

Tunnel Vision and Beyond: Unveiling Implicit Spatial Learning with the 'Mouse-Eye'**Approach**Shuchen Liu¹Ke Zhou^{1,2}¹*Department of Psychology & ^{1,2}Key Laboratory of Applied Experimental Psychology, Beijing**Normal University***Short title:** Implicit Spatial Learning in Peripheral Vision Loss**Send correspondence to:**

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The authors declare no conflicts of interest to disclose. The data supporting the findings of this study are available in an aggregate form at the following link: <https://osf.io/7s258/>. Study materials are available on OSF. Correspondence should be directed to Shuchen Liu (201911950109@mail.bnu.edu.cn), No. 19, Xijiekouwai Street, Haidian District, Beijing 100875.

Abstract

What is the role of peripheral vision in unconsciously guiding spatial attention? Previous studies using contextual cueing showed that removing peripheral vision during a “tunnel vision” training phase prevented participants from using repeated spatial contexts to speed up visual search. However, in a subsequent full vision testing phase, the previously repeated spatial context facilitated search in one study but not in another. The discrepant findings may be attributed to small sample sizes and the challenges in scaling up gaze-contingent eye tracking. To investigate the impact of peripheral vision loss on implicit attention guidance and to scale up testing, we used a novel, online, “mouse eye” paradigm to simulate tunnel vision. Participants searched for a T target among L distractors over 24 trial blocks, with half of the displays repeated across blocks. During the initial 20 training blocks, participants were tested under tunnel vision conditions, limiting the visible area to the central 6.7 degrees diameter region around the mouse cursor. In contrast to prior studies, with nearly 100 participants, a moderate yet significant contextual cueing effect emerged during training, reflected in faster reaction times in the repeated condition compared to the novel condition. This effect persisted during full-vision testing in the last 4 blocks. Thus, while contextual cueing was diminished under tunnel vision training conditions, it remained significant. These findings underscore the effectiveness of the mouse-eye paradigm. They suggest that implicit spatial context learning remains robust despite peripheral vision loss, offering promise for interventions in individuals with peripheral vision impairments.

Keywords: Visual search; contextual cueing; implicit learning; visual attention; peripheral vision

Introduction

Visual perception typically involves a series of rapid eye movements known as saccades, which direct objects of interest to the fovea - the area of the retina with the highest visual acuity. When central vision is compromised, as in age-related macular degeneration (MD), tasks like reading and recognizing faces become challenging (Congdon et al., 2004). However, peripheral vision also plays a crucial role in perception. Despite its lower acuity, peripheral vision captures the majority of visual input, allowing us to extract global spatial information and comprehend the gist of a scene (Rosenholtz, 2016). Loss of peripheral vision, seen in conditions such as glaucoma and retinitis pigmentosa, significantly impairs a person's ability to navigate their surroundings (Vater et al., 2022).

Central and peripheral vision not only complement each other in visual perception but also help direct visual attention towards relevant aspects of a display. For example, the influential Guided Search Model (now version 6.0) suggests that visual attention operates through two pathways: a selective pathway that shifts attention between objects and a nonselective pathway that assesses the overall scene gist in parallel (Wolfe, 2021). Central and peripheral vision align with the selective and nonselective pathways, respectively. Extensive research has focused on the selective pathway, producing robust quantitative models about the speed and mode (serial, parallel, or a combination) of attentional shifts (Itti & Koch, 2001; Treisman, 1996; Wolfe, 2021). Yet less is known about the role of peripheral vision in guiding the nonselective pathway. The current study aims to explore how peripheral vision contributes to a specific aspect of attention: the implicit guidance of attention towards target locations within repeated spatial contexts, known as spatial contextual cueing (Sisk et al., 2019).

Studies on contextual cueing typically ask participants to perform a visual search task, such as finding a T target among L distractors, with the items appearing in random locations. Unbeknownst to participants, some displays repeat every 20-30 trials, whereas others are new except for the target's location, which also repeats in these novel displays. Even though few participants spontaneously notice the repeated displays, and most cannot reliably distinguish the repeated displays from novel ones in a recognition test, visual search becomes faster on repeated displays compared to novel ones. This finding indicates that the spatial context - specifically, the locations of distractor surrounding the target - acts as a cue for attention, directing spatial attention to the corresponding target location (Chun & Jiang, 1998, 2003; Goujon et al., 2015; Sisk et al., 2019).

Since its initial discovery, contextual cueing has played an important role in establishing implicit selection history as a major driver of selective attention (Awh et al., 2012; Jiang, 2018; Sisk et al., 2019). Learning in this paradigm is largely implicit (though see Vadillo et al., 2020), meaning that few participants are consciously aware of the display repetition (Chun & Jiang, 1998, 2003), and the level of conscious awareness does not appear to be correlated with the magnitude of reaction time (RT) facilitation from repeated displays (Colagiuri & Livesey, 2016).

Another key aspect of contextual cueing is the disproportionate influence of adjacent spatial context compared to the far spatial context. Olson and Chun (2001) found that repeating item locations within the same hemifield as the target resulted in much greater benefits than repeating item locations in the opposite hemifield, underscoring the importance of nearby context over distant context for learning. Brady and Chun (2007) presented compelling evidence that contextual cueing was primarily driven by the local context. In one experiment, they repeated only the locations of distractors in the same visual quadrant as the target, while allowing

distant items to change locations. This quadrant-repetition condition produced the same RT benefit as full-display repetition, a result they successfully simulated in a connectionist network model that characterized learning as driven by the local context. Both the implicit nature and the significance of local context distinguish the “T-among-Ls,” array-based contextual cueing from scene-based contextual cueing. In scene-based contextual cueing, participants search for a target in a specific location within a natural scene. Repeated presentation of the same scene/target combination leads to much faster search RT compared to searching in new scenes (Brockmole & Henderson, 2006). Scene-based contextual cueing involves explicit learning - participants not only recognize the repeated scenes but also have explicit memory of where the target is located within those scenes. It is primarily driven by the global layout of the scene rather than the local context surrounding the target (Brockmole et al., 2006).

The implicit and local nature of array-based contextual cueing has prompted researchers to investigate whether central or peripheral vision plays a more important role in guiding attention implicitly. Geringswald et al. (2013) focused on central vision’s role by testing patients with age-related Macular Degeneration (MD), which impairs central vision. Whereas control participants exhibited contextual cueing, those with MD displayed a smaller contextual cueing effect. To determine whether central vision is crucial for learning the repeated context or for expressing that learning, Geringswald and Pollmann (2015) conducted a follow-up study. They induced an artificial central scotoma in normally sighted participants using gaze-contingent eye tracking during a training phase where repeated and novel displays were intermixed. Participants showed no contextual cueing during this phase, mirroring the impaired contextual cueing observed in MD patients. However, in a subsequent testing phase with intact vision, participants were faster at finding the target on previously trained displays, showing a rebound of contextual

cueing. This rebound implies that participants had acquired latent learning during the scotoma-training phase, but the expression of that learning was hindered by central vision loss. In contrast, participants with age-related MD were still able to acquire scene-based contextual cueing, consistent with the notion that scene-based effects rely more on overall configuration and global perception compared to array-based contextual cueing (Pollman et al., 2020).

Geringswald and Pollmann (2015) extended their two-phase training-testing design to examine the role of peripheral vision in contextual cueing. They simulated “tunnel vision” search conditions using gaze-contingent eye tracking, restricting the visible area to the central 7-degree diameter of the current fixation. After tunnel vision training, participants were permitted to search with full vision. Geringswald and Pollmann (2015) found no evidence of contextual cueing during the training phase, suggesting that peripheral vision was crucial for the manifestation of contextual cueing. Furthermore, they observed no rebound of this effect during the full-vision testing phase, indicating that participants had not acquired latent learning of the repeated context. They concluded that central and peripheral vision played distinct roles in array-based contextual cueing. Whereas central vision loss impaired the expression of learning, peripheral vision loss was detrimental to implicit spatial context learning itself.

