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Simulated central vision loss does not impair implicit location probability learning when participants search through simple displays

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Abstract
Central vision loss disrupts voluntary shifts of spatial attention during visual search. Recently, we reported that a simulated scotoma impaired learned spatial attention towards regions likely to contain search targets. In that task, search items were overlaid on natural scenes. Because natural scenes can induce explicit awareness of learned biases leading to voluntary shifts of attention, here we used a search display with a blank background less likely to induce awareness of target location probabilities. Participants searched both with and without a simulated central scotoma: a training phase contained targets more often in one screen quadrant and a testing phase contained targets equally often in all quadrants. In Experiment 1, training used no scotoma, while testing alternated between blocks of scotoma and no-scotoma search. Experiment 2 training included the scotoma and testing again alternated between scotoma and no-scotoma search. Response times and saccadic behaviors in both experiments showed attentional biases towards the high-probability target quadrant during scotoma and no-scotoma search. Whereas simulated central vision loss impairs learned spatial attention in the context of natural scenes, our results show that this may not arise from impairments to the basic mechanisms of attentional learning indexed by visual search tasks without scenes.

Keywords visual attention · visual search · central vision loss · selection history

Central vision loss (CVL) is among the most common forms of visual impairment globally, affecting over 170 million people worldwide (Pennington & Deangelis, 2016). In addition to impairing tasks requiring high-acuity central vision like reading, CVL can also impair eye movements (Caldani et al., 2019; Thibaut et al., 2017), and perhaps as a result, goal-driven visual behaviors like searching for objects of interest (for a review, see Crabb & Taylor, 2017). Most studies on CVL have focused on understanding its functional consequences. Less understood is how CVL disrupts oculomotor and attentional mechanisms.

Studies that have investigated the basic attentional impairments arising from central vision loss have often simulated central vision loss using gaze-contingent viewing paradigms in order to control for such factors as scotoma size, age, and other demographic confounds (Bertera, 1988; Kwon et al., 2013; McIlreavy et al., 2012). This strategy has been used to investigate how central vision loss affects not only voluntary control of attention (as when someone intentionally guides their search to where they thought they put their keys) but also the effects of experience on attention (as when attention is involuntarily biased towards places where keys were often found). Learned attention plays a major role in guiding everyday search behavior (Awh et al., 2012; Jiang, 2018) and may compensate for deficits in goal-driven attention in clinical populations (e.g., due to Autism Spectrum Disorders, Parkinson's, or hemifield neglect; Geng & Behrmann, 2002; Jiang, Capistrano, et al., 2013a; Sisk et al., 2018). Thus, recent research has focused on investigating the effects

Significance statement

Central vision loss disrupts many everyday tasks like searching for objects. Here we show that visual search behaviors induced via experience – in which participants are faster to find targets when they are found frequently in one spatial region – are largely intact in people searching with simulated central vision loss. These results diverge from those showing that central vision loss impairs goal-driven attention. Our results have implications for future clinical studies investigating how learned attention could compensate for goal-driven attentional impairments arising from central vision loss.

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of central vision loss on learned attention (Addleman et al., 2021; Geringswald & Pollmann, 2015; Pollmann et al., 2020).

For example, we reported how simulated central vision loss impaired the acquisition of attentional biases via location probability learning (Addleman et al., 2021). Participants searched for a target among distractors overlaid on a natural scene image, both with and without a simulated central scotoma. In one experiment, participants completed a training phase with the scotoma (in which targets appeared in one quadrant on 50% of trials), while in another experiment participants were trained with no scotoma. In testing (when targets were found equally often in all quadrants), all participants completed alternating blocks of scotoma and no-scotoma search. In similar paradigms with typical viewing conditions, participants with no vision loss rapidly develop attentional biases to the high-probability quadrant, causing them to persistently respond faster on trials in which the target is placed in the high-probability quadrant (Jiang, Swallow, et al., 2013b). By selectively introducing simulated vision loss at different stages of the experiment, we intended to isolate what components of probability learning, if any, were impaired by simulated central vision loss. If simulated scotomas impair attentional guidance, this would have been reflected in all instances of scotoma search, regardless of when learning occurred; in contrast, impairments restricted to statistical learning itself would have only shown up in the experiment in which participants were trained with the scotoma, not in scotoma search following a no-scotoma training phase.

We found that our results differed based on whether participants could accurately identify the region likely to contain the target – that is, whether they reported awareness of the probability bias and therefore may have directed voluntary, rather than learned, attention to that region. When trained without a central scotoma, both aware and unaware participants acquired learning that persisted into testing regardless of whether they searched with or without the scotoma. The benefit of past learning with no simulated vision loss on search with a scotoma indicates that the scotoma did not itself interfere with attentional biases acquired via location probability learning. In contrast, when trained with the central scotoma, only aware participants acquired learning, and only aware participants showed effects in the testing phase even when searching with no scotoma. We also reported data on the proportion of first saccades directed to the high-probability quadrant, a measure shown to reliably index early allocation of attention (Jiang et al., 2014). In both experiments, only aware participants directed more saccades to the high-probability quadrant, a pattern that was consistent in scotoma and no-scotoma search and in both training and testing. Unaware participants did not bias saccades towards the high-probability quadrant. Overall, learning in aware participants showed that simulated central vision loss did not eliminate voluntary guidance once participants became aware of the high-probability location; however, the lack of effects in unaware participants indicates that implicit learning of target location probabilities was impaired by the central scotoma.

Although the data from this previous study demonstrated impairments to implicit location probability learning, the study differed from many others of probability learning in presenting the search array on top of natural images. While these images were task-irrelevant, several studies of learned attention indicate that the rich information contained in natural images induces greater use of explicit attentional strategies than search for simple stimuli like letters (Brockmole & Henderson, 2006a, 2006b). Some of this work uses contextual cueing, which occurs when repeated non-target information (e.g., letter distractors or scene information) predicts the location of a target, speeding search when that context repeats (Chun & Jiang, 1998). Scene-based contextual cueing is not only explicit in a way that letter-based cueing is not, but when both are independently predictive of the target location, the explicit scene-based effect completely eliminates learning of target-distractor letter associations (Rosenbaum & Jiang, 2013). A similar pattern has been shown in recent studies investigating the effects of simulated central vision loss on contextual cueing, with different results in learning with and without visual scenes. Contextual cueing was largely intact in search with a simulated scotoma for items in visual scenes (Pollmann et al., 2020), which the authors attributed to explicit recall of the locations of targets in specific scenes. In contrast, contextual cueing for target letters on a uniform background – a largely implicit process – was completely absent during simulated scotoma search (Geringswald & Pollmann, 2015).

This striking divergence based on the nature of the search display suggests that our previous results may not generalize beyond search in visual scenes. While search among scenes is clearly relevant due to its resemblance of everyday vision, it may not speak to how the well-studied mechanisms supporting implicit probability learning are affected by central vision loss. In addition, superimposing a simulated scotoma on natural scenes provided participants with real-time feedback on the scotoma's location, potentially enhancing their ability to control their eye movements (Walsh & Liu, 2014). The present study investigated the effects of removing visual scenes, and as a result salient feedback of the scotoma's location, on probability learning with simulated central vision loss.

