HHS Public Access
Author manuscript
J Exp Psychol Hum Percept Perform. Author manuscript; available in PMC 2015 October 15.

Published in final edited form as:
J Exp Psychol Hum Percept Perform. 2012 February ; 38(1): 152–160. doi:10.1037/a0026233.

Global Statistical Learning in a Visual Search Task

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Abstract

Locating a target in a visual search task is facilitated when the target location is repeated on successive trials. Global statistical properties also influence visual search, but have often been confounded with local regularities (i.e., target location repetition). In two experiments, target locations were not repeated for four successive trials, but with a target location bias (i.e., the target appeared on one half of the display twice as often as the other). Participants quickly learned to make more first saccades to the side more likely to contain the target. With item-by-item search first saccades to the target were at chance. With a distributed search strategy first saccades to a target located on the biased side increased above chance. The results confirm that visual search behavior is sensitive to simple global statistics in the absence of trial-to-trial target location repetitions.

Keywords

visual search; statistical learning; repetition; eye movements

Efficiently identifying relevant stimuli in the environment is central to behavioral adaptation and survival. Under familiar conditions people cope with a highly variable environment by selectively attending to portions of the sensory array that are expected to be the most likely source of diagnostic or discriminative information. In the visual modality, for example, once a search context is recognized eye movements proceed to a probable target location (Chun & Jiang, 1998; Hoffmann & Kunde, 1999; Peterson & Kramer, 2001). That is, people make use of schematic and semantic knowledge to facilitate visual processing (e.g., Biederman, 1972; Biederman, Mezzanotte, & Rabinowitz, 1982; Brockmole, Castelhano, & Henderson, 2006; Neider & Zelinsky, 2006). In Biederman's terms, one expects objects to be in certain locations given the presence of a meaningful context or familiar setting. There is a growing body of evidence that cohesion of features in the environment become meaningful and familiar through statistical learning (e.g., Conway & Christiansen, 2006; Fiser & Aslin, 2001, 2005; Saffran, Aslin, & Newport, 1996). This observation suggests that the behavior of visually searching for a certain item is shaped by expectations about regularities in the environment.

Expectations about a search target's location can be developed by a mechanism that tracks environmental regularities on a global scale. For example, facilitated responding in a visual

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search task may be the result of the tracking probabilistic information about target locations that is gleaned over the course of several experimental trials. Examples of such regularities that have appeared in the visual search literature include both configuration repetitions (Chun & Jiang, 1998; Hoffmann & Kunde, 1999; Hoffmann & Sebald, 2005; Peterson & Kramer, 2001) and target/location associations (Geng & Behrmann, 2002, 2005; Musen, 1996). As one illustration, Williams, Pollatsek, Cave, and Stroud (2009) demonstrated that when the search target was more likely to appear in one cluster of distractors, participants tended to search that cluster first (although see Araujo, Kowler, & Pavel, 2001, for conditions in which participants do not use statistical information in clustered search). The observation of learning effects in visual search tasks is consistent with a broad range of literature showing statistical learning in other visual tasks (Turk–Browne, Jungé, & Scholl, 2005; Fiser & Aslin, 2001, 2005), in language learning tasks (e.g., Saffran et al., 1996), and sequence learning in various modalities (e.g., Cohen, Ivry, & Keele, 1990; Conway & Christiansen, 2005).

Whereas the process of finding a target in a visual display can be facilitated by the acquisition of global probabilistic structure within an experiment (i.e., overall, where is the target most likely to appear?), the acquisition of such information appears to be furthered by the presence of local regularities that occur within a small cluster of trials. The repetition of target features, such as color, orientation, singleton dimension, and especially spatial location across adjacent trials leads to facilitation in responding to targets (Hillstrom, 2000; Lamy, Bar–Anan, & Egeth, 2008; Maljkovic & Nakayama, 1994, 1996; Sigurdardottir, Kristjánsson, & Driver, 2009). These benefits can last with up to five to eight intervening trials between repetitions (Maljkovic & Nakayama, 1996). Indeed, Geng and Behrmann (2005) concluded that a part, but not all, of the response facilitation in their experiments was due to repeated target locations across trials. However, Walthew and Gilchrist (2006) have challenged the notion that the process of visual search should benefit from global statistics in a visual world that is constantly changing. They provide evidence that effects of statistical learning in visual search are driven by repetition effects. In essence, their claim is that participants generally do not acquire probabilistic information about the likely location of search targets unless they experience consecutive trials on which the target appears in the same location.

The purpose of the current work is to examine Walthew and Gilchrist's (2006) claims about statistical learning in visual search more closely. We do this by addressing the saccade-to-target task used in Walthew and Gilchrist's (2006) experiments that we believe may not have been sensitive to effects of global statistical properties of the display on visual search performance. Participants in Walthew and Gilchrist's (2006) Experiment 3 were asked to find a search target in a circular array of objects with a radius subtending 6°. The display was in view for 1,000 ms. Participants responded by making their first saccade to the target which appeared on one side of the display (the biased side) twice as often as on the other. When target locations were repeated on successive trials, participants made more correct first saccades to targets on the biased side than to targets on the unbiased side. However, when target locations did not repeat for at least three intervening trials the proportion of first saccades to the target on the biased side was not different than first saccades to targets on the unbiased side.

There are two observations about their design to note. First, participants were encouraged to delay eye movements and to make their first saccade to the target. Second, trials on which the first saccade was to the target object account for about 50% of their data in both the biased and unbiased conditions. This may not seem like an appreciable portion of the data, but consider that, on average, chance performance in this task would be to make the first saccade to the target on 12.5% of the trials (there were eight possible target locations). And, as Walthew and Gilchrist conclude, participants were quite successful in doing the task regardless of whether the target appeared on the biased side or not.