Chen and Lee (2024a) expanded on this finding by examining another type of implicitly guided attention - location probability learning. In their study, participants searched for a T target that appeared more frequently in one specific visual quadrant. Under full-vision conditions, participants became faster at locating the target in the quadrant where it appeared most often, and this effect was independent of participants’ explicit awareness of the target’s location probability. In contrast, when participants performed the task with restricted peripheral vision, they only showed location probability learning if they were explicitly aware of which quadrant had the

higher probability of the target appearing. This suggests that tunnel vision search impairs the ability to implicitly learn the location probability of the target.

While the two aforementioned studies suggest that peripheral vision is important for implicit attentional learning, Zang et al. (2015) found evidence that implicit spatial context learning was preserved in participants trained under tunnel vision conditions. Similar to Geringswald and Pollmann (2015), Zang et al. (2015) did not observe contextual cueing during the tunnel-vision training phase, indicating the importance of peripheral vision for the expression of contextual cueing. However, Zang et al. (2015) found a rebound of contextual cueing in the intact-vision testing phase. After tunnel vision training, participants were allowed to search the displays without restriction. Despite not showing contextual cueing during the training phase, participants were faster at finding the target on previously trained, repeated displays compared to novel displays when tested with full vision. This rebound led Zang et al. (2015) to suggest that while peripheral vision loss affected the expression of contextual cueing, it still allowed latent learning to occur.

Even though similar experimental manipulations were used by Geringswald and Pollmann (2015) and Zang et al. (2015), the discrepant findings raise questions about the role of peripheral vision in implicit spatial contextual cueing. Considering the local nature of array-based contextual cueing, it is puzzling that contextual cueing was absent in both studies during the training phase. Participants had access to the local context of distractors surrounding the target when they found it, which should have enabled them to associate the local distractor context with the target. Since repeating the context adjacent to the target produced similar learning as repeating the entire display (Brady et al., 2007), one would expect that learning from the local context would prevail under tunnel vision conditions. Yet Geringswald and Pollmann

(2015) and Zang et al. (2015) found no indication of contextual cueing in the training phase.

Also perplexing was the rebound in Zang et al. (2015)'s intact vision testing phase. How does revealing the entire display, much of which comprises the far context for the target, reintroduces contextual cueing, when learning is presumed to arise from the region adjacent to the target?

Three issues may have contributed to the discrepant findings and lack of resolution to the two studies mentioned above. First, both studies had small sample sizes. Geringswald and Pollmann (2015) tested 25 participants in their tunnel vision condition, while Zang et al. (2015) tested only 13 participants. Previous research has shown that under full-vision conditions, a minimum of 14 participants is needed to achieve a power of .80 for the standard contextual cueing effect (Jiang & Sisk, 2019). Any reduction in effect sizes due to tunnel vision would likely result in much lower statistical power.

Second, it is challenging to scale up studies that use gaze-contingent eye tracking. While eye-tracking technology is becoming increasingly standard in psychology, it remains an expensive tool not available to all labs. Also, conducting in-person eye-tracking studies is technically challenging and time-consuming, which may deter other researchers from replicating the studies with a higher-powered design. In contrast, the online mouse-eye paradigm is accessible at virtually no cost, making it broadly available to a wider range of researchers.

Third, neither Geringswald and Pollmann (2015) nor Zang et al. (2015) provided a clear description of how the full-vision testing phase was conducted. In their studies, the testing phase consisted of 5 blocks, meaning each repeated display would have appeared 5 times, offering new learning opportunities. To control for potential new learning, novel displays would also need to repeat in the testing phase. However, neither paper's method section indicated whether repetition occurred for both the repeated and novel displays in the testing phase. This raises the possibility

that any rebound observed in the testing phase could be due to new learning rather than the transfer of learning from the training phase.

To understand the role of peripheral vision in implicit attentional guidance, we conducted three experiments to investigate how tunnel vision affected the learning and expression of contextual cueing. To address concerns about statistical power, we increased the sample size for the tunnel vision experiments, totaling nearly 100 participants in Experiments 2 and 3. To make testing more scalable, we used a “mouse-eye” paradigm (Chen & Lee, 2024b; Jiang et al., 2015) that simulated gaze-contingent eye tracking. In this setup, the mouse cursor served as a proxy for eye fixation, restricting the visible area to the central 6.7-degree diameter around the cursor as participants navigated the display using the mouse. This setup not only eliminated the need for gaze-contingent eye tracking but also enabled online testing, making data collection more efficient.

Our study methodology was an extension of Chen and Lee (2024a, 2024b), who conducted both gaze-contingent eye tracking and mouse-eye tunnel search using a location probability learning paradigm. Chen and Lee’s findings showed strong correspondence between the two methodologies, allowing us to extend their approach to the investigation of contextual cueing. We provide additional discussions about the similarities and differences between the two methodologies in the General Discussion section.

To ensure the reliability of contextual cueing in online testing, we first tested participants in a standard, full-vision contextual cueing task in Experiment 1, using the same stimulus parameters as those used in the tunnel vision task of Experiments 2 and 3. Additionally, to explore how the design of the testing phase influenced the results, we conducted two tunnel vision experiments that differed in whether novel displays were repeated in the testing phase. In

Experiment 2, during the full-vision testing phase, novel displays were newly generated in each testing block, a design likely also used in Geringswald and Pollmann (2015) and Zang et al. (2015). In contrast, Experiment 3 controlled for potential new learning by repeating both the repeated and novel displays in the testing phase. The combination of a large sample size and careful experimental design enabled us to address the role of peripheral vision in contextual cueing. These experiments elucidated the effects of peripheral vision loss on implicit attentional guidance and helped resolve contradictory findings from previous studies.

Experiment 1

Experiment 1 used a full-vision, standard contextual cueing task to establish a baseline for comparison with Experiments 2-3 involving tunnel vision. This baseline is needed because unlike previous contextual cueing studies (Jiang & Sisk, 2019), the current study was conducted online, resulting in increased variability in testing conditions such as monitor size and viewing distance. In addition, the tunnel vision task in Experiments 2 and 3 restricted certain screen locations from containing search items. Therefore, it is important to demonstrate that we can still observe a strong contextual cueing effect using the same stimulus parameters as those used in Experiments 2 and 3. Because of the minor differences in stimulus parameters, Experiment 1 was not meant as a quantitative comparison with previous in-person studies that allowed items to be in central locations and in the far corners of the screen. Rather, Experiment 1 provided a qualitative comparison with previous in-person studies, but a quantitative comparison with the mouse-eye experiments (Experiments 2-3) that used the same stimulus parameters.

Building on the methodology used by Chen and Lee (2024b), we were able to standardize viewing angles despite variations in viewing distance and monitor size. Specifically, we

implemented Q. Li et al. (2020)'s "virtual chinrest" technique to estimate viewing distance. In this procedure, participants used a standard-sized real-world object (e.g., a credit card) to adjust the size of a rectangle on the screen, allowing us to determine their monitor's pixel size. Subsequently, participants tracked a moving dot with their left eye until the dot disappeared into their blind spot. Since the horizontal distance between the fovea and the blind spot is consistent across individuals, this method enables us to estimate viewing distance. With these two measures, we could adjust stimulus size to ensure that the visual angles were what we intended, regardless of the pixel size and viewing distance of the participants.