We conducted two experiments investigating the effects of simulated central vision loss on location probability learning in visual search for simple stimuli, modeled after our experiments using natural scenes (Addleman et al., 2021). In both experiments, participants searched for a white T among white Ls on a uniform black background. In Experiment 1, participants first completed a training phase with no scotoma in which targets were found on 50% of trials in a specific visual quadrant. In Experiment 2, the training phase was conducted with a central scotoma. Then, to test the persistence of learning, participants completed a testing phase with alternating blocks of search with and without the scotoma, in which the target appeared equally often in all quadrants. Based on evidence from other forms of learned attention, we expected that the use of sparse visual displays would reduce effects of awareness on our results. Of interest is whether scotomas would impair probability learning, as in studies on contextual cueing, or leave it largely intact, as is the case in many other clinical conditions.

Experiment 1

Method

All experimental methods were adapted from Addleman et al. (2021).

Participants We recruited participants from the University of Minnesota Psychology subject pool. Participants were given the choice of $10/hr or, if eligible, offered extra course credit. Participants were between 18 and 45 years of age with normal or corrected-to-normal visual acuity and no reported visual field loss. We initially planned to recruit data from 24 participants, the sample size used in Addleman et al. (2021). Data collection was halted early due to COVID-19, resulting in a dataset of 16 participants: 13 women and 3 men, with a mean age of 21 years (range: 18-31). Based on effect sizes from Addleman et al. (2021), power to detect location probability learning at an alpha level of .05 is still high with 16 participants: nearly 100% to detect learning in the training phase and 99% to detect persistence into the testing phase. This study was approved by the University of Minnesota Institutional Review board and all participants provided informed consent.

Equipment Participants completed the study at a viewing distance of 90 cm with their head in a chinrest. Stimuli were displayed on a 19-inch CRT monitor (100Hz vertical refresh rate, 1024 x 768 pixel resolution). The experiment was programmed in MATLAB using Psychtoolbox (Kleiner et al., 2007). Eye tracking was conducted with an Eyelink 1000 Plus (S. R. Research) sampling at 1,000 Hz and calibrated using 9-point calibration and drift correction before each trial.

As reported in Addleman et al. (2021), we verified that our simulated scotoma eliminated useful vision at the scotoma location using a previously reported method (Geringswald et al., 2013). This verification test involved a separate set of 9 participants performing a gap detection task both with and without the scotoma. The gap is big enough to be detected well in central vision, while being undetectable by regions of the periphery not occluded by the scotoma. Thus, if the scotoma is being rendered quickly enough to avoid brief glimpses of the stimuli in central vision, performance should be at chance in the scotoma condition but high in the no-scotoma condition. In each of the 9 participants, bootstrapped standard errors confirmed that performance was at chance during scotoma search (Mean accuracy = 26%, SE = 1%) and above chance during no-scotoma search (M = 91%, SE = 3%).

Stimuli Search items were always white (RGB: 255, 255, 255) letters ('T's and 'L's) approximately 1° x 1° and the background was a uniform black (RGB: 0, 0, 0). Search arrays consisted of 12 items per trial (one 'T' and 11 'L's) located at random locations on an invisible 10 x 10 grid (12.5° x 12.5°), except 3 items always occurred in each quadrant and the target's probability of appearing in each quadrant varied as described in the procedure. The scotoma was a black (RGB: 0, 0, 0) circle approximately 6.7° in diameter centered on the participant's fixation and updated at 100Hz. See Fig. 1 for an example trial.

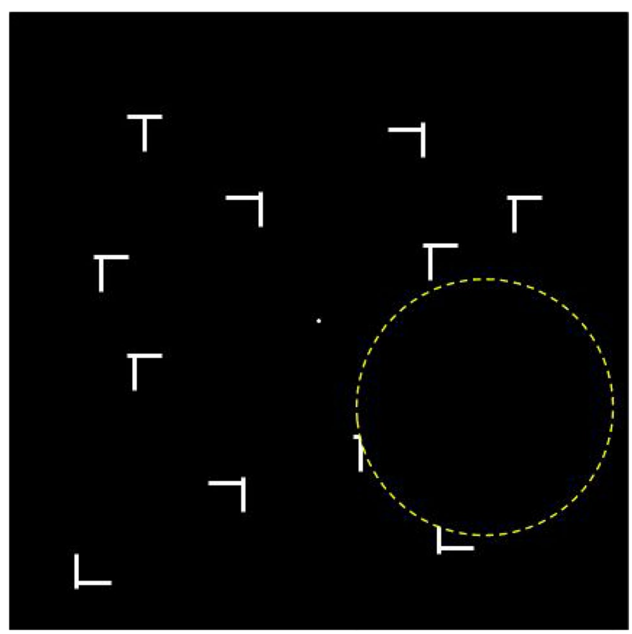

Fig. 1 A trial schematic, not to scale. Participants searched among L-shaped distractors for a target 'T' and reported its orientation. A 6.7° scotoma was presented at the participant's fixation location in real-time that occluded any items under the scotoma. The schematic outlines the scotoma in yellow; in the experiment, the scotoma had no outline and was indistinguishable from the background

Procedure Participants completed a single session of 36 practice trials of scotoma search and 576 experimental trials of a mixture of scotoma and no-scotoma search. In each trial, participants pressed a button to begin the trial, then searched for a target 'T' among 11 distractor 'L's, each in one of four random orientations (0, 90, 180, or 270°). Participants were instructed to use the arrow keys to identify the T's orientation as quickly and accurately as possible. The display was present until participants responded or for a maximum of 10 s, followed by auditory feedback indicating accuracy on that trial.

Participants completed 16 blocks of 36 trials each (see Fig. 2, left). The first eight blocks were 'training' blocks. In training, targets occurred in one consistent visual quadrant on 50% of trials (this high-probability or 'rich' quadrant was counterbalanced across participants). Experiment 1's training never included the scotoma. The last eight blocks ('testing') contained targets equally often in each quadrant, and alternated between scotoma and no-scotoma blocks (with vision status in the first testing block counterbalanced across participants).

After the search task, we asked participants two questions to gauge their awareness of the target location probability: (1) "Was the T equally likely to appear anywhere on the screen?" and (2) "If you had to choose one quadrant you feel the target T occurred most often, which would you choose?" As in previous work (Addleman et al., 2021), we classified participants as "aware" if they correctly answered the second question, and "unaware" if they responded incorrectly to that question. As a secondary analysis, we evaluated if location probability learning differed based on self-reported awareness.

Analysis We conducted analyses of accuracy as well as RT. Mean accuracy was high in both no-scotoma search (over 99%) and scotoma search (88%). In most cases, there was no effect of target quadrant on accuracy, so here we report only RT analyses. Data files recording both accuracy and RT can be found at https://osf.io/k3nfh/. In all cases when there were effects of quadrant on accuracy, they were consistent with reported RT effects.

To increase the number of trials per condition, we grouped every 2 blocks into an epoch: epochs 1-4 in the no-scotoma training phase and epochs 5-6 in both scotoma and no-scotoma conditions of the testing phase. For convenience, we refer to epochs 5 and 6 in both conditions even though vision status alternated by block with order counterbalanced across participants. Analyses were conducted in R, including rstatix (Kassambara, 2020) and BayesFactor (Morey et al., 2015).