The argument from Walthew and Gilchrist's perspective is that if participants were sensitive to the 2-to-1 bias in the materials that they should have been more successful when the target appeared on the biased side. One way of thinking about this is that if participants learned and expected that the target was more likely to appear on one half of the display they could covertly initiate their search for the target to the biased side. Given the limited display duration, this would lead to more success when the target appeared on the biased side. However, the validity of the saccade-to-target measure as a test of bias rests upon the assumption that detecting the target required sampling discrete portions of the display covertly at the outset of the trial. It is conceivable that the entire display could be perceived all together. If one could locate the target without covertly searching one side of the display before the other, then the saccade-to-target task may have masked effects of global statistical properties because they were irrelevant to completing the task.

We present two experiments that attempt to replicate the findings reported by Walthew and Gilchrist (2006). We included an additional measure of the effect of target location bias: the proportion of first saccades to the biased side (as opposed to target location). In Experiment 1 participants responded by key press without time pressure which resulted in a typical sequential item-by-item[1] search. Under these circumstances we observed statistical learning of which side of the display most likely contained the target in the absence of consecutive trials on which the target appears in the same location. Experiment 2 was an effort to fully replicate the critical result from Walthew and Gilchrist's third experiment. As in the first experiment, we observed statistical learning of target locations in the absence of the repetition of target locations across consecutive trials.

EXPERIMENT 1

The first experiment was designed to address the possibility that the saccade-to-target dependent measure in Walthew and Gilchrist's (2006) Experiment 3 was not sensitive to the effects of the target location bias in their materials. Their participants were encouraged to make only one eye movement, to the target, per trial. Eye movements were further constrained by limiting the viewing time of the search display to 1,000 ms. Because the search display was relatively small (6° radius), it may have been possible to acquire the

[1]The phrase "item-by-item," along with its analogs "serial," "difficult," "overt," and "less-efficient" and contrasting terms, such as "distributed," "parallel," "easy," "covert," and "more-efficient" describe certain visual search conditions, but bring a lot of theoretical baggage along with them regarding the debate about one-process or two-process search mechanisms. The terminology used in this article (item-by-item and distributed) is not intended to make claims regarding this debate but to conveniently describe contrasting conditions eliciting more or fewer eye movements on a given experimental trial.

target location without a saccade regardless of whether or not the target was on the biased side of the display. Thus, the global statistical properties were not useful in completing the task and either were not learned or not used to guide search.

We reasoned that under less-constrained viewing conditions our participants would elect to search with eye movements (Findlay & Gilchrist, 1998; Zelinsky & Sheinberg, 1997) and, that with this, the utility of the global statistical properties in the materials would emerge. That is, we predicted that participants would engage eye movements before acquiring the target location and, over the course of several trials, find the target on one side more often than on the other. It is at this point that the utility of the global statistical properties would emerge and bias participants to making their first eye movement to the side of the display that was most likely to contain the target. We proposed that participants' learning would be revealed as a bias in their tendency to first saccade to the side of the search display that most often contained the target.

This experiment is a replication of Walthew and Gilchrist's Experiment 3 no-repeats condition with two exceptions. First, our participants responded by button press rather than by saccade. Second, whereas in Walthew and Gilchrist's experiment the visual display was viewable for 1,000 ms, in this experiment the visual display was on screen until participants responded. These changes were made to encourage an item-by-item search strategy rather than a distributed search strategy. Under these circumstances we predicted that participants would tend to make their first saccade to the side of the display that was most likely to contain the target, regardless of where the target was located on a given trial.

Method

Participants—Sixteen students at Florida State University participated for partial course credit. All participants reported normal or corrected-to-normal vision.

Stimuli—The stimuli were modeled after those used by Walthew and Gilchrist (2006) and consisted of eight light gray Landolt C symbols (0.7° in diameter) arranged in an invisible circle (6° radius) in the center of a black background. The gap in the Cs subtended 0.2° degrees and faced down for the seven distractors and up for the target. The search objects were equally spaced (45°) on the invisible circle with the first one offset from the horizontal at 22.5°. This divided the invisible circle into eight sectors evenly distributed over each possible object location. In this configuration there are four target locations on the left of the display and four on the right (see Figure 1).

Apparatus—The display presentation was controlled by a Pentium personal computer attached to a cathode ray tube monitor using Experiment Builder software (SR Research). Each participant's head was stabilized on a chin rest placed 60 cm away from the monitor. The display resolution was 1024 by 768 pixels. Eye movements were recorded with an Eyelink CL (SR Research) eye tracker sampling from the right eye at 1,000 Hz and a spatial resolution of 0.1°. An eye movement was considered to be a saccade if its acceleration reached 8,000°/s^2 or its velocity reached 30°/s. A nine-point calibration and validation procedure was completed at the beginning of and, as needed, throughout each session.

Procedure—Participants were tested individually in a normally lit room. First, participants were informed that they would complete a visual search task and then viewed an example display of what the search region would look like. The task description instructed participants to locate which side the target was on, left or right, and respond by pressing buttons with their left or right index finger on a hand held response pad. The instructions included asking the participants to make their first eye movement to the target object, but was not further emphasized (i.e., no feedback or correction to item-by-item search behavior was offered).

Participants initiated each trial by pressing a button on the response pad (this button was different from those used to respond) while fixating a central drift correction stimulus. Next, participants saw a central fixation cross for 500 ms which then remained on the screen when the search display appeared.[2] The search display remained visible until the participant responded. After each trial feedback was visually displayed for 1,000 ms that indicated if the given response was correct or incorrect. Participants were asked to respond as quickly as they could without sacrificing accuracy. After every 96 trials participants were provided a brief break to avoid effects of fatigue. The duration of each experimental session ranged from 35 to 45 min depending on the pace of the participant.