Method

Participants

Sample Size Determination. According to Jiang and Sisk (2019), the typical effect size, Cohen's d , in standard contextual cueing studies ranges from 0.84 to 0.99. A sample of 14 participants is needed to reach a power of .80 at an alpha-level of .05 in a two-tailed test. Owing to increased variability in online testing relative to in-person testing, we pre-specified 24 as the targeted sample size for Experiment 1. Effect sizes in the tunnel vision experiments are likely smaller, leading us to pre-specify 48 as the targeted sample size in Experiments 2 and 3. Forty-eight also matched the sample size of a recent study on tunnel vision search (Chen & Lee, 2024b).

Participant Characteristics. Participants enrolled in this study met the following criteria. Healthy adults aged between 18 and 45 years, possessing normal or corrected-to-normal visual acuity, proficient in English, no history of neurological or psychiatric conditions, no cognitive impairments, naive to the study design, and their computer's viewport size (i.e., visible

size in pixels within the browser) was adequate to present the entire search display. Furthermore, they were required to complete the experiment on a Desktop or Laptop computer with a vertical refresh rate of 60 Hz. The testing procedure used the PsychoPy program (v2023.2.3; Peirce et al., 2019), which detected and recorded the monitor refresh rate. The Beijing Normal University Institutional Review Board approved the study procedures.

The 24 participants in Experiment 1 included 3 females and 21 males, with a mean age of 29.3 years (S.D. = 8.2).

Material, Equipment, and Procedure

Participants who satisfied our inclusion criteria were provided with an online testing link. They were directed to carry out the task in a noise-free environment using a desktop or laptop computer with a refresh rate of 60 Hz. The informed consent process took place on Qualtrics, after which participants were redirected to Pavlovia.org for the virtual chinrest test and the experiment.

Virtual Chinrest Test. Our experiments were conducted online. Although we cannot keep participants at the same viewing distance or force them to use the same screen or pixel size, we were able to measure their screen pixel size and estimate their viewing distances. First, to measure the pixel size, we asked participants to adjust a rectangular area to match the size of a standard-sized card, such as a driver's license or credit card (85.6 mm in width). This, along with the automatically returned values about their screen setup (e.g., 1,920 x 1200 pixels), allowed us to calculate the size of a pixel on the participant's screen and ascertain their viewport size.

Second, to estimate viewing distance, we used a "virtual chinrest" to measure where the participants' blindspot was. Relying on the fact that the horizontal distance between one's blindspot and the fovea was 13.5°, and knowing the distance between the fixation point and the

entry to the blindspot, this allowed us to measure the number pixels corresponding to 13.5° visual angle. To this end, participants were asked to sit at a comfortable distance from the screen, cover their right eye, and keep their left eye's focus on a black square on the right side of the screen. A red circle smoothly moved from the fixation point to the left side of the screen. Participants were directed to covertly track the red circle's movement while maintaining fixation on the black square, pressing the spacebar the moment the red circle vanished from sight (i.e., entered the blindspot). In this setup, the black square served as then fixation point, while the red dot helped identify the blindspot location. By recording when the red dot disappeared from sight, we estimated the participant's viewing distance. The blindspot test was repeated seven times. After removing the maximal and minimal measurements, we averaged the remaining five observations which recorded the location of where the red circle disappeared to estimate the blindspot location. Relying on the fact that the blindspot is approximately 13.5° horizontally from the fixation (Q. Li et al., 2020), we determined the participants' viewing distance. In combination, these parameters provided us with (1) the viewing distance of the individual, and (2) their screen pixel size. With these two values, we then adjusted our stimulus size, such that at the measured viewing distance and with the specific monitor, our stimuli were presented at the same (and known) visual angle to all participants. Participants were instructed to maintain this viewing distance throughout the experiment.

Stimuli. The letters, each measuring $1^\circ \times 1^\circ$, were presented against a gray background and positioned in randomly selected locations drawn from a 10×10 invisible grid ($17^\circ \times 17^\circ$) within a white rectangular boundary, except that the central 16 cells (4 x 4 grid) and 3 out-most cells in each corner of the screen could not contain a search item. The central cells were excluded because they covered the initial mouse location of Experiments 2 and 3, bypassing the need to

move the mouse. The corner cells were excluded because they were often missed unless participants aimed their mouse cursor at those extreme locations. The 12 items were evenly distributed to the four quadrants, with 3 items per quadrant. To guarantee consistent real-time visual updates for all participants in subsequent mouse-eye experiments, we required that tests be conducted on monitors with a 60 Hz refresh rate.

Practice. The experiment began with 12 trials of practice where all items were constantly visible. Participants clicked on a central fixation point to initiate a trial. Their task was to locate the letter T and identify its orientation as accurately and as quickly as possible, pressing the A key for a left-facing T and the S key for a right-facing T. Upon the keypress response, the search display was cleared, and participants received feedback— “correct!” printed in green for 200ms following a correct response or “incorrect!” printed in red for 2s after an incorrect response. Following the practice trials, participants received a multiple-choice question about what their task was. All participants correctly answered this question.

Main Experiment. In the main experiment, participants first completed 20 blocks of trials in a training phase, with a brief, self-paced break between blocks. Item locations and trial order were individually randomized for each participant, selected from a pool of 12 pre-designed stimulus condition files that differed in the item locations used for the repeated and novel displays. Each block comprised 16 trials, with 8 displays repeatedly presented across blocks. The remaining 8 displays were newly created for each block, with the constraint that the target’s location also repeated across blocks. Following the method described by Jiang and Sisk (2019), we controlled for the target’s eccentricity between the repeated and novel displays. Specifically, for a given repeated display with a target located at coordinates $[x, y]$, there was a novel display with a target located at coordinates $[-x, -y]$. Finally, the target appeared in each of the four

quadrants equally often in both the repeated and novel displays. After each block, participants were presented with the accuracy and mean response time for that block.

Following the training phase, participants continued with 4 additional blocks that were designed the same way as in the training phase. These last 4 blocks were labeled the “testing phase” to facilitate comparison with Experiments 2-3. No specific instructions were given regarding the phase transition, and no change in viewing condition or design occurred.