We also analyzed the proportion of first saccades directed to the high-probability, 'rich' quadrant versus other quadrants. To ensure analyses excluded saccades initiated before the start of a trial, we analyzed only saccades occurring at least 100 ms following stimulus onset. To ensure that participants were using overt attention to complete the task, we also removed trials without any saccades from RT and saccade analyses (fewer than 1% of trials in each experiment).

Results

Acquisition of probability learning: Training phase RT We assessed acquisition of location probability learning during the no-scotoma training phase using a repeated-measures ANOVA on RT, with target quadrant (rich vs. sparse) and epoch (1-4) as factors (Fig. 3a; see Figure S1 for visualization of subject-level data). Responses were faster when targets were in the rich quadrant than in other quadrants, $F(1, 15) = 73.16$, $p < .001$, $\eta_p^2 = .83$. RTs decreased across

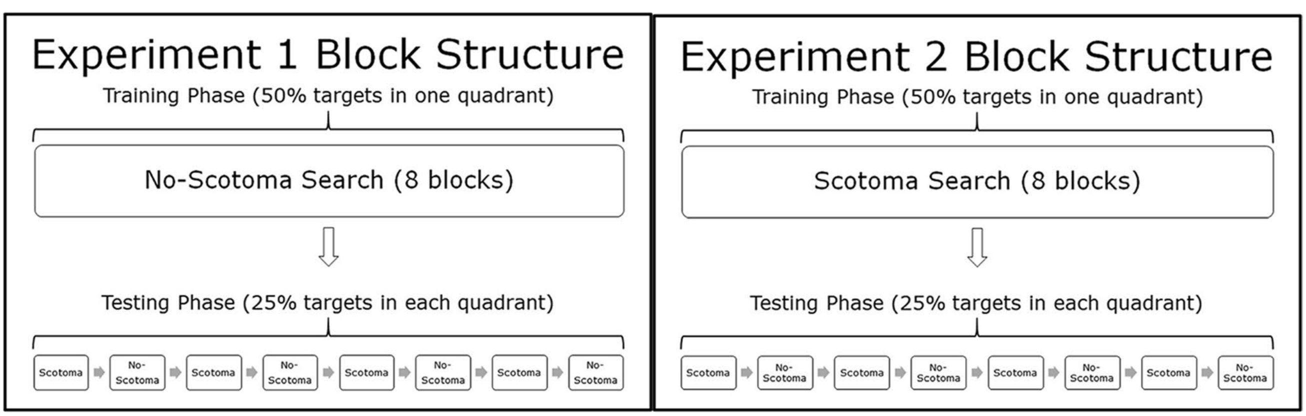

Fig. 2 Block schematics for Experiment 1 (left) and 2 (right). In both experiments, training and testing each consisted of eight 36-trial blocks. The target's location was biased toward one high-probability quadrant. In Experiment 1, training did not include the scotoma, while in Experiment 2 training did include the scotoma. In both experiments, testing blocks alternated between scotoma and no-scotoma conditions, and the target's location was unbiased

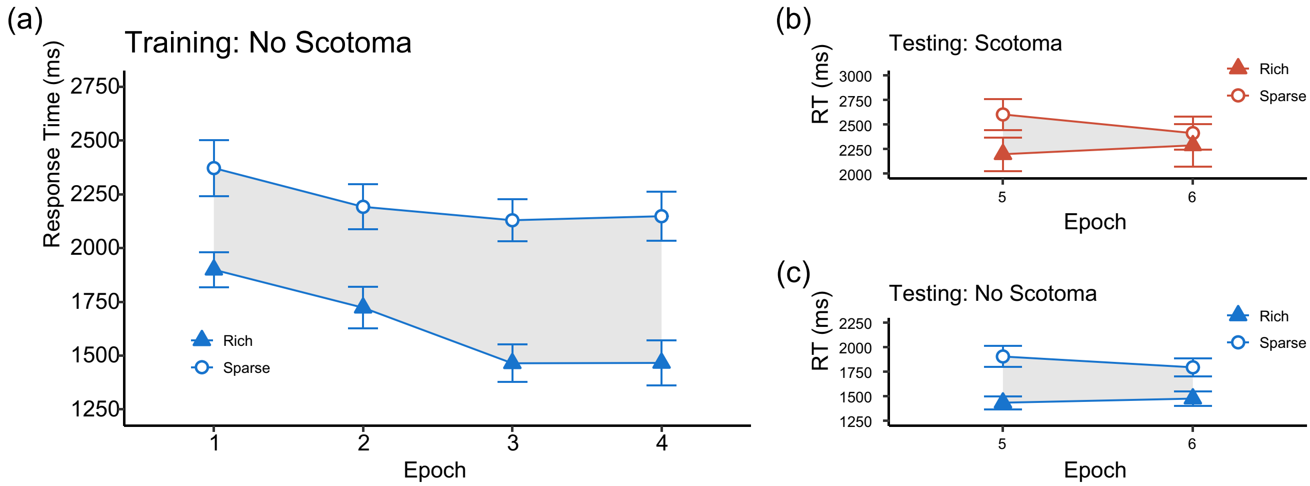

Fig. 3 Response times for Experiment 1, plotted by epoch and separated by whether the target occurred in the high-probability 'rich' quadrant or another 'sparse' quadrant. (**a**) Data from the no-scotoma training phase that contained targets most often in the high-probability quadrant. In all epochs, participants were faster when targets were in the rich quadrant. (**b**) Data from the scotoma testing blocks, which contained targets equally often in all quadrants. The target quadrant by vision status interaction was not significant, so data were analyzed together with the no-scotoma condition shown below. (**c**) Data from the no-scotoma testing blocks. Together with scotoma testing blocks, participants responded faster when targets were in the rich quadrant versus a sparse quadrant, an effect which diminished from epoch five to six but was significant in both epochs. Error bars denote +/- 1 S.E. of the mean

epochs, $F(3, 45) = 18.94$, $p < .001$, $\eta_p^2 = .56$. There was also a condition-by-epoch interaction, $F(3, 45) = 3.29$, $p = .029$, $\eta_p^2 = .18$, indicating that the size of probability learning increased throughout training. T-tests of RT based on target quadrant (rich vs sparse) in each training epoch revealed significant effects in all epochs, suggesting that probability learning benefited search in the rich quadrant throughout the training phase.

Persistence of probability learning: Testing phase RT To assess persistence of location probability learning into the testing phase, we conducted a repeated-measures ANOVA assessing the effects of vision status (scotoma vs no-scotoma), target quadrant (rich vs sparse), and epoch (5 vs 6) on response time. There was a significant effect of target quadrant, $F(1, 15) = 22.69$, $p < .001$, $\eta_p^2 = .60$, indicating that probability learning persisted in testing. However, this effect interacted with epoch, $F(1, 15) = 10.48$, $p = .006$, $\eta_p^2 = .41$, indicating that learning was smaller in epoch 6 than epoch 5. Results also showed a significant effect of vision status, $F(1, 15) = 32.14$, $p < .001$, $\eta_p^2 = .68$, indicating that search was slower with the simulated scotoma. This effect did not interact with either target quadrant or epoch, suggesting that scotoma status did not affect the magnitude or extinction of probability learning in testing. To evaluate the strength of evidence either for or against a null effect of the quadrant-vision status interaction, we used Bayesian ANOVAs with within-subject factors of quadrant and vision status and a default fixed prior of 0.5 (Rouder et al., 2012). The model with the main effects of target quadrant and vision status was preferred to one with both main effects and their interaction (the ratio of Bayes Factors was 1.77 in favor of no interaction). Overall, results indicate that probability learning persisted into testing and did not depend on whether participants searched with or without a scotoma. Figure 3b-c shows RT data from testing.