Design—For each participant a unique series of 384 search displays was generated with the target appearing randomly and independently in any one of the eight possible locations with the following two constraints. First, the target was located approximately twice as often on one side of the screen as the other. This value was slightly different for each participant with a mean proportion of .67 (standard error of the mean [SEM] = .004) of the targets appearing on the biased side. Participants were naive to this feature of the design. The target bias side (left or right) was counterbalanced across participants. Second, for all participants, the target location repeated only after four intervening trials at one of the other seven possible locations. For example, if the target appeared in positions 1, 2, 3, and 4 on the first four trials it could not appear in position 1 again until the sixth trial (note that this configuration includes one more intervening trial before a target could repeat than in the design of Walthew & Gilchrist).

Analysis—On each trial, the latency and accuracy of the manual response was recorded as well as the latencies, locations, and number of saccades. Following Walthew and Gilchrist (2006), the data were trimmed before analysis. First, trials on which there was no saccade or the amplitude of the first saccade was less than 2.0° or greater than 10.0° were not included in the analysis. Second, trials on which the first saccade latency less than 80 ms or greater than 1,000 ms were excluded. Finally, trials were trimmed for an incorrect response. For the remaining trials the first saccade was scored in two ways: 1) toward or away from the biased side of the display and 2) to the correct target sector or not.

[2]This was done because in previous unrelated experiments the abrupt offset of a central fixation elicited uncontrolled eye movements. Walthew and Gilchrist did not use a central fixation during the presentation of the search display. This difference is not a problem for our findings because our goal was to induce and measure the locations of controlled eye movements.

Results

Twelve percent of the data were trimmed because the first saccade was either less than 2° or greater than 10°. An additional 5.5% were discarded for first saccade latency less than 80 ms or greater than 1,000 ms. Finally, 2.5% of the data were trimmed because the response was incorrect. Thus 80% of the trials remained for analysis. On average there were 306 trials per participant (SEM = 7.2).

Search profile—On average participants made 4.39 (SEM = 0.23) saccades per trial before making their response which suggests that participants tended to look item-by-item until the target was found. In order to put this value into perspective we can consider it against other reports of serial search in the literature. For example, Zelinsky and Sheinberg (1997, Figure 4) report 2 saccades per trial in a serial search with O's as targets and Q-like stimuli as distractors with a set size of 17. Williams, Reingold, Moscovitch, and Behrmann (1997, Figure 1) report 3.5 in a similar search task and 2.5 in a "T and L" search task.

The mean of the median first saccade latency was 205 ms (SEM = 14), which is much lower than the 373 ms reported by Walthew and Gilchrist (2006, Table 1) and suggests that participants were not delaying the onset of their first eye movement in order to process the entire display simultaneously. Although there is no statistical analysis to confirm these differences, the number of saccades and the latencies of the first saccades are consistent with the idea that participants' search was more item-by-item than it was distributed.

First saccade location—The mean proportion of first saccades to the biased side (.67) was significantly greater than to the unbiased side (.33), $t(15) = 3.16$, $p < .007$, $d = 0.79$. These proportions may be the result of participants' sensitivity to the tendency of the target to appear on the biased side. However, two possible alternatives exist. First, if participants used a last-location strategy and merely looked to the location of the target from the previous trial they would end up looking at the biased side twice as often as the unbiased side. Second, eye movements may have been directed by subthreshold guidance: the target may not have been discriminable enough to guide a saccade directly to it, but it may have been discriminable enough to guide saccades in its general direction (i.e., to the side on which it was located) which would yield identical results. However, if first saccades were guided either by a last-location strategy or subthreshold guidance then the proportion of first saccades to the biased side when the target was on the biased side should be roughly equivalent to the proportion of first saccades to the unbiased side when the target was located on the unbiased side. Table 1 displays proportions of first saccades to the biased side as a function of target location on the current trial and on the previous trial. Participants did not reliably use a last-location strategy. There were more first saccades to the biased side when the target had been on the biased side on the previous trial (.69) than there were first saccades to the unbiased side when the target had been on the unbiased side on the previous trial (.35), $t(15) = 3.10$, $p = .007$, $d = 0.78$. A similar analysis indicates little, if any, subthreshold guidance. There were more first saccades to the biased side when the target was on the biased on the current trial (.72) than there were first saccades to the unbiased side when the target appeared on the unbiased side on the current trial (.41), $t(15) = 2.73$, $p = .02$, *d* = 0.68. These analyses indicate that initial saccades were not guided solely by the target's location.

Because participants were not made aware of the target location bias but made more first saccades to the biased side, it is reasonable to expect that their visual search behavior changed over the course of the experiment. Specifically, if learning of the global statistical properties of search display occurred participants should be more likely to look at the biased side of the display than the unbiased side at the end of the experiment than at the beginning. To evaluate this hypothesis we conducted a mixed logit model with trial number as a predictor and participants as a random factor and first saccade location (biased or unbiased) was the binary dependent variable. The odds of looking at the biased side significantly increase by 1.4 over the course of the experiment. Although participants were twice as likely to look at the biased side at the beginning of the experiment, they were 3.4 times as likely to do so at the end of the experiment, $\gamma = .0013$, standard error [SE] = .0003, $t(4896) = 4.06$, $p < .001$.

First saccades to target location. The proportion of first saccades to the target on the biased side and to the unbiased side is presented in two ways. First, to characterize the general success rate they will be presented as raw proportions. Second, for comparison to Walthew and Gilchrist we will present the conditional proportions.

In terms of raw proportions, there were more first saccades to the target on the biased side (.15) than to the unbiased side (.06), $t(15) = 5.48$, $p < .001$, $d = 1.37$. However, given that the target appeared on the biased side twice as often as the unbiased side this is not surprising. Furthermore, neither first saccades to the target when it was on the biased side nor when it was on the unbiased side occurred at a rate that is significantly different from chance,[3] both *ts* < 1.7, *ps* > .11.

The conditional proportions are simply the raw proportions corrected for the bias in target location. They are calculated for the biased and unbiased sides of the display separately by dividing the number of first saccades to the target by the total number of times the target appeared on a given side. The conditional proportion of first saccades to the target on the biased side (.22) was not significantly different than those to the unbiased side (.18), $t(15) = 1.27$, $p > .2$, $d = 0.32$.