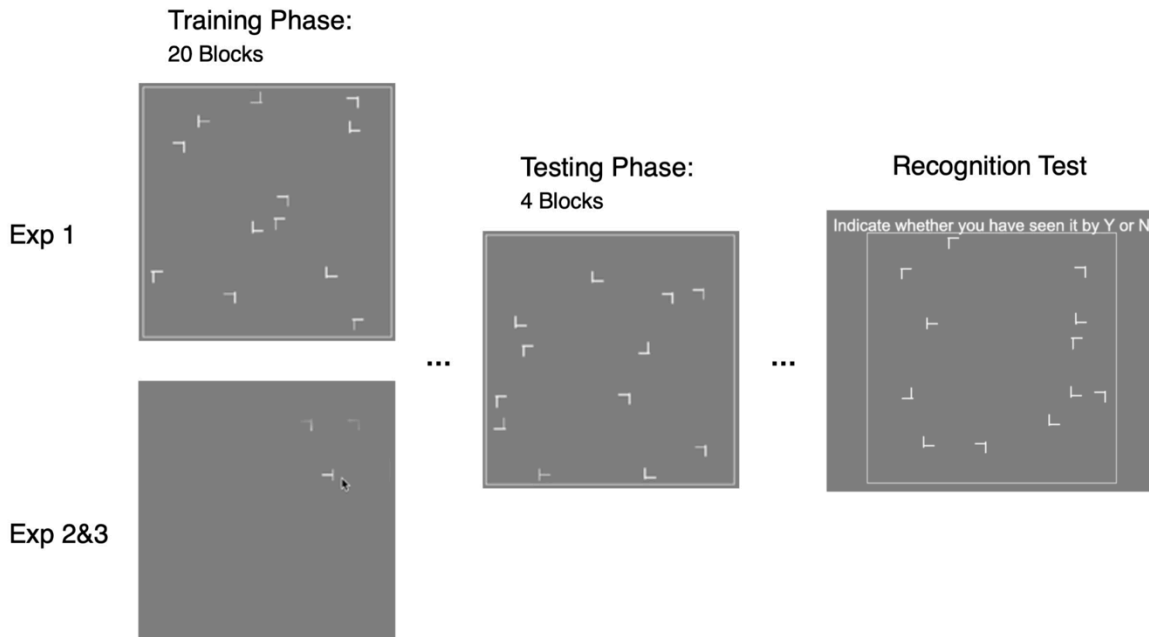


Figure 1. Diagram of search display and experimental design. Participants completed 20 blocks of training (8 repeated and 8 novel displays in each block) and 4 blocks of testing. Training was done under full vision conditions in Experiment 1 and tunnel vision conditions in Experiments 2 and 3. In the tunnel vision condition, participants engaged in the search task by moving the mouse cursor, and a circular area with a diameter of 6.7 degrees centered around the cursor was visible. Testing was done under full vision conditions in all experiments. The recognition test had one block of 16 displays (8 repeated and 8 novel).

Post-experiment Recognition Test. At the completion of the experiment, participants answered the following questions that gauged their awareness of the repeated configuration. First was, “During the experiment, did you notice that some displays were repeatedly presented across blocks?” Regardless of their answer, participants were then told that some displays were indeed repeatedly presented across blocks in the experiment. Following this disclosure, the recognition test included the original 8 repeated displays and another 8 newly generated displays presented in a random order. Participants were asked to indicate whether they had seen each display during the experiment by pressing Y for “yes” or N for “no.” No feedback about recognition response accuracy was given.

Data Exclusion

Three data exclusion criteria were applied for the analysis of RT. First, participants whose average accuracy fell below 90% were replaced. No participants in Experiment 1 were excluded according to this criterion. Second, trials with RT shorter than 200ms or longer than 3SD of an individual’s mean RT were removed from the RT analysis. This criterion led to the exclusion of 3.06% trials from Experiment 1. Third, RTs were analyzed for correct responses only.

Data Analysis

We performed all the statistical tests on response accuracy and RT using R (version 4.3.1; R Core Team, 2023). To increase statistical power we binned 24 blocks in the visual search task into 6 epochs, with 4 blocks in each epoch. The first five epochs were labeled the training phase while the last epoch was labeled the testing phase. Analyses of variance (ANOVAs) were performed using Type III sums of squares, and the alpha level for all statistical tests was 0.05.

To investigate contextual cueing, we conducted repeated-measures ANOVAs with within-subjects factors epoch and configuration for the training phase (epochs 1-5 in Experiment

1). To assess the end result of training, we conducted paired-samples t -test on the mean RT from the final training epoch, Epoch 5, between the repeated and novel displays. To assess the size of contextual cueing in the testing phase, we conducted paired-samples t -tests on the mean RT from the testing epoch, Epoch 6, between the repeated and novel displays. Effect sizes were indexed by partial eta squared (η_p^2) in ANOVA and Cohen's d in t -tests.

In addition, we studied the role of explicit awareness by gauging participants' awareness score, computed as the sensitivity measure d' from the forced-choice responses in the recognition task. We tested whether the mean d' across participants was significantly above zero. We also measured Pearson's correlation between each individual's recognition d' and their size of contextual cueing, indexed by the percentage of RT saving in the repeated condition relative to the novel condition (novel RT minus repeated RT divided by the mean RT of the two conditions). The correlation was conducted for the final training epoch (Epoch 5) and the testing epoch (Epoch 6) separately. To adjust for multiple-comparison errors, the critical alpha for the recognition Pearson's correlation analysis was set to .025.

The data supporting the findings of this study are available in an aggregate form at the following link: <https://osf.io/7s258/>. Study materials are available on OSF.

Results

Accuracy

Mean accuracy across all 6 blocks was high, 97.9% (SE = 0.29%) in the novel condition and 97.9% (SE = 0.31%) in the repeated condition. This difference was not significant, $t(23) = 0.097$, $p = .924$, Cohen's $d = 0.020$. We analyzed RT from correct trials, after removing outliers.

RT

Figure 2 displays mean RT across the six epochs. Although participants performed the search task under intact vision conditions in all epochs, this was not the case in subsequent experiments, where tunnel vision occurred in the first 5 epochs and intact vision in the 6th epoch. To enable comparisons across experiments, we designated the first 5 epochs as the “training phase” and the last epoch as the “testing phase.”

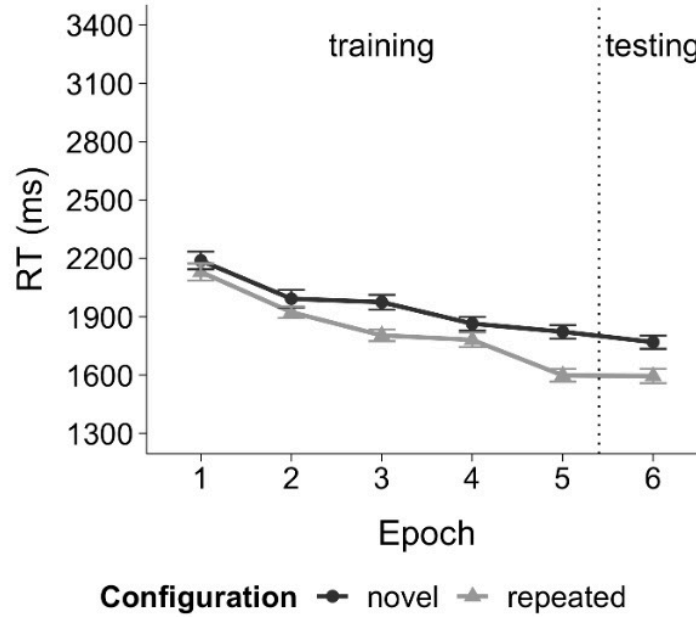


Figure 2. Mean RT in Experiment 1 across the 6 epochs (1 epoch = 4 blocks). Participants were trained and tested under full-vision conditions. Epoch 6 was labeled as the “testing phase” for comparison with subsequent experiments; it did not differ from the other epochs in design in Experiment 1. Error bars show ± 1 within-subject S.E.M.

Training Phase with Intact Vision. A repeated-measures ANOVA on RT using configuration (novel vs. repeated) and epoch (1-5) as factors revealed a significant main effect of configuration, $F(1, 23) = 10.559, p = .004, \eta_p^2 = .315$, showing faster RT in the repeated than the novel condition. The main effect of epoch was significant, $F(4, 92) = 14.809, p < .001, \eta_p^2 =$

.392, as participants became faster in later epochs than earlier ones. There was also a significant interaction between the two, $F(4, 92) = 2.708, p = .035, \eta_p^2 = .105$. The Helmert contrast showed that the difference between the repeated and novel configurations became greater in later epochs relative to the earlier ones, $t(159) = 5.909, p < .001$, indicating that the contextual cueing effect increased with training.

We calculated the size of contextual cueing in the final training epoch, Epoch 5, to facilitate comparisons with subsequent experiments. The repeated condition was 224 ms faster than the novel condition, $t(23) = 6.624, p < .001$, Cohen's $d = 1.352$. This corresponded to a 12.3% RT saving.