Direction of the first saccadic eye movement We expected that part of the RT advantage for targets in the rich quadrant would be reflected in a higher proportion of first fixations directed to the rich quadrant. Data supported this: in training (which had no scotoma), more first saccades were directed to the rich quadrant (M = .51, SE = 0.05) than expected by chance (.25), $t(15) = 5.12$, $p < .001$, $d = 1.28$. In no-scotoma search during testing, participants again directed more first saccades to the rich quadrant (M = .46, SE = .06) than expected by chance, $t(15) = 3.27$, $p = .005$, $d = 0.82$. The same pattern was found for scotoma search in testing (M = .44, SE = .04), $t(15) = 4.99$, $p < .001$, $d = 1.25$. The proportion of first saccades to the rich quadrant did not reliably differ between scotoma and no-scotoma search in testing, $t(15) = 0.36$, $p = .722$, $d = 0.09$, and a Bayesian t-test with a default prior of 0.707, with a BF_{10} greater than one representing the evidence for the alternative hypothesis and values below one representing evidence for the null hypothesis. Results provided moderate evidence for no difference in first saccade quadrant between scotoma and no-scotoma search (BF_{10}=0.27; Rouder et al., 2009). Overall, participants in Experiment 1 learned to direct more first saccades towards the rich quadrant than other quadrants, an effect which transferred to search with a scotoma. Figure 4 shows first saccade data from Experiment 1.

Awareness We evaluated whether there were effects of self-reported awareness on location probability learning (aware N = 8; unaware N = 8) using Bayesian ANOVAs. Figures S3-S6 in the supplementary material show Experiment 1's RT and first saccade data separated by awareness. We did this separately for the no-scotoma training phase, scotoma testing, and no-scotoma testing. In all cases, the strength of evidence was weaker for the model including the interaction and main effects of quadrant and awareness than the model including only the main effects of quadrant and awareness (ratios of quadrant BF to interaction BF were 3.59, 2.85, and 2.93 for training, scotoma testing, and no-scotoma testing, respectively). This is consistent with moderate evidence against the effect of awareness on location probability learning, a pattern that was consistent with traditional repeated-measures ANOVA results showing no significant quadrant by awareness interaction (Fs < 1).

We compared the proportion of first saccades to the rich quadrant between aware and unaware participants separately for scotoma and no-scotoma search using independent-samples t-tests. The proportion of first saccades to the rich quadrant was also not significantly different between aware and unaware participants. This was true for search with no scotoma (collapsed across phases), $t(14) = 0.78$, $p = .446$, Cohen's $d = 0.39$, and for search with the scotoma, $t(14) = 0.47$, $p = .646$, $d = 0.23$. Bayesian tests provided minimal evidence in favor of the null hypothesis of no effect of awareness on first saccade direction, both during search with no scotoma ($BF_{10} = 0.53$) and during search with a scotoma ($BF_{10} = 0.46$). The informativeness of these tests is constrained by small sample sizes when splitting our sample into aware and unaware groups, and as such should be interpreted with caution.

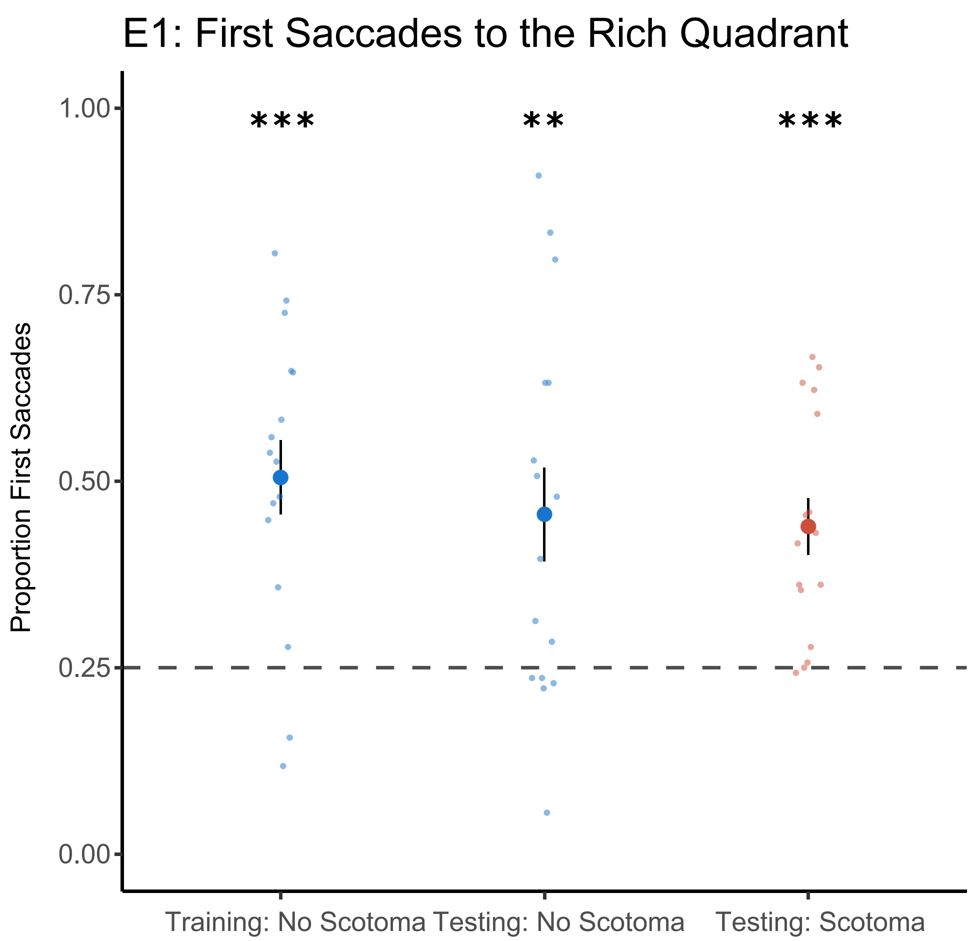

Fig. 4 From Experiment 1, the proportion of first saccades to the high-probability quadrant in the training phase (no-scotoma) and testing phase (separately for no-scotoma and scotoma search). Large circles represent overall means and small circles represent individual subject means. In all three conditions, participants directed significantly more first saccades to the high-probability quadrant. Asterisks denote statistical significance relative to the proportion expected by chance (0.25). * $p < .05$; ** $p < .01$; *** $p < .001$; ns = not significant

Discussion

Participants in Experiment 1 acquired location probability learning when searching with no simulated scotoma, an effect that persisted into testing regardless of whether participants searched with a scotoma. This was true both for response times (participants found targets in the previously target-rich quadrant faster) and the proportion of first saccades (participants directed more first saccades to the rich quadrant). There was no evidence that self-reported awareness influenced these results, though future research should examine this in higher-powered designs. These results demonstrated that, consistent with search with a scene background (Addleman et al., 2021), once participants acquired location probability learning in a no-scotoma training condition, the learned spatial bias persisted without further reinforcement and when searching with a simulated scotoma. That is, the scotoma did not interfere with attentional guidance after the successful acquisition of an implicit spatial bias.