Response and saccade latencies—The means of the median manual response latencies and saccade latencies were each analyzed with identical 2 (target location) by 2 (first saccade location) repeated-measures analyses of variance (ANOVAs). The two-way interaction was significant for both analyses, response: $F(1, 15) = 29.05$, mean standard error [MS_e] = 22857.12, $p < .001$; saccades: $F(1, 15) = 11.73$, $MS_e = 515.37$, $p < .005$. Participants were faster to respond when the target was on the unbiased side and the first saccade went to the unbiased side (992 ms) than when the first saccade went to the biased

[3]Chance was calculated as the product of conditional probability of a target appearing in any of four possible locations given that it appeared on the biased or the unbiased side of the display and the probability that the target appeared on the biased or unbiased side of the display. When the target appeared on the unbiased side this was .33 times the probability of the target appearing in one of the four positions on that side of display .25 equals .083. For the biased side this was .67 times .25 equals .167.

(1,217 ms), $F(1, 15) = 9.54$, $MS_e = 84958.52$, $p < .008$. Similarly, responses were faster when the target was on the biased side and the first saccade was to the biased side (956 ms) than when the first saccade was to the unbiased side (1,138 ms), $F(1, 15) = 13.52$, MS_e = 39,375.43, $p < .003$. First saccade latencies were longer when the target was on the unbiased side and the first saccade was to the unbiased side (222 ms) than when it was to the biased side (191 ms), $F(1, 15) = 7.3$, MS_e = 2,136.67, $p < .017$. There was no difference in saccade latencies when the target appeared on the biased side and the first saccade was to the biased side (212 ms) and when it was to the unbiased side (204 ms), $F(1, 15) = 1.15$, $MS_e = 817.46$, $p > .3$.

Response latencies were significantly shorter when the first saccade was to the target (687 ms) than when it was not to the target (1,097 ms), $t(15) = 13.18$, $p < .001$, $d = 3.29$. First saccade latencies to the target were significantly slower (226 ms) than those that were not to the target (195 ms), $t(15) = 4.06$, $p = .001$, $d = 1.01$.

Discussion

The data clearly indicate that participants looked to the biased side on more trials than to the unbiased side. Furthermore, the odds of this behavior increased over the course of the experiment. These results suggest that participants developed expectancies about the target's probable location.

Because of the very low performance in looking to the target on the first saccade, it is also clear that the bias in first saccade to the biased side was not a result of looking to the target. That is, if participants' first looks are to the target they are, by definition, to the biased side twice as often as to the unbiased side. It is also notable that the level of saccade-to-target performance in the current data does not replicate that of Walthew and Gilchrist (2006). This is likely a result of the item-by-item search strategy employed by participants. To some extent the pattern of first saccade latencies replicates Walthew and Gilchrist's findings. Slower first saccades to the target are consistent with the idea that on these trials participants are waiting until the target location was acquired before starting an eye movement.

EXPERIMENT 2

The first experiment showed that participants' initiated search to the biased side of the display more than to the unbiased side. That is, search behavior was shaped by the statistical structure of the stimuli in a task that encouraged item-by-item search. To explore the effect that item-by-tem search has on learning statistical structure this experiment was composed of two parts. The first half of the experiment was a complete replication of Walthew and Gilchrist's (2006) Experiment 3. We encouraged participants to adopt a distributed search strategy and to delay eye movements until the target had been located. The duration of the display was limited to 1,000 ms. We anticipated that rates of making first saccades to the target would increase. In the second half of the experiment, the radius of the visual display was increased from 6° to 10°. Our intuition was that with a larger display distributed search would be more difficult, and in turn induce eye movements. The purpose of this manipulation was to compare performance on trials with distributed search to those trials more characteristic of item-by-item search from the same participants.

A potential complication of the results of Experiment 1 is that participants made a manual response indicating whether the target was on the left or right side of the display. The statistical properties of the materials (the target location bias) were also reflected in the manual responses. It is conceivable that learning the global statistical properties was a result of 1) focusing participants on the left/right dimension of the display or 2) to the repetition of manual responses. The design of Experiment 2 will allow us to rule out these alternatives because no mention of the left/right dimension was made to participants and there was no overt response aside from eye movements for participants to make.

Method

The apparatus and stimuli in this experiment were identical to those of the first experiment save one difference. For the second half of this experiment the radius of the display was increased to 10°.

Participants—Sixteen students at Florida State University participated for partial course completion. All participants reported normal or corrected-to-normal vision.

Procedure—The procedure of this experiment was modeled as closely as possible to that of the no-repeats condition reported in Experiment 3 of Walthew and Gilchrist (2006). Participants were tested individually in a normally lit room. Each session began with calibration and validation of the eye tracker. After an introduction to the stimuli, the experimenter explained that the task was to find the upward facing Landolt C among the seven downward facing ones and that the search display would only be visible for 1,000 ms. At this point the experimenter explicitly instructed participants not to move their eyes until the target location had been acquired and to make their first eye movement to the target location. To illustrate the process every participant heard the following instructions. "Try to expand your focus so that you can see all of the objects at once. First locate the upward facing C and then make your first eye movement." Next, participants had a chance to practice the task until they understood that the goal was to make their first eye movement to the target location. For all but two participants this consisted of six trials, for one it was 12 trials, and for the last it took 18 trials. Finally, participants were informed that halfway through the experiment the size of the display would get bigger and that they should continue as they had been before that point.

Each trial was initiated by the participant by pressing a button on a response pad while fixating a central drift correction stimulus. Next, the search display was immediately presented for 1,000 ms after which the screen was blank for 100 ms. Finally, the drift correction stimulus reappeared which cued the participant to start the next trial. There was no central fixation cross present in the search display as there was in Experiment 1. After every 96 trials participants had a brief break to avoid the effects of fatigue. Accuracy of the tracking device was monitored and if needed recalibrated and revalidated.