Testing Phase with Intact Vision. A paired-samples t -test on mean RT in the testing phase showed that participants were significantly faster in the repeated condition than the novel condition, $t(23) = 3.374, p = .003$, Cohen's $d = 0.689$. The repeated condition was 174 ms faster than the novel condition, corresponding to a 9.9% RT saving.

Role of Awareness

The average accuracy for all participants in the recognition task was 50.5% (SE = 14.0%), a level that did not differ significantly from chance, $t(23) = 0.182, p = .857$. We calculated d' ($Z(\text{hit}) - Z(\text{false alarm})$) for each participant. The mean d' was -0.023 (SE = 0.48), which did not differ significantly from chance, $t(23) = -0.239, p = .813$. But regarding the distribution of d' , it approximated a bimodal distribution. Bayesian analysis for null results revealed a Bayes Factor B_{10} (alternative vs. null; Jeffreys–Zellner–Siow prior) of 0.220, providing strong support for the null hypothesis (Dienes, 2014). Thus, participants could not reliably tell the repeated displays from the novel ones.

For each participant, we computed percent RT saving (the RT difference between the novel and repeated conditions divided by the mean of the two conditions) in the final training epoch (Epoch 5) and the testing epoch (Epoch 6). If awareness contributed to learning, we would expect a significant positive correlation between an individual's recognition d' and their contextual cueing score. To the contrary, the correlation did not differ significantly from zero: Pearson's $r = 0.102$, $p = .635$ between Epoch 5's contextual cueing and recognition d' , and Pearson's $r = -0.158$, $p = .461$, between Epoch 6's contextual cueing and recognition d' . Consistent with previous in-person studies (Chun & Jiang, 1998; Colagiuri & Livesey, 2016), learning in array-based contextual cueing is largely implicit.

Discussion

Using parameters similar to the tunnel vision conditions of subsequent experiments, Experiment 1 revealed a strong contextual cueing effect among participants trained under full-vision conditions. Data collection was conducted online, showing satisfactory data quality in the online sample. Additionally, we found that participants lacked explicit awareness of the repeated displays, supporting previous assertions regarding contextual cueing as a form of implicitly guided attention (Awh et al., 2012; Chun & Jiang, 2003; Sisk et al., 2019). Results from Experiment 1 were qualitatively similar to classical contextual cueing studies (such as Chun & Jiang, 2003), supporting the utility of online testing in this paradigm. We turn next to the role of peripheral vision in contextual cueing.

Experiment 2

In Experiments 2 and 3, to limit participants' peripheral vision, we used the "mouse-eye" paradigm (Chen & Lee, 2024b; Jiang et al., 2015), restricting visible information to the central area with a diameter of 6.7 degrees around the current mouse cursor position. Participants navigated the mouse cursor until locating the target. As identification of items within the visible area requires foveation, the mouse-eye setup restricted visible input primarily to central vision. Following 20 blocks of training (i.e., 5 epochs) under the tunnel vision condition, participants underwent testing in 4 additional blocks (i.e., Epoch 6) with full-vision. During this testing epoch, all items were visible regardless of the mouse cursor's location.

An important consideration in the testing epoch was whether the novel displays were generated for each of the 4 testing blocks or just once before the first testing block and then repeated in subsequent blocks. In principle, an investigation into what participants had learned in the training phase required a design where no additional contextual learning was possible in the testing phase. That is, the novel displays should only be novel at the start of testing; subsequently, they should be repeated in later testing blocks just like the repeated displays (Chun & Jiang, 2003). However, we could not verify if this was the design used in previous studies. Geringswald and Pollmann (2015) described the novel condition as follows: "The other 12 target positions were combined with randomly generated distractor configurations for each experimental block ("novel" condition)" (page 1487). They did not specify if the novel displays were repeated in the testing phase. The only mention of the testing phase was: "During the test phase, the scotoma was removed" (page 1487). Similarly, Zang et al. (2015) stated: "New configurations, by contrast, consisted of eight newly generated displays for each block" (page 809). If the new configurations had been repeated in the testing phase, the authors would likely have mentioned this in the method. The omission of this information suggests that only the

repeated configurations were repeated in the testing phase, allowing for additional learning during that phase.

Faced with this ambiguity, we conducted two experiments that differed in how the new displays were designed in the testing phase. In Experiment 2, novel displays were regenerated for each of the 4 testing blocks, a design likely similar to the previous studies. In Experiment 3, novel displays were generated once at the start of the testing phase. Alongside repeated displays, these novel displays were repeatedly used in all 4 blocks of the testing phase, equalizing the opportunities for new learning of the repeated and novel displays during that phase. The two experiments were otherwise identical, including 20 training blocks under tunnel vision conditions.

These experiments aimed to answer several questions. First, is peripheral vision necessary for contextual cueing in the training phase? If so, contextual cueing may be absent in the training phase of Experiments 2 and 3, as observed by Geringswald and Pollmann (2015) and Zang et al. (2015). Alternatively, the local context around the target, extracted by central vision, may still support contextual cueing. If so, we might observe a significant contextual cueing effect in our high-powered design. The size of the effect may be smaller compared to that in Experiment 1, indicating that peripheral vision enhances contextual cueing. Second, does contextual cueing persist when participants search under intact vision? If so, does this signify a genuine transfer from tunnel vision to intact vision, or is it a result of new learning inadvertently introduced by the imperfect design of Experiment 2?

Method

Participants

We prespecified a targeted sample size of 48, taking into account both the observed effect sizes and the requirements for counterbalancing. Forty-eight new participants from the same participant pool as in Experiment 1 completed Experiment 2. The participants in Experiment 2 included 12 females and 36 males, with a mean age of 28.7 years (S.D. = 7.1).

Design and Procedure

Experiment 2 closely replicated the setup of Experiment 1, except for the viewing condition during the training phase. Instead of making the entire search display fully visible, only the area within the central 6.7° diameter of the mouse cursor was visible. A gaussian filter was applied at the border between visible and invisible areas to mimic a gradual transition. A frame-by-frame analysis showed that 2.83 out of the 12 items were visible on average at any given time. Therefore, participants had reduced access to information in the peripheral regions, prompting them to explore by moving the mouse. The visible region was continuous: whenever the 6.7° window intersected with a segment of a stimulus, the parts of the stimulus within the circular window would become visible.

All study procedures in Experiment 2 were the same as those in Experiment 1, including virtual chinrest test, practice, training phase, testing phase and post-experiment recognition test. Recognition data from both Experiments 2 and 3 are reported after the visual search data report of Experiment 3.

Data Exclusion

We applied the same data exclusion criteria as in Experiment 1. First, no participants in Experiment 2 were excluded for falling below the pre-specified cutoff of 90% in accuracy. Second, 3.09 % individual trials with RT shorter than 200ms or exceeding the outlier threshold (3SD) of the correct trials were eliminated. Last, RTs were examined for correct responses.

Results

Accuracy

Mean accuracy across all 6 blocks was high for both configuration conditions, despite a restricted search window in the training session. The accuracy for the novel configurations was 97.3% (SE = 0.23%) and for the repeated configurations was 97.1% (SE = 0.25%). This difference was not significant, $t(47) = 0.449$, $p = .656$, Cohen's $d = 0.065$.

RT

Figure 3A shows the mean RT across epochs in Experiment 2.

Training Phase with Tunnel Vision. A two-way repeated-measures ANOVA on *mean* RT using configuration (novel vs. repeated) and epoch (1-5) as factors showed a significant main effect of training epoch, $F(4, 188) = 25.521$, $p < .001$, $\eta_p^2 = .352$, showing faster RT in later epochs than earlier ones. The main effect of configuration was not significant, $F(1, 47) = 3.007$, $p = .089$, $\eta_p^2 = .060$, nor did it interact with epoch, $F(4, 188) = 1.279$, $p = .280$, $\eta_p^2 = .026$.

