw two important conclusions from the results of these lag analyses. First, there is modest evidence for the conclusion that search performance is facilitated when the current target was also the target on a recent trial, and that this facilitation decays as the number of intervening trials increases. Second, our results show that this effect is relatively short-lived. By the time three trials have intervened (slightly more than 10 seconds), search for an earlier target is no longer facilitated relative to search for an arbitrary target in the same condition. This rate of decline in facilitation is likely to reflect a combination of the capacity limitations of spatial working memory, and of the growing discrepancy between the target's location on the early trial and its location on the evaluated trial. Given the evidence that spatial working memory is impaired by eye-movements during retention (e.g. Awh & Jonides, 2001), the relatively brief search facilitation seen in our experiments is perhaps not surprising. Additionally, the failure to detect differences between the non-random stability conditions on this measure suggests that the majority of the decline in facilitation results from decay of the memory, as opposed to diffusion in the physical display.

Although the lag analyses show only a memory for items when they were observed as targets, we have also demonstrated in the preceding analysis that the location of an item when it is a distractor can be remembered when it appears as a target in a successive trial. Both of these findings are difficult to reconcile with a model of search not using trial-to-trial memory.

1.3.3 Target Preview Effects

Having assessed several stability and sequential effects, we now turn to the influence of target preview. As a reminder, the experimental design we have employed enables consideration of the target preview manipulation from two perspectives: as preview, and as load (see Figure 1). For each of the primary measures, we conducted a preview by load by stability ANOVA to evaluate the effects of the target preview manipulation. Several predictions are reasonable given these manipulations.

Regarding whether a trial's target has or has not been previewed, we would expect one of two outcomes. First, it is possible that the ability to benefit from target previewing would increase with stability, as it should be easier and more reliable to use this information when successive displays are more similar. Alternatively, it is possible that only at intermediate levels of stability would target previewing have an effect. On this account, the highest levels of stability are sufficiently informative, and the effects of trial-to-trial memory sufficiently strong that target previewing can confer no additional performance benefits. Only when stability is low enough that general trial-to-trial memory alone does not reliably facilitate performance should benefits from target previewing emerge. By neither account should an effect of target previewing be observed in the random condition. In addition to the direct effects of preview, our manipulation afforded the opportunity to study how these effects might be impacted by load. Since memory loads have been shown to impair search (e.g. Woodman, Vogel, & Luck, 2001), we might expect that benefits afforded by target previewing might be magnified under load, providing relief from the additional burden.

Errors. The mean error rates for each condition are shown in Table 2. The preview by load by stability ANOVA revealed a marginal effect of preview ($F(1, 87) = 3.72$, $MSE = 1.588$, $p = .057$) and a significant preview by stability interaction ($F(3, 87) = 2.94$, $MSE = 1.588$, $p < .05$). This interaction was driven by a reduction in errors at the 2 step level of stability only ($t(14) = 3.09$, $p < .01$), with no differences at the other levels (ts < .5, ps > .6). No other effects or interactions reached significance.

Response Times. The RTs, plotted as a function of preview, load and stability, are shown in Figure 10. An ANOVA assessing the effects of preview, load and stability revealed significant main effects for all three factors. Response times increased with decreasing stability ($F(3, 87) = 5.765$, $MSE = 205{,}023$, $p < .005$), decreased with preview ($F(1, 87) = 7.241$, $MSE = 15{,}643$, $p < .01$), and increased with load ($F(1,87) = 8.772$, $MSE = 12{,}344$, $p < .005$). Additionally, a significant stability by preview interaction was observed ($F(3,87) = 2.735$, $MSE = 15{,}643$, $p < .05$), driven by the selective presence of a preview effect at the 3-step level of stability (collapsing across load: t(19) = 3.968, p < .001; all other ts < 1.4, ps > .2). There was also a non-significant trend towards a preview by load interaction (F(1,87) = 2.483, MSE = 11,534, p = .119). The nature of this interaction is readily observed in Figure 9. Selectively at the 3-step stability level, though showing a similar pattern at higher stabilities, we find no significant preview effect in the absence of load (t(19) < 1.6, p > .1), but a substantial preview benefit when there is load (t(19) = 4.260, p < .001). This pattern suggests that the primary impact of preview is to counteract the effect of load, which otherwise produces a substantial increase in mean RTs for all non-random stability conditions.