Experiment 2

Experiment 2 was identical to Experiment 1 except that the training phase included the scotoma. While Experiment 1 tested how previously learned attentional biases are affected during scotoma search, Experiment 2 primarily served to test how simulated CVL affects the statistical learning mechanisms supporting probability learning. If statistical learning is intact and, as suggested by results from Experiment 1, attentional guidance is as well, participants should show effects of location probability learning during scotoma and no-scotoma search. If statistical learning is eliminated by CVL as reported in our previous study using natural scenes (Addleman et al., 2021), there should be no effects of learning during either scotoma or no-scotoma search.

Methods

Experimental design and data analyses were identical to those in Experiment 1, except the training phase now contained the scotoma (see Fig. 2, right).

Participants In Experiment 2, we collected data from 24 participants, 19 women and 5 men, with a mean age of 20 years (range: 18-30).

Analysis We conducted analyses of accuracy, RT, and first saccades as in Experiment 1. Again, accuracy was high (over 99% during no-scotoma search and 88% in scotoma search) and did not vary meaningfully across conditions, so we reported RT and first saccades. A computer error prevented the recording of eye tracking data from two participants (this error did not affect the gaze-contingent rendering of the scotoma, only recording of data), so we analyzed RT data from all 24 participants and saccade data from 22 participants.

Results

Acquisition of probability learning: training phase RT Training phase analyses were similar to those in Experiment 1 (Fig. 4a; see Figure S2 for visualization of subject-level data). RTs were faster in the rich condition than the sparse condition during training, $F(1, 23) = 5.19$, $p = .032$, $\eta_p^2 = .18$. RTs became faster across epochs, $F(3, 69) = 16.44$, $p < .001$, $\eta_p^2 = .42$. There was again a condition-by-epoch interaction, $F(3, 69) = 2.92$, $p = .04$, $\eta_p^2 = .11$ reflecting growing probability learning throughout training. This pattern of results suggests that participants were able to acquire probability learning even when trained with a simulated central scotoma.

Persistence of probability learning: testing phase RT Testing results showed that search was slower with the scotoma than without it, $F(1, 23) = 14.83$, $p < .001$, $\eta_p^2 = .39$. Most critically, there was a significant effect of the target quadrant, $F(1, 23) = 5.46$, $p = .029$, $\eta_p^2 = .19$, indicating that probability learning persisted in testing. This effect interacted with epoch, $F(1, 23) = 17.64$, $p < .001$, $\eta_p^2 = .43$, as the effect diminished in epoch 6 relative to epoch 5. This effect did not interact with either target quadrant or epoch, suggesting that scotoma status did not affect the magnitude or extinction of probability learning. This was confirmed by a Bayesian ANOVA, in which a model with the main effects of target quadrant and vision status was preferred to one with both main effects and their interaction (the ratio of Bayes Factors was 4.73 in favor of no interaction). Overall, results demonstrated persistent probability cueing into testing that did not depend on whether participants searched with or without a scotoma. Figure 5b-c show RT data from testing.

Direction of the first saccadic eye movement We expected first saccade data to follow the same pattern as RT data. This was the case in training (which included the scotoma), where more first saccades were directed to the rich quadrant (M = .39, SE = 0.04) than expected by chance, $t(21) = 3.79$, $p = .001$, $d = 0.81$. In scotoma search during testing, participants again directed first saccades to the rich quadrant at above-chance rates, (M = .35, SE = .03), $t(21) = 3.16$, $p = .005$, $d = .67$. The same general pattern was found for no-scotoma search in testing (M = .32, SE = .04), but was only marginally significant, $t(21) = 1.99$, $p = .060$, $d = .42$. The proportion of first saccades to the rich quadrant did not reliably differ between scotoma and no-scotoma search in testing, $t(21) = 1.22$, $p = .234$, $d = 0.26$, and a Bayesian t-test yielded

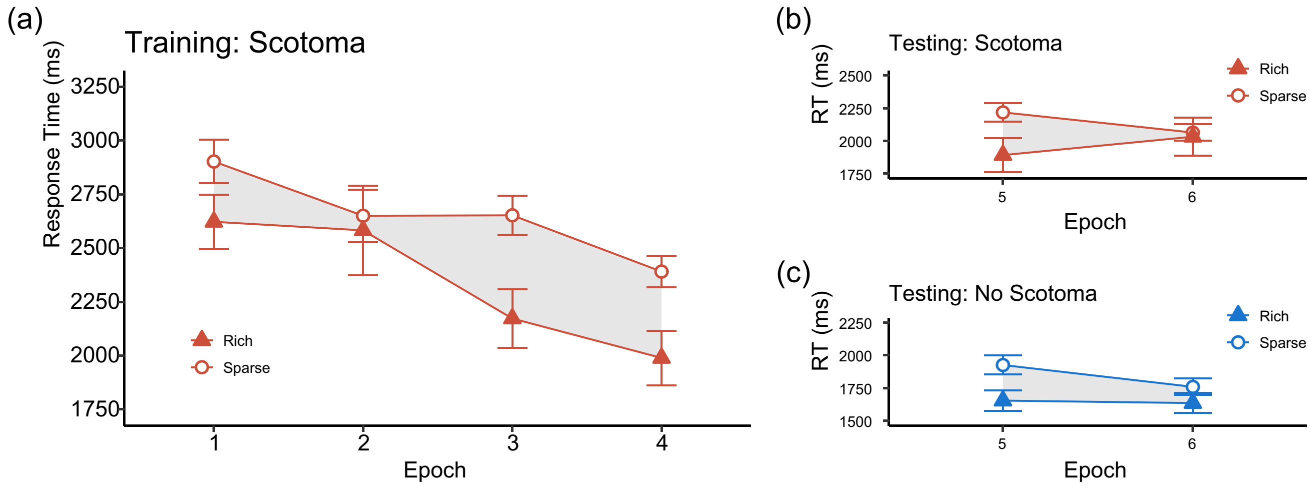

Fig. 5 Response times for Experiment 2, plotted by epoch and separated by whether the target occurred in the rich quadrant or a sparse quadrant. (**a**) Data from the scotoma training phase. (**b**) Data from the scotoma testing blocks, which contained targets equally often in all quadrants. The target quadrant by vision status interaction was not significant, so data were analyzed together with no-scotoma search shown below. (**c**) Data from the no-scotoma testing blocks. Together with scotoma testing blocks, participants responded faster when targets were in the rich quadrant versus a sparse quadrant, an effect which diminished from epoch five to six but was significant in both epochs. Error bars denote +/- 1 S.E. of the mean

minor evidence for no difference ($BF_{10} = 0.43$). Overall, participants in Experiment 2 learned to direct more first saccades towards the rich quadrant than other quadrants, an effect which possibly transferred to scotoma search. Figure 6 shows first saccade data from Experiment 2.