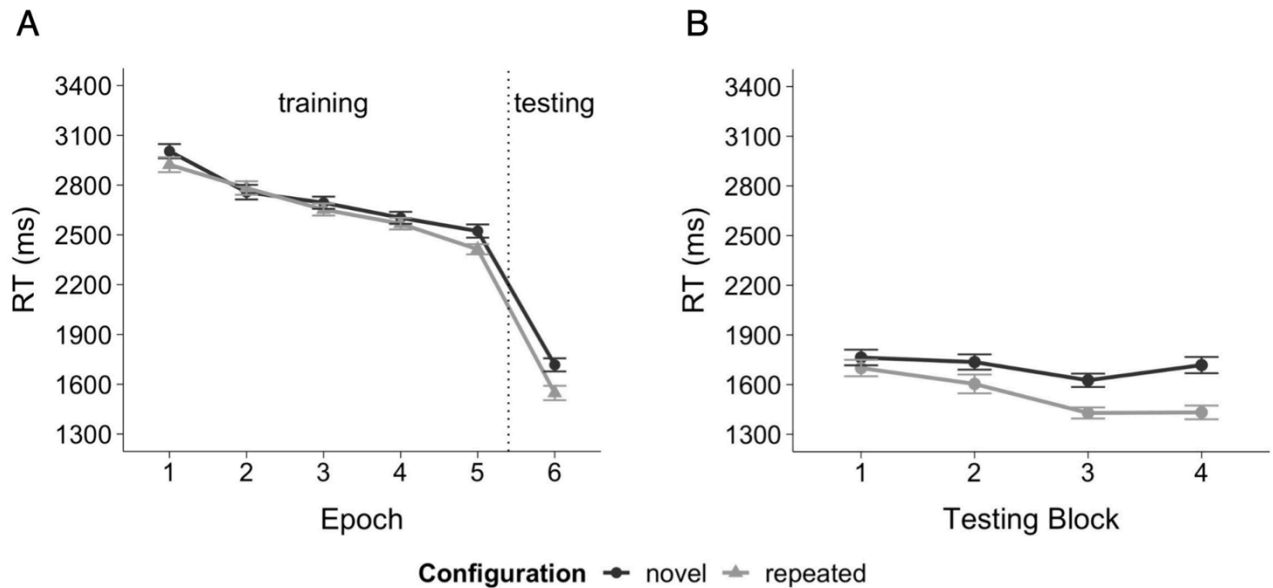


Figure 3. Mean RT in Experiment 2 across the 6 epochs (1 epoch = 4 blocks). Participants were trained under tunnel vision conditions in Epochs 1-5 and under full-vision conditions in Epoch 6. New configurations did not repeat across the 4 testing blocks. A. Data across the 6 epochs (4 blocks per epoch). B. Data in Epoch 6 (testing phase) across the 4 testing blocks. Error bars show ± 1 within-subject S.E.M.

As in Experiment 1, we assessed the size of contextual cueing in Epoch 5, the final training epoch. Although the overall contextual cueing effect in the training phase was not significant, the effect became significant by the end of training. The repeated condition was 108 ms faster than the novel condition in Epoch 5, $t(47) = 3.042$, $p = .004$, Cohen's $d = 0.439$. This corresponds to a 4.3% RT saving.

Testing Phase with Intact Vision. Paired-samples t -test on the testing epoch RT showed a significant main effect of configuration, $t(47) = 3.261$, $p = .002$, Cohen's $d = 0.471$. RT was 170 ms faster in the repeated condition than the novel condition, corresponding to a 9.9% RT saving.

Because repetition of the repeated but not novel displays in the testing phase may have introduced additional learning for the repeated displays, we examined block-by-block data in the testing phase. Figure 3B shows data from the four blocks that constituted Epoch 6. An ANOVA using configuration (novel vs. repeated) and testing blocks (1-4) as within-subject factors showed significant main effects of configuration, $F(1, 47) = 10.636$, $p = .002$, $\eta_p^2 = .185$, block, $F(3, 141) = 8.141$, $p < .001$, $\eta_p^2 = .148$, and their interaction, $F(3, 141) = 2.791$, $p = .043$, $\eta_p^2 = .056$. The Helmert contrast revealed that contextual cueing increased over the 4 successive testing blocks, $t(255) = 3.027$, $p = .003$.

Effects of Viewing Condition

To examine whether tunnel vision impaired contextual cueing, we compared the size of contextual cueing between Experiments 1 and 2. An ANOVA on experiment as a between-subject factor, and configuration (repeated vs. novel) and training epoch (1-5) as within-subject factors showed a significant main effect of experiment, $F(1, 70) = 18.768, p < .001, \eta_p^2 = .211$, as RT was substantially longer in tunnel vision search than in full-vision search. The main effect of configuration was significant, $F(1, 70) = 12.839, p < .001, \eta_p^2 = .155$, demonstrating contextual cueing. The main effect of training epoch was significant, $F(4, 280) = 33.943, p < .001, \eta_p^2 = .327$, showing faster RT in later epochs than earlier ones. Importantly, we found a significant interaction between configuration and experiment, $F(1, 70) = 4.847, p = .031, \eta_p^2 = .065$. That is, contextual cueing was significantly weaker in tunnel vision training than in intact vision training. The interaction between configuration and epoch was significant, $F(4, 280) = 2.411, p = .049, \eta_p^2 = .033$, showing increased contextual cueing in later epochs than earlier ones. The three-way interaction was not significant, $F(4, 280) = 0.768, p = .547, \eta_p^2 = .011$. Thus, contextual cueing was significantly weaker when trained under tunnel vision in Experiment 2 than when trained under full vision in Experiment 1.

We then tested whether contextual cueing was weaker in the testing phase of Experiment 2 relative to Experiment 1. An ANOVA on configuration (repeated vs. novel) and experiment showed a significant main effect of configuration, showing contextual cueing, $F(1, 70) = 17.479, p < .001, \eta_p^2 = .200$. The main effect of experiment was not significant, $F(1, 70) = 0.190, p = .664, \eta_p^2 = .003$, showing comparable search RT in the testing phase between the two experiments. Unlike the training phase, we did not find a significant interaction between experiment and configuration, $F(1, 70) = 0.003, p = .956, \eta_p^2 < .001$. Contextual cueing was

similar in magnitude in the testing phase of Experiments 1 and 2. The repeated condition was faster than the novel condition by 174 ms in Experiment 1, a value comparable to the difference of 170ms in Experiment 2.

Discussion

In Experiment 2, we simulated tunnel vision search using a mouse-eye setup, where only information within the 6.7-degree diameter around the mouse cursor was visible during the training phase. Similar to previous studies by Geringswald and Pollmann (2015) and Zang et al. (2015), tunnel vision search weakened contextual cueing during the training phase. The main effect of configuration was not significant in the training phase. Although it became significant in the final training epoch, we found a significant interaction between configuration and experiment in the training phase, indicating a weaker contextual cueing in Experiment 2 than in Experiment 1 during the training phase.

However, when participants were allowed to view all items in the testing phase, we observed a significant contextual cueing effect that was nearly identical in magnitude to that observed in Experiment 1. This finding supports Zang et al. (2015)'s observation, suggesting that tunnel vision impairs contextual cueing in the training phase but not in the testing phase. Zang et al. (2020) further extended the maintenance of contextual cueing across low- and high-contrast conditions. However, the design used in the testing phase of Experiment 2 complicated the interpretation. Because the novel displays in the testing phase did not repeat across blocks while the repeated displays did, the experimental design allowed for the acquisition of additional contextual cueing during testing. In fact, in the testing phase of Experiment 2, contextual cueing grew in size in each successive testing block, suggesting that the testing phase of Experiment 2

may have reflected not just an effect from training, but also new learning acquired during the testing phase.