Further confirmation of this pattern was obtained by looking at the correlation between the cost of Load in the absence of Preview, with the benefit from Preview when under Load. Given the above results, we should expect that the more costly the load for a given participant, the greater the potential benefit from preview. Figure 11 shows these correlations for each level of Stability. The load effect without preview, plotted on the x-axis, was calculated as the difference between response time on trials with load but no preview and response time on trials without load and without preview. The preview effect under load, plotted on the y-axis, was calculated as the difference between response time on trials with both load and preview, and the response time on trials with load but no preview. Positive values on the x-axis indicate that response times were slower under load, in the absence of preview. Positive values on the y-axis indicate that response times were slower on trials with preview than on those without preview (when under load). Highly significant correlations were found in all three stability conditions (1 Step: r(19) = -.627, p < .005; 2 Step: r(15) = -.742, p < .005; 3 Step: r(20) = -.565), but not in the Random condition, r(37) = -.214, p > .2. This conclusion, that the benefits from Preview are directly related to the impairments from Load, suggests that whether preview items are used or ignored may be subject to strategic tradeoffs, providing a potential explanation for the selective benefit at intermediate levels.

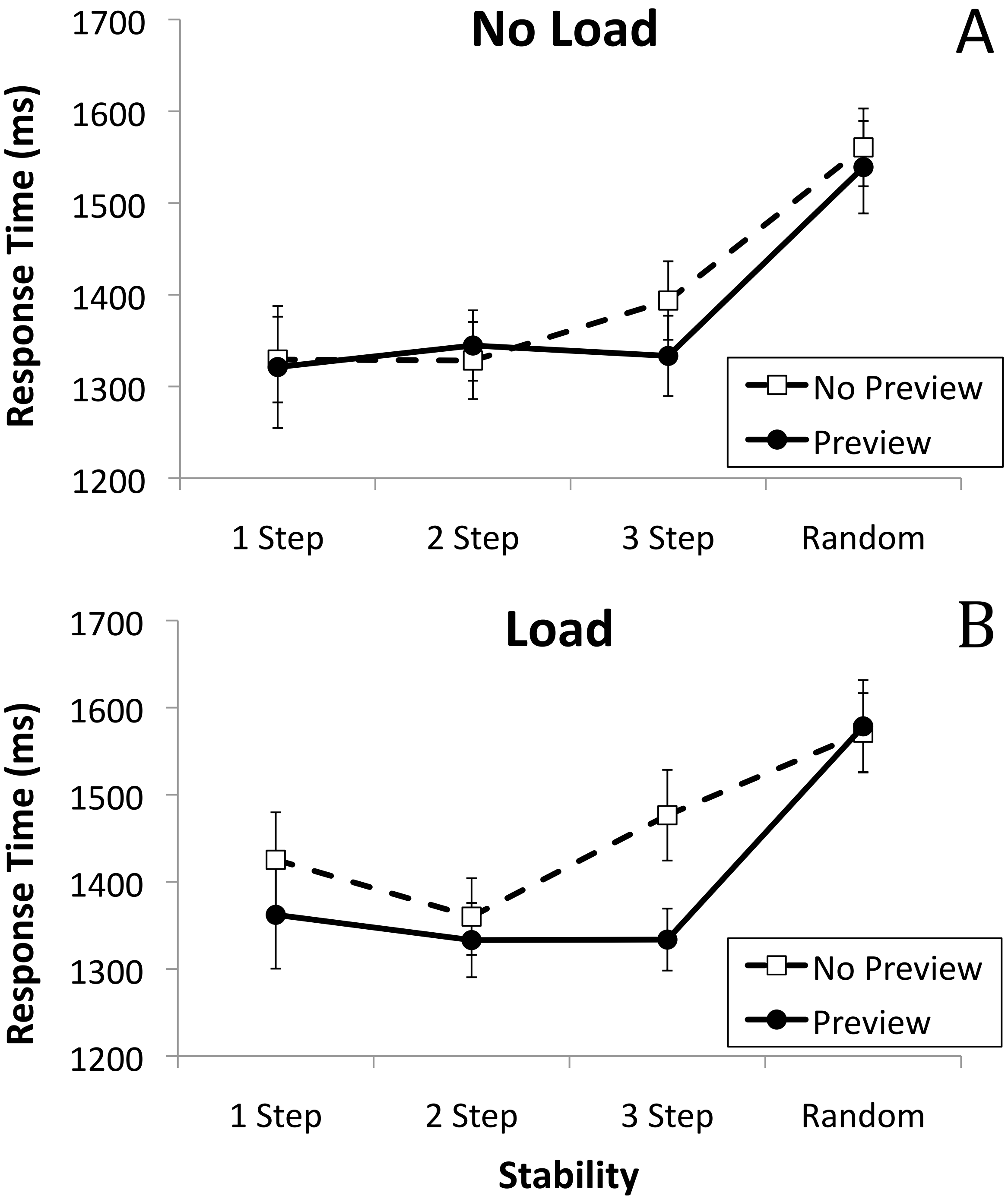

Figure 10. Response times (ms) for trials where the target was previewed or was not previewed, **(A)** without load and **(B)** with load. Error bars depict one standard error of the mean.

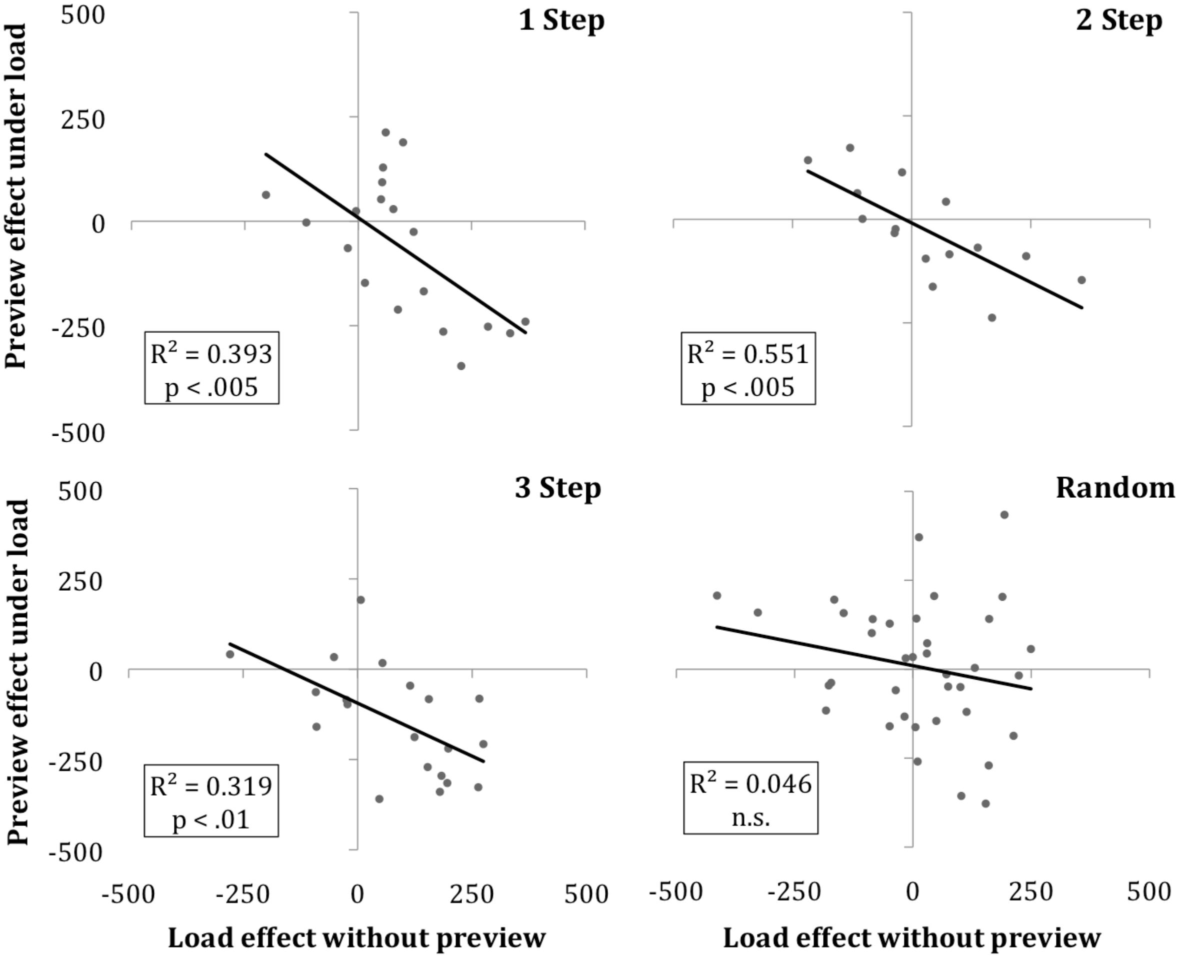

Figure 11. Scatter plots for each Stability condition, showing the correlation between Load costs and Preview benefits (see text).