Design—A unique series of 384 search displays was made for every participant using the same constraints on target location selection as in Experiment 1. The target appeared on average twice as often on the biased side (mean proportion = .66, SEM = .003) than on the unbiased side. The radius of the display size was also manipulated. In the first half of the experiment it was 6° and in the second half it was 10°.

Analysis—Data trimming was similar to that of Experiment 1 except that the range of valid first saccade amplitudes for the 10° display was 4° and 12°. First saccades were scored as in Experiment 1.

Results

A total of 93% of the trials remained for analysis after the data were trimmed. Trials on which the first saccade was less than 2° or more than 10° for the small display or less than 4° or more than 12° for the large display were discarded (total 6%). An additional 1% of trials were discarded for saccade latencies less than 80 ms or greater than 1,000 ms.

Search profile—On average 2.98 saccades (SEM = .14) were made per trial. There was not a significant difference in the number of saccades on 6° (3.05) and 10° (2.91) displays, $t(15)$ 1.34, $p > .19$. Although, this is roughly the same number reported by Zelinsky and Sheinberg (1997) and Williams et al. (1997) as discussed in the results of Experiment 1, it is also significantly less than in Experiment 1 (4.39), by an independent samples *t* test, $t(30) = 5.28$, $p < .001$, $d = 1.93$. The mean of median saccade latency of 328 ms (SEM = 27) was not as long as the 373 ms reported by Walthew and Gilchrist, but significantly slower than that of Experiment 1 (205 ms), $t(30) = 4.04$, $p < .001$, $d = 1.49$. By these criteria it is concluded that participants were relatively successful at inspecting the display as a whole before beginning search with eye movements.

First saccade location. The mean proportion of first saccades to the biased side (.67) was significantly greater than to the unbiased side of the display (.33), $t(15) = 10.30$, $p < .001$, $d = 2.57$. As in Experiment 1, we conducted an analysis to determine if this effect was a result of a last-location strategy or subthreshold guidance. Proportions of first saccades to the biased side as a function of target location on the current trial and on the previous trial can be found in Table 1 (analyses conducted on the 6° and 10° trials separately yielded identical results). There were more first saccades to the biased side when the target had been on the biased side on the previous trial (.69) than there were first saccades to the unbiased side when the target had been on the unbiased side on the previous trial (.37), $t(15) = 9.61$, $p < .001$, $d = 2.4$. Similarly, there were more first saccades to the biased side when the target was on the biased on the current trial (.77) than there were first saccades to the unbiased side when the target appeared on the unbiased side on the current trial (.53), $t(15) = 5.86$, $p < .001$, $d = 1.47$. The location of the first saccade, therefore, cannot be attributed to either a last-location strategy or subthreshold guidance.

To evaluate learning over the course of the experiment we conducted a mixed logit model with trial number as a predictor and participants as a random factor and first saccade location (biased or unbiased) was the binary dependent variable. The odds of a participant making a first saccade to the bias side of the display increased by 1.30 over the course of the experiment. At the end experiment they were 2.81 times as likely to saccade to the biased side than the unbiased side, $\gamma = .0016$, SE = .0003, $t(5728) = 6.06$, $p < .001$.

First saccades to target location—The mean raw proportion of first saccades to the target on the biased side (.25) was significantly greater than on the unbiased side (.10), $t(15) = 9.32$, $p < .001$, $d = 2.33$. The proportion of first saccades to the target was reliably greater than chance on the biased, $t(15) = 2.84$, $p < .02$, $d = .71$, but not on the unbiased side, $t(15) = 1.2$, $p > .24$, $d = .30$.

The mean conditional proportion of first saccades to the target on the biased side (.37) was significantly greater than on the unbiased side (.30), $t(15) = 3.61$, $p < .003$, $d = 0.90$. To evaluate the effect of increasing the size of the display halfway through the experiment we conducted a 2 (target location [biased, unbiased]) by 4 (quartile) repeated-measures ANOVA on the conditional proportions. The main effect of bias was significant, $F(1, 15) = 12.55$, $MS_e = .013$, $p = .003$, indicating that participants made more first saccades to the target on the biased side than on the unbiased consistently over the course of the entire experiment. The main effect of quartile was also significant, $F(3, 45) = 13.00$, $MS_e = .021$, $p < .001$. The two-way interaction was not significant, $F < 1$. Figure 2 graphs the proportion of first looks to the target for the biased and unbiased sides across all four quartiles. Note that performance declined in the third quartile when the display increased in size. In order to determine if this decrease was reliable we conducted four follow-up comparisons with the data collapsed across the target location factor. To decrease the probability of making a Type I error we adjusted for four comparisons (Bonferroni method) to .0125. The mean proportion of the third quartile (.30) was significantly smaller than that of the second quartile (.43), $t(15) = 3.29$, $p < .005$, and the fourth quartile (.40), $t(15) = 4.55$, $p < .001$. There was not a significant difference between the first quartile (.23) and the third quartile, $t(15) = 2.32$, $p = .035$, or between the second and fourth quartiles, $t(15) = .80$, $p = .44$.

Saccade latencies—First saccade latencies were analyzed with a 2 (target location) by 2 (first saccade location) by 4 (quartile) repeated-measures ANOVA. The main effect of quartile was significant, $F(3, 45) = 6.93$, $MS_e = 17{,}811.52$, $p < .001$, indicating that latencies slowed over the course of the experiment. None of the interactions involving quartile were statistically reliable, *Fs* < 2.2, *ps* > .10. The two-way interaction between target location and first saccade location was significant, $F(1, 15) = 12.27$, $MS_e = 5413.44$, $p < .003$. This interaction is driven by a significant difference between first saccades latencies to the unbiased side (352 ms) and those to the biased side (292 ms) when the target was on the unbiased side, $F(1, 15) = 26.28$, $MS_e = 2{,}128.25$, $p < .001$. When the target was on the biased side, however, first saccades to the unbiased side (321 ms) were not significantly different from those to the biased side (326 ms), $F < 1$. As in Walthew and Gilchrist (2006), the mean of the median first saccade latencies to the target was significantly longer (376 ms) than those that were not to the target (296 ms), $t(15) = 4.59$, $p < .001$, $d = 1.15$.