Awareness Awareness analyses were conducted as in Experiment 1. There were 16 unaware and eight aware participants. Figures S7-S10 in the supplementary material show Experiment 2's RT and first saccade data separated by awareness. In all cases, the strength of evidence was weaker for a Bayesian model including the interaction and main effects of quadrant and awareness than the model including only the main effects of awareness and quadrant, though in some cases this evidence was negligible (ratios of quadrant BF to interaction BF were 1.18, 2.93, and 2.07 for training, scotoma testing, and no-scotoma testing, respectively). This is consistent with moderate evidence against the effect of awareness on location probability learning, in line with null-hypothesis significance testing using repeated-measures ANOVA (Fs < 1 for all quadrant-awareness interactions).

We again compared the proportion of first saccades to the rich quadrant in unaware (two excluded for corrupted eye tracking datafiles; analyzed N = 14) and aware participants (N = 8). This proportion did not significantly differ between aware and unaware participants. This was true for search with no scotoma, $t(20) = 1.69$, $p = .106$, $d = 0.75$, and for search with the scotoma, $t(20) = 0.48$, $p = .640$, $d = 0.21$. Bayesian tests provided negligible evidence for the effect of awareness on saccade direction during search with no scotoma in testing ($BF_{10} = 1.05$, negligibly favoring the alternative hypothesis), but did provide minor evidence for the lack of an awareness effect during scotoma search ($BF_{10} = 0.43$).

Discussion

Experiment 2 showed that participants could learn to bias attention to the high-probability quadrant even when trained to search with the central scotoma. These results diverged from data from participants learning to search for letters amidst natural scenes (Addleman et al., 2021). Whereas search among scenes produced probability learning only when participants could accurately identify the rich quadrant, search without a background scene resulted in location probability learning that did not depend on awareness. This was supported by Bayesian tests demonstrating moderate evidence for the lack of an effect of self-reported awareness on probability learning. These results show that simulated scotomas did not eliminate location probability learning during letter search.

General Discussion

In this study, we found that location probability learning was not eliminated in participants searching for simple stimuli with a simulated scotoma. In Experiment 1, participants who first learned to bias attention toward a specific location when finding targets there more often also biased attention to that region when searching with a simulated scotoma during the testing

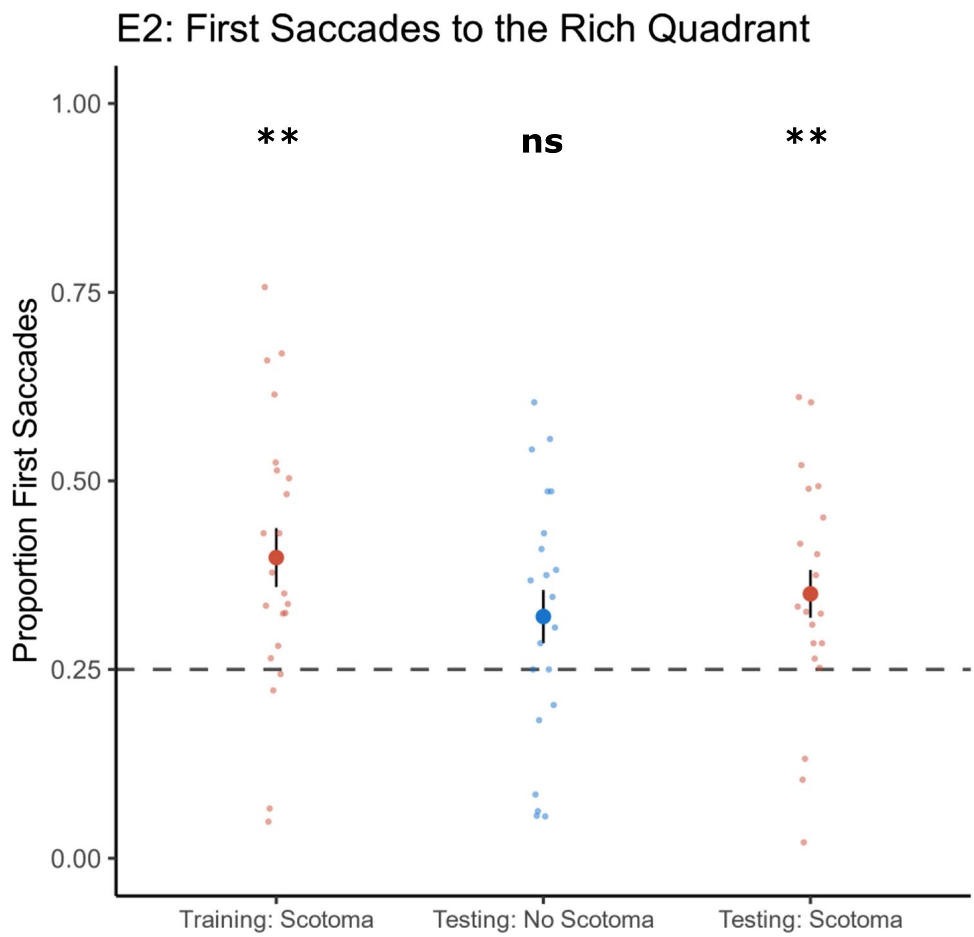

Fig. 6 In Experiment 2, the proportion of first saccades to the high-probability quadrant in the training phase (no-scotoma), and testing phase (separately for no-scotoma and scotoma search). Large circles represent overall means and small circles represent individual subject means. Participants directed significantly more first saccades to the rich quadrant during scotoma search in both training and testing; in testing with no scotoma, the same general pattern was found but was not statistically reliable. Asterisks denote statistical significance relative to the proportion expected by chance (.25). * $p < .05$; ** $p < .01$; *** $p < .001$; ns = not significant

phase. Thus, simulated scotomas did not impair guidance based on previously learned target location probabilities. In Experiment 2, participants acquired probability learning when searching with a scotoma, an effect which persisted into testing regardless of scotoma condition. The acquisition of attentional biases during scotoma search indicates that statistical learning mechanisms are not eliminated by simulated central vision loss. These attentional biases manifested both in RT advantages when targets occurred in the rich quadrant and in the proportion of first saccades directed to the rich quadrant. Together, these results reflect the extraordinary durability of attentional learning to simulated central vision loss.