Guidance Effects. Figure 12 shows the proportion of trials having high accuracy (less than 15°) first saccades during search as a function of preview, load and stability conditions. Evaluating first saccade accuracy with the preview by load by stability ANOVA revealed a significant effect of stability, F(3, 87) = 9.74, MSE = .006, p < .001, with higher stability conditions having a greater proportion of high-accuracy first saccades. In addition, there was a significant effect of Preview, such that previewed trials had a greater proportion of high-accuracy first saccades than did non-previewed trials, F(1, 87) = 14.22, MSE = .003, p < .001, and a marginal interaction between Preview and Stability, F(3, 87) = 2.54, MSE = .003, p = .062. No other effects reached significance. The nature of the interaction is clear in Figure 11, showing that neither Preview nor Load had any impact on the Random condition. This was confirmed with a Preview by Load ANOVA run on only the Random condition (all Fs < 1, ps > .35). A second Preview by Load by Stability ANOVA was run on only the stable conditions, revealing only an effect of Preview, F(1, 51) = 12.03, MSE = .004, p < .005, and no interaction with Stability (F < 2, p > .2). As in the full ANOVA, no other effects reached significance (all Fs < 2, ps > .15).

Summary. The dominant pattern observed in preview and load effects is that costs incurred by load are recouped by benefits resulting from preview, and that these effects are restricted to non-random stability conditions. Additionally, though this effect is suggested across non-random stability levels, it is accentuated at the intermediate stability level. In RTs the selective nature of this effect appears to arise because performance at the higher stability levels seems to be less impaired by load. This is consistent with the fact that at these higher levels there is no observable overall preview benefit either, suggesting simply that the preview is largely ignored in these conditions. This may reflect a strategic shift in the use of preview at the higher levels, such that the costs of preview (from its role as load) are deemed greater than its benefits. In contrast, at the intermediate (3-step) level of stability, performance is perhaps sufficiently unreliable that it is worthwhile to make use of the preview item despite its cost.