To clarify these findings, Experiment 3 used an improved design in the testing phase, where all displays repeated in the four testing blocks.

Experiment 3

Experiment 3 served as both a replication and extension of Experiment 2, featuring an improved design for the testing phase. First, we tested the possibility that although weakened, contextual cueing was significant in the training phase, even under tunnel vision conditions. Experiment 3's training phase was identical to that of Experiment 2, affording another opportunity to examine the potential emergence of contextual cueing during training.

Second, to mitigate the influence of new learning during the testing phase, we repeated both the trained configurations and the novel configurations introduced during testing. To achieve this, at the beginning of the testing phase, we generated a set of 8 novel configurations. These were intermixed randomly with the 8 trained (repeated) configurations to form a single testing block. Subsequently, the same 16 displays were presented in three additional testing blocks, each time in a different random trial order. Consequently, participants encountered every configuration four times during the testing phase, thereby ensuring that any contextual cueing effect during testing could be attributed only to differences in the training phase.

If peripheral vision loss impairs both the acquisition and expression of contextual cueing, as suggested by Geringswald and Pollmann (2015), then we would expect a lack of configuration effect in both the tunnel-vision training and the intact-vision testing phases. Alternatively, if peripheral vision only disrupts the expression of learning but not latent learning, then the

configuration effect should be absent during the tunnel-vision training phase but present during the intact-vision testing phase. Finally, it is possible that tunnel vision diminishes the expression of contextual cueing without eliminating it. In this case, contextual cueing, albeit weakened, may manifest during the training phase and rebound in the testing phase.

Method

Participants

Forty-eight new participants were recruited online from the same participant pool as in Experiment 1 and 2. There were 15 females and 33 males with a mean age of 29.29 years (S.D. = 6.49).

Design and Procedure

This experiment was the same as Experiment 2, except for the following change. Unlike the testing phase in Experiment 2, both the old configurations and the new configurations introduced during the first block of the testing phase were repeated across the 4 blocks of the testing phase. The order of the 16 displays was randomized in each testing block.

Data Exclusion

The same data exclusion criteria as in previous experiments were applied here. No participants in Experiment 3 were excluded for falling below the pre-specified cutoff of 90% in accuracy. Trials with RT shorter than 200ms or longer than 3SD of an individual's overall RT were excluded (1.55% of trials). Last, RTs were analyzed for correct responses only.

Results

Accuracy

Mean accuracy across all 6 blocks was high in both conditions: 97.3% (SE = 0.26%) for the novel configurations, and 97.2% (SE = 0.26%) for the repeated configurations. This difference was not significant, $t(47) = 0.440$, $p = .662$, Cohen's $d = 0.063$.

RT

Figure 4A illustrates the average RT across epochs.

Training Phase with Tunnel Vision. A two-way repeated-measures ANOVA on RT using configuration (novel vs. repeated) and epoch (1-5) as factors revealed a significant main effect of epoch, $F(4, 188) = 39.719$, $p < .001$, $\eta_p^2 = .458$, reflecting faster search as training progressed. The main effect of configuration was significant, $F(1, 47) = 5.860$, $p = .019$, $\eta_p^2 = .111$, showing contextual cueing. The interaction between configuration and epoch was not significant, $F(4, 188) = 1.034$, $p = .391$, $\eta_p^2 = .022$.

As in Experiment 1, we assessed the size of contextual cueing in Epoch 5, the final training epoch. The repeated condition was 146 ms faster than the novel condition, $t(47) = 2.801$, $p = .007$, Cohen's $d = 0.404$. This corresponds to a 5.6% RT saving.

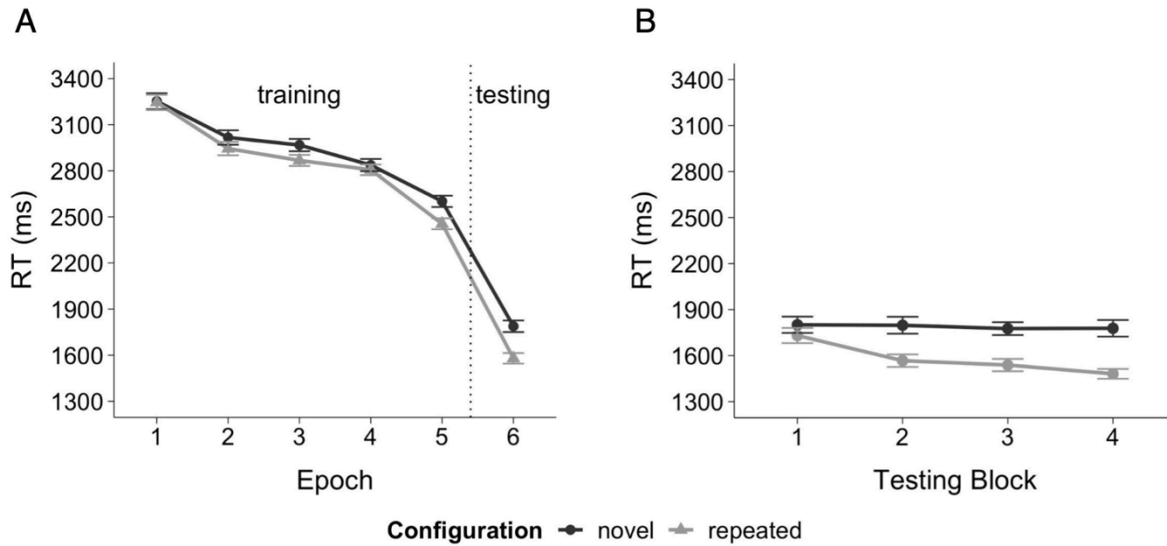


Figure 4. Mean RT in Experiment 3 across the 6 epochs (1 epoch = 4 blocks). Participants were trained under tunnel vision conditions in Epochs 1-5 and under full-vision conditions in Epoch 6. New configurations were novel at the beginning of the testing phase, but were repeated across the 4 testing blocks. A. Data across the 6 epochs (4 blocks per epoch). B. Data in Epoch 6 (testing phase) across the 4 testing blocks. Error bars show ± 1 within-subject S.E.M.

Testing Phase with Intact Vision. By repeating both the novel and the repeated configurations in the testing phase, we equated learning for the two types of displays in the testing phase. A paired-samples t -test on the mean RT in the testing phase revealed a significantly main effect of configuration, $t(47) = 6.176, p < .001$, Cohen's $d = 0.892$. The repeated condition was 209 ms faster than the novel condition, corresponding to a 11.7% RT saving.

Although contextual cueing appeared to be numerically stronger in Experiment 3 than in Experiment 2, a direct comparison showed statistically comparable results. An ANOVA on configuration (repeated vs. novel) and experiment (2 vs. 3) in the testing phase found a significant main effect of configuration, $F(1, 94) = 37.208, p < .001, \eta_p^2 = .284$. However, the main effect of experiment was not significant, $F(1, 94) = 0.341, p = .561, \eta_p^2 = .004$, nor did experiment interact with configuration, $F(1, 94) = 0.397, p = .530, \eta_p^2 = .004$. The fact that contextual cueing was not weaker in Experiment 3, compared to Experiment 2, suggests that any new learning one could gain in Experiment 2's design was relatively insignificant.