Discussion

There were several important findings from this experiment. First, as in Experiment 1, visual search behavior in this experiment was shaped by the statistical structure in the experimental materials. Over the course of the experiment the likelihood that participants would make their first saccade to the biased side of the display increased. It is important to note that this learning occurred in the absence of any explicit mention of the left/right dimension and with no response other than eye movements.

Second, the statistical bias in the materials shaped visual behavior in making first saccades to the target. In contrast with Walthew and Gilchrist (2006, Experiment 3, no-repeats condition), over the course of the experiment participants consistently made more first saccades to the target on the biased side of the display. However, there is some evidence that participants in our version of the experiment did not make their first saccade to the target as successfully as Walthew and Gilchrist's participants. In the first half of the current experiment (with 6° display size) first saccades were to the target on 33% of trials whereas in the first half of Walthew and Gilchrist's experiment it was 42%. Although this difference is not statistically significant, $t(24) = 1.27$, $p > .21$, it is consistent with the idea that the targets in the current stimulus set was not as easily discriminable as it was in Walthew and Gilchrist's. A more easily discriminable target would provide a stronger signal to direct eye movements and if strong enough should be readily available regardless of which side of the display it is on. As it turns out, there was one potentially important difference between our version of the task and the one used by Walthew and Gilchrist. Whereas we used light gray stimuli on a black background, they used black stimuli on a light gray background. There is some evidence of foreground/background color asymmetries in target location acquisition in visual search (e.g., Rosenholtz, Nagy, & Bell, 2004). However, to our knowledge, this particular color combination has not been tested. Furthermore, it is difficult to determine if there are other differences. For example, the thickness of the ring in our stimuli was 3 pixels, which is approximately .11° of visual angle. Also, we used anti-aliasing to smoothe the perimeter of the stimuli. As these stimulus parameters are not reported by Walthew & Gilchrist, it is difficult to pinpoint stimulus differences that may have lead to a different outcome.

The third finding of interest in this experiment is that changing the size of the search display disrupted search performance, but only transiently. When the display increased in size, performance in locating the target on the first saccade declined. Participants learned over the course of the experiment to make use of distributed search strategy and had to readjust for the larger display. During the postexperiment debriefing, participants were asked about how the increase in display size affected their strategy. Fourteen of the 16 participants indicated that it disrupted their ability to see the entire display at once, but that they readjusted very rapidly (modal estimate to readjust 10 trials). One participant claimed that the increase in size had no effect and the remaining participant's response was uncertain. Our intuition regarding the saccade-inducing effect of increasing the display size is not wholly supported. We suggest that participants became accustomed to the parameters of the display during the first half of the experiment and were not prepared for the increase in size. However, readjustment to the increase in size was trivial.

GENERAL DISCUSSION

In these experiments we have demonstrated that the global statistical properties of a visual search display affect visual search behavior. In both experiments the search target appeared on one half of the display twice as often as the other half. The main finding was that participants ultimately initiated search to this side of the display more than to the other side. In addition, the odds of making the first saccade to the biased side of the display increased over the course of the experiment which provides strong evidence of learning. These findings are consistent with other work that has implicated sensitivity to target location probability (e.g., Geng & Behrmann, 2005; Hoffmann & Kunde, 1999). More important, the current findings redress the challenge to effects of target location probability advanced by Walthew and Gilchrist (2006) who claimed that the effects were uniquely due to transient facilitation on trials that the target location was the same as the previous trial. When Walthew and Gilchrist prohibited target location repetition they did not find effects of target location bias on a saccade-to-target task. They hypothesized that if visual search was sensitive to target location bias that participants would be more successful at making first saccades to the target when it was on the biased side of the display because that would be the first side of the display to be covertly inspected.

We propose that in Walthew and Gilchrist's results, the effect of target location probability was masked by their method of measurement coupled with instructions to participants to make their first eye movement to the target. These instructions most likely lead participants to engage in a distributed kind of visual search in which the entire search display was effectively viewed as a single stimulus. The search display was visible for a limited duration which further encouraged distributed search over the more typical item-by-item search strategy spontaneously used by participants. Thus, the target was equally likely to be detected regardless of whether it appeared on the biased or unbiased side of the display. When we permitted unlimited search time in Experiment 1 participants searched in a fashion more consistent with item-by-item search which lead to significantly shorter first saccade latencies. Under these conditions the target location was not acquired before eye movements began and saccade-to-target performance was at chance levels.

In Experiment 2 we replicated the method and instructions used by Walthew and Gilchrist, however, we failed to replicate their results. We found both more first saccades to the biased side in general and more first saccades to the target on the biased side. Although the longer saccade latencies in this experiment suggest more distributed search, performance on the saccade-to-target task was lower in our version than in that of Walthew and Gilchrist. This discrepancy suggests that target discriminability was lower in our experiment which may have made it more difficult for participants to locate the target before making the first saccade. If this is the case it is plausible that our participants covertly searched the biased side of the display first and were therefore more successful at making the first saccade to the target than when the target appeared on the unbiased side of the display. The cause of this discrepancy will require additional research to be determined.

Acknowledgments

This research was supported by National Science Foundation Grant 0842620 to Michael P. Kaschak. We thank Carol Walthew and Iain D. Gilchrist for graciously sharing their data for further analysis and Walter R. Boot for discussions concerning the research and comments on an earlier version.