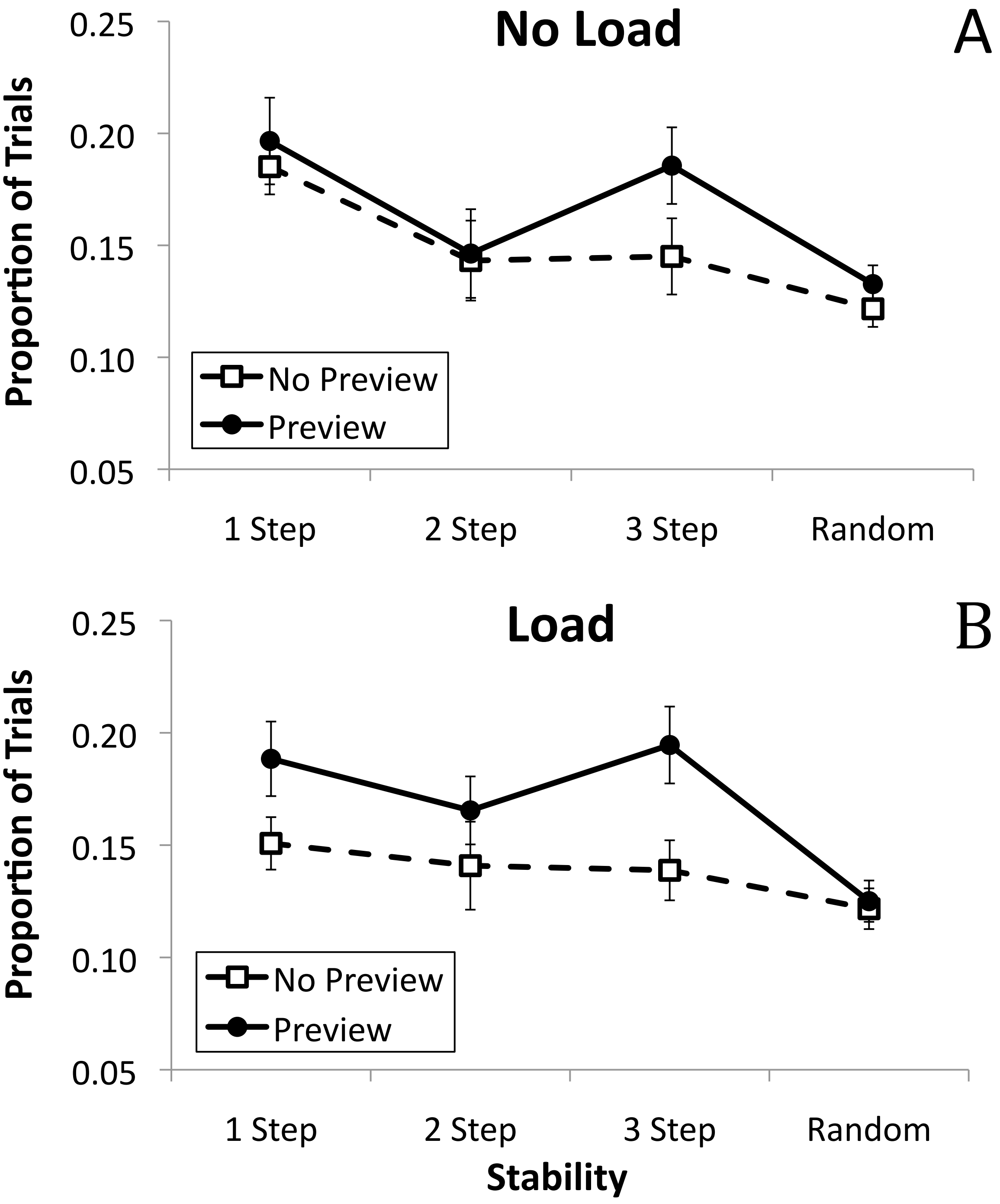

Figure 12. Proportion of trials on which the first saccade accuracy was very high, where the target was previewed or was not previewed, **(A)** without load and **(B)** with load. Error bars depict one standard error of the mean.

This proposal is in part supported by the observation at the 3-step stability level of a marginal, though non-significant, preview benefit even in the absence of load. These results are consistent then with a cost-benefit tradeoff being implemented near floor performance levels, resulting in a compression of effects at the highest stability levels. It remains an open question as to whether this floor results from a performance criterion for a strategic shift in preview use, or else a fundamental limit for benefits from stability using this experimental design.

1.4 General Discussion

Our results show that visual search performance can be considerably improved when search displays are stable from one trial to the next, and that these improvements vary with the degree of stability. Manual response times were improved by roughly 200-ms in stable conditions versus the random condition, and the major part of this improvement could not be attributed to differences in first saccade latency (preparatory processes), or in the time taken to generate a response once the target had been fixated (decision processes). Instead, the major part of the improvement was during the actual search process. Additionally, by recording eye-movements we were able to show that early guidance as measured by the accuracy of the first saccade during search also improved as a function of stability, and that that this effect was driven primarily by differences across stability in the proportion of saccades made directly towards the target.

We were also able to provide a direct demonstration that search for a target on a given trial is influenced by where a participant has looked on the preceding trials. Specifically, we found significant relations between both first saccade accuracy and response times on a given trial and the accuracy with which that trial's target had been fixated while it was a distractor on the previous trial. Furthermore, we demonstrated that response times improved when a trial's target was also the target on a recent previous trial, and that this improvement decayed as the number of intervening trials increased.

Finally, we have found evidence that providing a preview of an upcoming search target influenced performance, conditional on trial-to-trial stability. We found that on trials in which the preview was presented along with the target for that trial, this previewed item created a memory load and hurt performance. However, the negative effects of load on a given search trial were overcome by also previewing that trial's search target on a previous trial. Additionally, two features of the preview results suggest potential strategic differences across conditions. First, the negative impact of load was selective to stable conditions, and was not observed in the random condition, which suggests that the target preview only acts as a load in those circumstances where it could potentially also be useful as a preview (e.g. when an item's location on one trial is predictive of its location on the next). Secondly, a significant interaction between preview and load effects was observed only at the intermediate (3-step) stability level. Together, these factors suggest that although performance can be improved by using a target preview, use of this preview also incurs a performance cost on the trial on which the preview is presented (where it acts as a load). Whether or not a participant uses the preview then, seems to be a function of stability. When stability is high, baseline search performance is also high, and the costs of using a preview outweigh its benefits. However, as stability decreases, baseline performance also decreases, and the benefits of using a preview outweigh its costs.