The role of scene context in implicit spatial attention

Unlike our recent study using a similar paradigm but with search for items amidst natural scenes (Addleman et al., 2021), here the effects did not depend on whether participants could correctly identify the high-probability quadrant following the search task. This is consistent with evidence from contextual cueing suggesting that scene information induces explicit awareness of, and voluntary attention based on, repeated target-distractor relationships (Brockmole & Henderson, 2006a, 2006b). Related work on contextual cueing with a simulated scotoma suggest that implicit, but not explicit, effects of contextual cueing paradigms are eliminated by simulated scotomas: learned guidance is partly preserved when people have some explicit awareness due to scene context (Pollmann et al., 2020), while there is no evidence for implicit effects of contextual cueing during scotoma search through simple displays that are unlikely to produce awareness (Geringswald et al., 2012; Geringswald & Pollmann, 2015). In probability learning, on the other hand, search among scenes shows no evidence of implicitly learned biases (because only aware participants showed learning), whereas location probability learning appeared intact in scotoma search in the present study's simple displays regardless of awareness. Given known difficulties with precise control of spatial attention with simulated scotomas (Bertera, 1988; Kwon et al., 2013; McIlreavy et al., 2012), the divergent results of probability learning and contextual cueing during letter search may reflect the greater difficulty of guiding attention to precise locations based on distractor configurations rather than to a single screen quadrant – a difficulty that can be overcome in the case of contextual cueing that relies on explicit guidance to scene regions.

Differences between effects of CVL on probability learning and contextual cueing may be explained by differences in how they are acquired and implemented (Jiang, 2018). For instance, while contextual cueing largely involves learning the spatial associations between nearby distractors and targets that may be difficult to identify during search due to occlusion from the scotoma (Brady & Chun, 2007), location probability learning involves a consistent pattern of attentional shifts to one region that is likely possible when searching with a scotoma (Addleman et al., 2021). Therefore, we are not surprised that location probability learning is intact during scotoma search. More surprising, however, is that implicit learning appears intact in this simple search paradigm but was absent in unaware participants searching with a scotoma for letters amidst scenes. Even if the presence of scenes caused more participants to voluntarily attend to the high-probability quadrant, this alone does not explain why unaware participants would not show the same implicit learning effects during scotoma search when scenes were added.

One important possibility is that measurement error contributed to the difference in how awareness affected the present study and our experiments using natural scenes. Classifying participants based on a four-alternative forced choice question will inevitably classify some participants as aware who were only guessing, or who only became aware of the bias upon reflecting on it when prompted by the question. Similarly, some proportion of aware participants may have answered the question incorrectly for various reasons (e.g., thinking the target was more often in the left hemifield rather than the upper-left, and incorrectly identifying the lower-left quadrant when prompted). Recent research has highlighted the importance of considering these sources of measurement error in assessments of awareness, suggesting that they may fail to accurately index awareness during the search task itself, particularly in small samples (Giménez-Fernández et al., 2020; Vadillo et al., 2019). Conclusive answers regarding the relationship between central vision loss, probability learning, and visual context will require larger sample sizes, validation of awareness measures and, ideally, tests in clinical populations in addition to those using simulated scotomas.

Even so, the divergent effects of awareness in our data based on the presence of natural scenes are striking and consistent with evidence from contextual cueing. If these patterns do prove reliable, how might scenes disrupt implicit, but not explicit, location probability learning during scotoma search? Perhaps the sharp boundary between scotoma and background introduced by scenes – which provides participants real-time feedback about their fixation location – shifts the balance between explicit and involuntary control of spatial attention. Another possibility is that, in the absence of voluntary attention to the high-probability quadrant, salient regions of the scenes might have out-competed implicit attentional biases in determining where to direct saccades, particularly the initial saccade. This is consistent with our eye tracking analyses from both studies. During scene search, aware participants biased first saccades to the rich quadrant, whereas unaware participants didn't in either scotoma or no-scotoma search. Here, in search without scenes, first saccades were biased to the rich quadrant in scotoma and no-scotoma search regardless of awareness. Together with the pattern of RT data we find across these studies, this suggests that drawing eye movements to salient scene content rather than the rich region, coupled with the difficult search conditions induced by the simulated scotoma, may have eliminated implicit probability learning during search among visual scenes.

Relationship to clinical central vision loss

In addition to showing that learning and guidance mechanisms supporting location probability learning were not eliminated by the simulated scotoma, data from the testing phases of these experiments also shows that learning in one condition induced attentional biases in the other. In fact, rich quadrant advantages in testing were comparable for the trained and the untrained vision status. Past research on the flexibility of location probability learning has shown that whether learning transfers to new tasks or stimulus contexts largely depends on the attentional behaviors involved in the task, rather than what participants see. For instance, learning can transfer from search for a yellow arrow in a natural scene to T-among-L search (Salovich et al., 2018), as both involve serial shifts of attention for a single target. In contrast, learning does not transfer across T-among-L search to a foraging 'treasure-hunt' where participants click on Ts or Ls to gain rewards (Jiang et al., 2015): despite similar stimuli, these tasks require different attentional behaviors that implicit learning can't transfer across. This suggests that, despite known effects of simulated scotomas on eye movement behaviors (Kwon et al., 2013; McIlreavy et al., 2012), these differences are not sufficient to prevent transfer between scotoma and no-scotoma search.

An interesting question for future research is whether this transfer would be expected in clinical populations with central vision loss (i.e., whether biases learned prior to vision loss would persist throughout progressive loss of vision). On the one hand, it is not clear which of our paradigms – presenting search amidst scenes or on a blank background – is a better approximation of central vision loss. While the presence of natural scenes in our previous experiments may be considered more ecologically valid, placing letters on high-contrast black backgrounds that stood out from the scene made this task much different from searching in the real world. Furthermore, these scenes also introduced sharp contrast between the scotoma and the background, providing participants in those experiments with precise fixational feedback which is not present in patients with central vision loss and which likely changes search behaviors (Walsh & Liu, 2014). Thus, perhaps the transfer found in the present experiments would be expected in clinical contexts. On the other hand, it is possible that transfer of learned attentional biases between scotoma and no-scotoma search depends on the relative inexperience of our participants with the scotoma, as research shows that experience with scotomas induces a preferred retinal locus for fixating outside the region of the scotoma (Kwon et al., 2013), after which learning may fail to transfer across these conditions. Given that patients with CVL typically use preferred retinal locations for many everyday behaviors, this is an important question for addressing the clinical implications of our findings (see also Addleman et al., 2021).

Conclusion

This study demonstrated that simulated central vision loss does not eliminate location probability learning during simple T-among-L letter search. By combining search with and without simulated scotomas, we were able to systematically investigate the impact of simulated vision loss on the two main components of probability learning, statistical learning and attentional guidance. Simulated scotomas did not prevent either statistical learning or attentional guidance. These results are in contrast with our previous work investigating probability learning with simulated scotomas within natural scene images, suggesting that combining letter search with natural scenes, as has been done in several recent studies of learned attention, may substantially change how people search in ways that prevent the acquisition of implicit learning, particularly during scotoma search. Future research should continue exploring the relationship between central vision loss, learned attention, and visual context.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13414-021-02416-9.