References

Araujo C, Kowler E, Pavel M. Eye movements during visual search: The costs of choosing the optimal path. Vision Research. 2001; 41:3613–3625.10.1016/S0042-6989(01)00196-1 [PubMed: 11718799]

Biederman I, Mezzanotte RJ, Rabinowitz JC. Scene perception: Detecting and judging objects undergoing relational violations. Cognitive Psychology. 1982; 14:143–177.10.1016/00100285(82)90007-X [PubMed: 7083801]

Biederman I. Perceiving real-world scenes. Science. 1972; 177:77–80.10.1126/science.177.4043.77 [PubMed: 5041781]

Brockmole JR, Castelhano MS, Henderson JM. Contextual cueing in naturalistic scenes: Global and local contexts. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2006; 32:699–706.10.1037/0278-7393.32.4.699

Chun MM, Jiang Y. Contextual cueing: Implicit learning and memory of visual context guides spatial attention. Cognitive Psychology. 1998; 36:28–71.10.1006/cogp.1998.0681 [PubMed: 9679076]

Cohen A, Ivry RI, Keele SW. Attention and structure in sequence learning. Journal of Experimental Psychology: Learning, Memory, and Cognition. 1990; 16:17–30.10.1037/0278-7393.16.1.17

Conway CM, Christiansen MH. Modality-constrained statistical learning of tactile, visual, and auditory sequences. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2005; 31:24–39.10.1037/0278-7393.31.1.24

Conway CM, Christiansen MH. Statistical learning within and between modalities: Pitting abstract against stimulus-specific representations. Psychological Science. 2006; 17:905–912.10.1111/j.14679280.2006.01801.x [PubMed: 17100792]

Findlay, JM.; Gilchrist, ID. Eye guidance and visual search. In: Underwood, G., editor. Eye guidance in reading and scene perception. Oxford, England, U.K: Elsevier Science Ltd; 1998. p. 295-312.

Fiser J, Aslin RN. Unsupervised statistical learning of higher-order spatial structures from visual scenes. Psychological Science. 2001; 12:499–504.10.1111/1467-9280.00392 [PubMed: 11760138]

Fiser J, Aslin RN. Encoding multielement scenes: Statistical learning of visual feature hierarchies. Journal of Experimental Psychology: General. 2005; 134:521–537.10.1037/0096-3445.134.4.521 [PubMed: 16316289]

Geng JJ, Behrmann M. Probability cuing of target location facilitates visual search implicitly in normal participants and patients with hemispatial neglect. Psychological Science. 2002; 13:520–525.10.1111/1467-9280.00491 [PubMed: 12430835]

Geng JJ, Behrmann M. Spatial probability as an attentional cue in visual search. Perception & Psychophysics. 2005; 67:1252–1268.10.3758/BF03193557 [PubMed: 16502846]

Hillstrom AP. Repetition effects in visual search. Perception & Psychophysics. 2000; 62:800–817.10.3758/BF03206924 [PubMed: 10883586]

Hoffmann J, Kunde W. Location-specific target expectancies in visual search. Journal of Experimental Psychology: Human Perception and Performance. 1999; 25:1127–1141.10.1037/0096-1523.25.4.1127

Hoffmann J, Sebald A. Local contextual cuing in visual search. Experimental Psychology. 2005; 52:31–38.10.1027/1618-3169.52.1.31 [PubMed: 15779528]

Lamy D, Bar–Anan Y, Egeth HE. The role of within dimension singleton priming in visual search. Journal of Experimental Psychology: Human Perception and Performance. 2008; 34:268–285.10.1037/0096-1523.34.2.268 [PubMed: 18377170]

Maljkovic V, Nakayama K. Priming of pop-out: I. Role of features. Memory & Cognition. 1994; 22:657–672.10.3758/BF03209251 [PubMed: 7808275]

Maljkovic V, Nakayama K. Priming of pop-out: II. The role of position. Perception & Psychophysics. 1996; 58:977–991.10.3758/BF03206826 [PubMed: 8920835]

Musen G. Effects of task demands on implicit memory for object location associations. Canadian Journal of Experimental Psychology/Revue Canadienne de Psyhchologie Expérimentale. 1996; 50:104–113.10.1037/1196-1961.50.1.104

Neider MB, Zelinsky GJ. Scene context guides eye movements during visual search. Vision Research. 2006; 46:614–621.10.1016/j.visres.2005.08.025 [PubMed: 16236336]

Peterson MS, Kramer AF. Attentional guidance of the eyes by contextual information and abrupt onsets. Perception & Psychophysics. 2001; 63:1239–1249.10.3758/BF03194537 [PubMed: 11766947]

Rosenholtz R, Nagy AL, Bell NR. The effect of background color on asymmetries in color search. Journal of Vision. 2004; 4:224–240.10.1167/4.3.9 [PubMed: 15086312]

Saffran JR, Aslin RN, Newport EL. Statistical learning by 8-month-old infants. Science. 1996; 274:1926–1928.10.1126/science.274.5294.1926 [PubMed: 8943209]

Sigurdardottir HM, Kristjánsson Á, Driver J. Repetition streaks increase perceptual sensitivity in visual search of brief displays. Visual Cognition. 2008; 16(5):643–658.10.1080/13506280701218364 [PubMed: 19325897]

Turk–Browne NB, Jungé J, Scholl BJ. The Automaticity of Visual Statistical Learning. Journal of Experimental Psychology: General. 2005; 134:552–564.10.1037/0096-3445.134.4.552 [PubMed: 16316291]

Walthew C, Gilchrist ID. Target location probability effects in visual search: An effect of sequential dependencies. Journal of Experimental Psychology: Human Perception and Performance. 2006; 32:1294–1301.10.1037/0096-1523.32.5.1294 [PubMed: 17002538]

Williams CC, Pollatsek A, Cave KR, Stroud MJ. More than just finding color: Strategy in global visual search is shaped by learned target probabilities. Journal of Experimental Psychology: Human Perception and Performance. 2009; 35:688–699.10.1037/a0013900 [PubMed: 19485685]