Prior research has provided little evidence that trial-to-trial memory plays a considerable role in visual search, with existing studies showing that trial-to-trial memory does not influence search efficiency as measured by search slopes except in restricted cases (e.g. the instance condition in experiment 6, Wolfe, Klempen, & Dahlen, 2000). The present results however, indicate that in some cases trial-to-trial memory does lead to substantial improvements in search performance. There are several possible reasons for the discrepancy between our results and those previously reported in similar studies. One reason is that the search displays we used involved a larger number of items than were used in previous studies. Indeed, the set size in our experiments was fully three times greater than the largest set size tested in previous studies (Wolfe, Klempen, & Dahlen, 2000; Olivia, Wolfe, & Arsenio, 2004). A second and related reason is that our displays were also physically much larger than the displays used in prior studies of trial-to-trial memory, and indeed larger than the displays used in most studies of visual search in general. We believe that both set size and display size may be critical factors for dissociating top-down guidance processes from bottom-up perceptually driven guidance processes. Increasing set size, viewing area, or both are likely to increase the burden on purely perceptual processing of the display. As the burden on perceptual processes increases, top-down mechanisms (e.g., prior knowledge) might begin to play a correspondingly larger role in search by directing attention to constrained regions of space where perceptual processing can be focused on a subset of the items. Our guidance measures of first saccade accuracy support this notion, demonstrating that with increasing stability, first saccades are more often directed straight to the location of the target. Given the available evidence that perceptual processing is quite efficient at finding targets at small set sizes, it seems a reasonable strategy that when set sizes become large, memory should be employed to constrain perceptual processes to an appropriately limited region.

Broadly, our results, in combination with previous research on stable and repeated search, suggest a dual-process model of search, wherein externally-driven perceptual processes dominate at local scales, while internally-driven factors such as memory act to constrain these perceptual processes to regions in which they can perform optimally. This is consistent with the Contextual Guidance Model (Torralba, Olivia, Catelhano, & Henderson, 2006), which suggests two pathways in scene processing: a local saliency-driven pathway, and a global pathway that draws on scene priors. In this model global processing is used to constrain local processing to those locations where the target is expected. This work, and similar studies (e.g. Eckstein, Drescher, & Shimozaki, 2006) follows earlier research demonstrating that object recognition in scenes is influenced by semantic and relational consistency (e.g. Biederman, Mezzanotte, & Rabinowitz, 1982; De Graef, Christiaens, & d'Ydewalle, 1990; Hollingworth & Henderson, 1998), and provides strong support for top-down mediation of bottom-up processes in search. The use of top-down information for gating and sequence planning in visual attention is further supported by anatomical and lesion data demonstrating a strong influence on saccade generation from prefrontal cortical areas, with lesions generally producing selective impairment to goal-directed and memory-driven saccades, but not to more reflexive orienting (Keating, 1991; Pierrot-Deseilligny et al., 1995; Berthoz, 1996; Ploner et al., 1999). Additionally, frontal lesions are also associated with impaired suppression of reflexive saccades, as indexed for instance in the anti-saccade task (e.g. Guitton, Buchtel, & Douglas, 1985). These findings demonstrate that reflexive and top-down saccade generation mechanisms are separable, and additionally that a prominent role for top-down mechanisms may be to exert a suppressive influence on reflexive mechanisms. Such an arrangement is precisely what one might expect for a system where bottom-up orienting is constrained by top-down influences.

Critically, our results do not suggest that search is purely top-down. Our results show not only that memory-driven guidance is somewhat unreliable, improving guidance on only a subset of trials, but also that it appears to be temporally short-lived. Additionally, as evidenced by prior studies, in conditions of low perceptual load, memory driven effects may be entirely negligible. From this perspective then, memory can be seen as an aide to perceptual analysis, whose role is primarily to bring attention ‘within range.’ Once the region is appropriately constrained however, local search is likely to be driven almost entirely by perceptual systems.

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