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References

Addleman, D. A., Legge, G. E., & Jiang, Y. V. (2021). Simulated central vision loss impairs implicit location probability learning. *Cortex*, *138*, 241–252. https://doi.org/10.1016/j.cortex.2021.02.009

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Bertera, J. H. (1988). The effect of simulated scotomas on visual search in normal subjects. *Investigative Ophthalmology & Visual Science*, *29*(3), 470–475. https://www.ncbi.nlm.nih.gov/pubmed/3343102

Brady, T. F., & Chun, M. M. (2007). Spatial constraints on learning in visual search : Modeling contextual cuing. *Journal of Experimental Psychology. Human Perception and Performance, 33*(4), 798–815. https://doi.org/10.1037/0096-1523.33.4.798

Brockmole, J. R., & Henderson, J. M. (2006a). Recognition and attention guidance during contextual cueing in real-world scenes: Evidence from eye movements. *Quarterly Journal of Experimental Psychology* https://doi.org/10.1080/17470210600665996

Brockmole, J. R., & Henderson, J. M. (2006b). Using real-world scenes as contextual cues for search. *Visual Cognition.* https://doi.org/10.1080/13506280500165188

Caldani, S., Chatard, H., Wiener-vacher, S., & Pia, M. (2019). Visual searching capabilities in Age-Related Macular Degeneration (AMD) subjects. *Applied Neuropsychology: Adult*, 1–8. https://doi.org/10.1080/23279095.2019.1678158

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*(1), 28–71. https://doi.org/10.1006/cogp.1998.0681

Crabb, D. P., & Taylor, D. J. (2017). Searching for unity: Real-world versus item-based visual search in age-related eye disease. *Behavioral and Brain Sciences*, *40*, e135. https://doi.org/10.1017/S0140525X16000054

Geng, J. J., & Behrmann, M. (2002). Probability cuing of target location facilitates visual search implicitly in normal participants and patients with hemispatial neglect. *Psychological Science*, *13*(6), 520–525. https://doi.org/10.1111/1467-9280.00491

Geringswald, F., Baumgartner, F. J., & Pollmann, S. (2013). A behavioral task for the validation of a gaze-contingent simulated scotoma. *Behavior Research Methods*, *45*(4), 1313–1321. https://doi.org/10.3758/s13428-013-0321-6

Geringswald, F., Baumgartner, F., & Pollmann, S. (2012). Simulated loss of foveal vision eliminates visual search advantage in repeated displays. *Frontiers in Human Neuroscience*, *6*, 134. https://doi.org/10.3389/fnhum.2012.00134

Geringswald, F., & Pollmann, S. (2015). Central and peripheral vision loss differentially affects contextual cueing in visual search. *Journal of Experimental Psychology. Learning, Memory, and Cognition41*(5), 1485–1496. https://doi.org/10.1037/xlm0000117

Giménez-Fernández, T., Luque, D., Shanks, D. R., & Vadillo, M. A. (2020). Probabilistic cuing of visual search: Neither implicit nor inflexible. *Journal of Experimental Psychology. Human Perception and Performance*, *46*(10), 1222–1234. https://doi.org/10.1037/xhp0000852

Jiang, Y. V. (2018). Habitual versus goal-driven attention. *Cortex*, *102*, 107–120. https://doi.org/10.1016/j.cortex.2017.06.018

Jiang, Y. V., Capistrano, C. G., Esler, A. N., & Swallow, K. M. (2013a). Directing attention based on incidental learning in children with autism spectrum disorder. *Neuropsychology*, *27*(2), 161–169. https://doi.org/10.1037/a0031648

Jiang, Y. V., Swallow, K. M., Rosenbaum, G. M., & Herzig, C. (2013b). Rapid acquisition but slow extinction of an attentional bias in space. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(1), 87–99. https://doi.org/10.1037/a0027611

Jiang, Y. V., Swallow, K. M., Won, B.-Y., Cistera, J. D., & Rosenbaum, G. M. (2015). Task specificity of attention training: the case of probability cuing. *Attention, Perception & Psychophysics*, *77*(1), 50–66. https://doi.org/10.3758/s13414-014-0747-7

Jiang, Y. V., Won, B.-Y., & Swallow, K. M. (2014). First saccadic eye movement reveals persistent attentional guidance by implicit learning. *Journal of Experimental Psychology. Human Perception and Performance*, *40*(3), 1161–1173. https://doi.org/10.1037/a0035961

Kassambara, A. (2020). Rstatix: pipe-friendly framework for basic statistical tests. *R Package Version 0. 6. 0*. https://cran.r-project.org/web/packages/rstatix/index.html

Kleiner, M., Brainard, D., & Pelli, D. (2007). *What's new in Psychtoolbox-3?*

Kwon, M., Nandy, A. S., & Tjan, B. S. (2013). Rapid and persistent adaptability of human oculomotor control in response to simulated central vision loss. *Current Biology*, *23*(17), 1663–1669. https://doi.org/10.1016/j.cub.2013.06.056

McIlreavy, L., Fiser, J., & Bex, P. J. (2012). Impact of simulated central scotomas on visual search in natural scenes. *Optometry and Vision Science, 89*(9), 1385–1394. https://doi.org/10.1097/OPX.0b013e318267a914

Morey, R., Rouder, J. N., Jamil, T., Urbanek, S., Forner, K., & Ly, A. (2015). *Package "BayesFactor."*

Pennington, K. L., & Deangelis, M. M. (2016). Epidemiology of age-related macular degeneration (AMD): associations with cardiovascular disease phenotypes and lipid factors. *Eye and Vision*, 1–20. https://doi.org/10.1186/s40662-016-0063-5

Pollmann, S., Geringswald, F., Wei, P., & Porracin, E. (2020). Intact contextual cueing for search in realistic scenes with simulated central or peripheral vision loss. *Translational Vision Science & Technology*, *9*(15), 1–11. https://doi.org/10.1167/tvst.9.8.15

Rosenbaum, G. M., & Jiang, Y. V. (2013). Interaction between scene-based and array-based contextual cueing. *Attention, Perception & Psychophysics, 75*(5), 888–899. https://doi.org/10.3758/s13414-013-0446-9

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. *Journal of Mathematical Psychology*, *56*(5), 356–374. https://doi.org/10.1016/j.jmp.2012.08.001

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*(2), 225–237. https://doi.org/10.3758/PBR.16.2.225

Salovich, N. A., Remington, R. W., & Jiang, Y. V. (2018). Acquisition of habitual visual attention and transfer to related tasks. *Psychonomic Bulletin & Review, 25*(3), 1052–1058. https://doi.org/10.3758/s13423-017-1341-5

Sisk, C. A., Twedell, E. L., Koutstaal, W., Cooper, S. E., & Jiang, Y. V. (2018). Implicitly-learned spatial attention is unimpaired in patients with Parkinson's disease. *Neuropsychologia*, *119*, 34–44. https://doi.org/10.1016/j.neuropsychologia.2018.07.030

Thibaut, M., Tran, T. H. C., Szaffarczyk, S., & Boucart, M. (2017). Impact of age-related macular degeneration on object searches in realistic panoramic scenes. *Clinical & Experimental Optometry*, 1–8. https://doi.org/10.1111/cxo.12644

Vadillo, M. A., Linssen, D., Orgaz, C., Parsons, S., & Shanks, D. R. (2019). Unconscious or underpowered? Probabilistic cuing of visual attention. *Journal of Experimental Psychology. General*. https://doi.org/10.1037/xge0000632

Walsh, D. V., & Liu, L. (2014). Adaptation to a simulated central scotoma during visual search training. *Vision Research, 96*, 75–86. https://doi.org/10.1016/j.visres.2014.01.005

Open Practices Statement

Experiments were not preregistered. Raw data, experimental code, and analysis code are available at https://osf.io/k3nfh/.