Williams DE, Reingold EM, Moscovitch M, Behrmann M. Patterns of eye movements during parallel and serial visual search tasks. Canadian Journal of Experimental Psychology/Revue Canadienne de Psyhocologie Expérimentale. 1997; 51:151–164.10.1037/1196-1961.51.2.151

Zelinsky GJ, Rao RPN, Hayhoe MM, Ballard DH. Eye movements reveal the spatiotemporal dynamics of visual search. Psychological Science. 1997; 8:448–453.10.1111/j.1467-9280.1997.tb00459.x

Zelinsky GJ, Sheinberg DL. Eye movements during parallel–serial visual search. Journal of Experimental Psychology: Human Perception and Performance. 1997; 23:244–262.10.1037/00961523.23.1.244 [PubMed: 9090154]

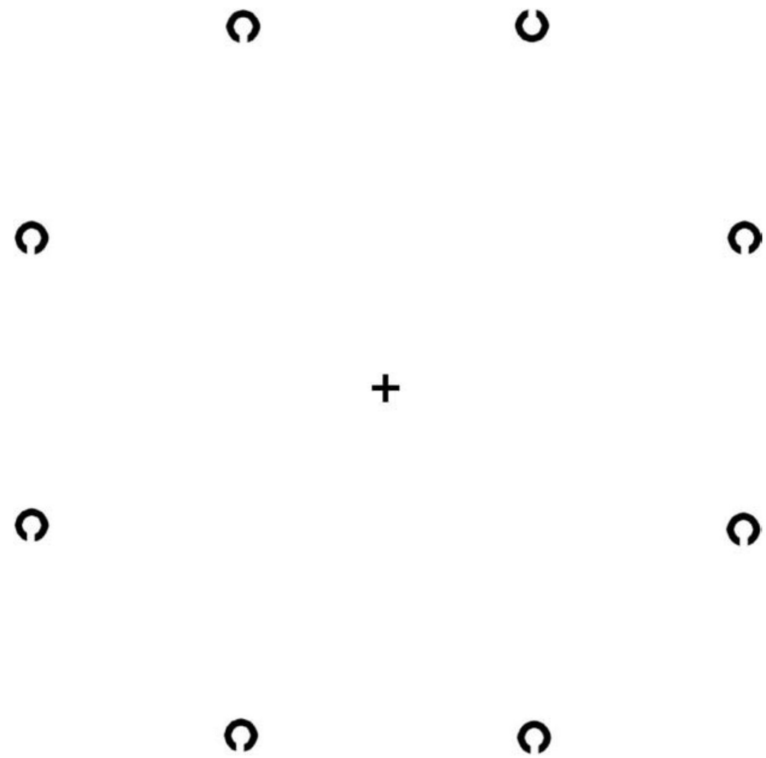

Figure 1.
Example display from both experiments. Example target is located in the top right position. Actual displays were light gray targets on a black background. Note that in Experiment 2 there was no central fixation stimulus (+).

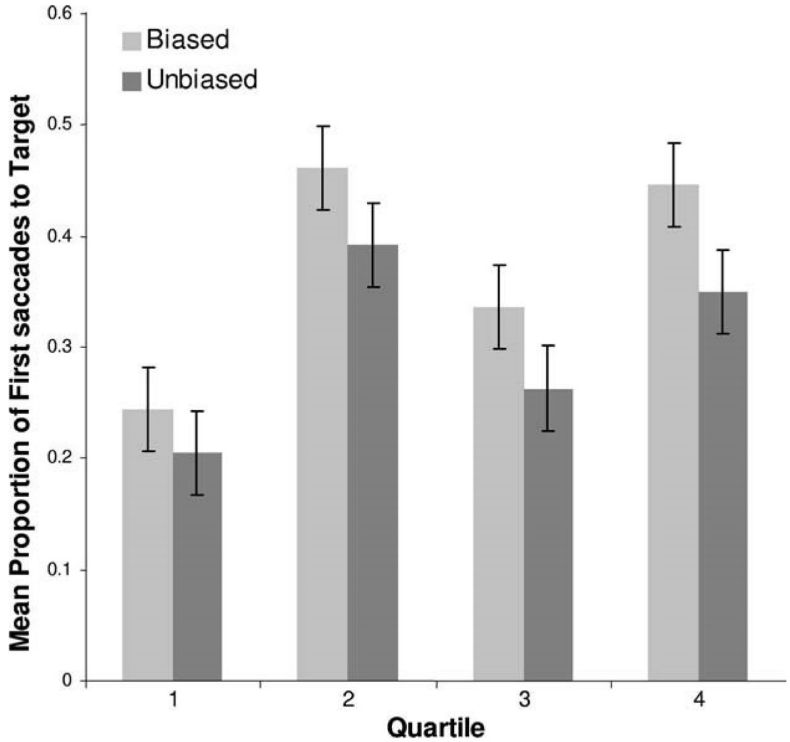

Figure 2.

Proportion of first saccades to the target for the biased and unbiased sides across all four quartiles of Experiment 2. The display size in the first two quartiles was 6° and in the third and fourth quartiles it was 10°. Error bars represent 95% confidence intervals. Note that these are the conditional proportions calculated for the biased and unbiased sides separately.

Table 1

Proportion of First Saccades to the Biased and Unbiased Side as a Function of Actual Target Location on the Current Trial *t* (Subthreshold Detection) and for the Previous Trial *t*-1 (Last-Location Strategy) for Experiments 1 and 2

		Target location			
		Trial 1		Trial 2	
Experiment	**First saccade location**	**Biased**	**Unbiased**	**Biased**	**Unbiased**
1	Biased	*.72*	.59	*.69*	.65
	Unbiased	.28	*.41*	.31	*.35*
2	Biased	*.77*	.47	*.69*	.63
	Unbiased	.23	*.53*	.31	*.37*

Note. Proportions were calculated for biased and unbiased target locations separately. Italicized values are those used in the analysis reported in the text.