Figure 4B shows the block-by-block RT in the testing phase. Although it seems that contextual cueing was smaller in the first testing block, likely due to a sudden change in viewing condition, an ANOVA on configuration and testing block (1-4) showed just a significant main

effect of configuration, $F(1, 47) = 38.149, p < .001, \eta_p^2 = .448$, no main effect of block, $F(3, 141) = 2.611, p = .054, \eta_p^2 = .053$, and no interaction, $F(3, 141) = 2.141, p = .098, \eta_p^2 = .044$.

Effects of Viewing Condition

To examine whether tunnel vision impaired contextual cueing, we compared the size of contextual cueing between Experiments 1 and 3. In the training phase, an ANOVA using experiment as a between-subject factor, and configuration (repeated vs. novel) and training epoch (1-5) as within-subject factors showed a significant main effect of experiment, $F(1, 70) = 45.903, p < .001, \eta_p^2 = .396$, as RT was longer in Experiment 3 than in Experiment 1. The main effect of configuration was significant, $F(1, 70) = 15.219, p < .001, \eta_p^2 = .179$, demonstrating contextual cueing. The main effect of training epoch was significant, $F(4, 280) = 41.437, p < .001, \eta_p^2 = .372$, showing faster RT in later epochs than earlier ones. Importantly, we replicated the significant interaction between configuration and experiment found in Experiment 2, $F(1, 70) = 5.103, p = .027, \eta_p^2 = .068$. That is, contextual cueing was significantly weaker in tunnel vision training of Experiment 3 than in intact vision training of Experiment 1. The interaction between configuration and epoch was not significant, $F(4, 280) = 2.277, p = .061, \eta_p^2 = .031$. The three-way interaction was not significant, $F(4, 280) = 0.148, p = .964, \eta_p^2 = .002$. Thus, although contextual cueing was significant under tunnel vision training of Experiment 3, the effect was significantly weaker than that of Experiment 1.

We then tested whether contextual cueing was weaker in the testing phase of Experiment 3 relative to Experiment 1. An ANOVA on configuration (repeated vs. novel) and experiment showed a significant main effect of configuration, showing contextual cueing, $F(1, 70) = 40.574, p < .001, \eta_p^2 = .367$. The main effect of experiment was not significant, $F(1, 70) = 0.001, p =$

.976, $\eta_p^2 < .001$, showing comparable search RT between the two experiments. Unlike the training phase, we did not find a significant interaction between experiment and configuration, $F(1, 70) = 0.330, p = .567, \eta_p^2 = .005$. The repeated condition was faster than the novel condition by 174 ms in Experiment 1, an effect that was not greater than the difference of 209 ms in Experiment 3.

Thus, we successfully reproduced the two main findings from Experiment 2. First, contextual cueing was attenuated during the training phase under tunnel vision compared to intact vision conditions. Second, the effect was comparable between the two experiments during the testing phase, when participants were allowed to search under full vision conditions. This latter finding held even when we had equated the opportunities for new learning in the testing phase for the repeated and novel displays in Experiment 3.

Statistical Power

The similarity in design between Experiments 2 and 3 allowed us to perform an analysis that combined data across the two, increasing the statistical power to detect small effects. The two experiments were identical in the training phase, justifying the use of an ANOVA on configuration and training epoch across all 96 participants. This analysis showed a significant main effect of configuration on mean RT, $F(1, 95) = 8.774, p = .004, \eta_p^2 = .085$, showing contextual cueing, and a significant main effect of epoch, $F(4, 380) = 63.388, p < .001, \eta_p^2 = .400$. Owing to the gradual increase in contextual cueing, the interaction between configuration and epoch was not significant, $F(4, 380) = 1.414, p = .229, \eta_p^2 = .015$. However, while the repeated and novel conditions did not differ from each other in the first training epoch (Epoch 1),

$t(95) = 1.150, p = .253$, Cohen's $d = 0.117$, this difference was significant in the final training epoch (Epoch 5), $t(95) = 4.040, p < .001$, Cohen's $d = 0.412$.

By the final training epoch (epoch 5), participants were 127 ms faster in the repeated condition than the novel condition. Cohen's d was 0.412, corresponding to a small effect size. This is in contrast to an effect size of 1.352 in Cohen's d in Experiment 1. Thus, tunnel vision search significantly reduced contextual cueing but did not abolish it in the training phase.

The small effect size in the tunnel search task may explain why previous studies failed to find contextual cueing in the tunnel vision training phase. At a sample size of 13 (Zang et al., 2015), the power to detect the effect reported here (Cohen's $d = 0.412$) was just 0.277. The sample size in Geringswald and Pollmann (2015) was larger – 25 – but still not large enough; the corresponding power to detect the contextual cueing effect was 0.507.

To demonstrate how sample size could influence the statistical results, we ran a simulation by randomly drawing n participants from our sample of 96, and tested for the main effect of configuration in the tunnel-vision training phase. We did this repeatedly for 1,000 times. When n was 13, just 25.2% of the simulation yielded a statistically significant contextual cueing effect. When n was 25, 48.8% of the simulation reached significance. This shows that previous studies may have missed the significant (albeit weakened) contextual cueing effect in the tunnel vision training phase.

Role of Awareness

Experiments 2 and 3 showed that contextual cueing, in a weakened form, survived the loss of peripheral vision. Given that central vision allows participants to see the distractors adjacent to the target upon its detection, the presence of contextual cueing in tunnel vision search

is consistent with the idea that learning is, in part, driven by the local context (Brady & Chun, 2007; Olson & Chun, 2001). However, recently, Chen and Lee (2024b) found that peripheral vision may be needed for implicit attentional guidance, even though central vision alone is sufficient to support explicit attentional guidance. That study used a different attentional cueing paradigm, location probability learning, in which participants learned to prioritize locations containing a search target disproportionately often. In contextual cueing, the target's location probability was equated between the repeated and novel conditions, removing location probability learning as a component of learning. Nonetheless, it is important to investigate whether the significant contextual cueing effect observed in Experiments 2 and 3 was driven by explicit awareness about repeated displays. Unless otherwise noted, this analysis combined data from all 96 participants to achieve maximal power.

The overall recognition accuracy was 58.6% (59.2% in Experiment 2 and 57.9% in Experiment 3), which was significantly above chance, $t(95) = 6.028, p < .001$. The longer time spent searching a display, together with the more deliberate approach in navigating the display with the mouse cursor, may have contributed to increased recognition accuracy in Experiments 2 and 3 compared to Experiment 1.

We computed the recognition d' for each participant, and correlated the d' with percent RT savings in contextual cueing in the last training epoch (Epoch 5). Pearson's correlation was $r = .015, p = .882$ (Figure 5A). We also examined Pearson's correlation between recognition d' and contextual cueing in the testing phase (Epoch 6). The correlation was $r = -0.311 (p = .002)$ across all 96 participants, $r = -0.304 (p = .036)$ in Experiment 2 alone, and $r = -0.342 (p = .017)$ in Experiment 3 alone (Figure 5b). The negative correlation meant that participants who had greater explicit awareness showed less contextual cueing. While counterintuitive, this finding

aligns with previous studies showing that explicit knowledge may hinder implicit learning (Chun & Jiang, 2003; Stadler & Frensch, 1998). Thus, unlike Chen and Lee (2024a; 2024b)’s studies on location probability learning, contextual cueing under tunnel vision search did not seem to be driven by explicit awareness about the repeated displays. If anything, explicit knowledge appeared to be counterproductive.

A previous study has found that explicit awareness of individual repeated configurations may result in greater learning of those configurations (Smyth & Shanks, 2008). We therefore conducted an item-analysis. For each participant, the repeated configurations were divided into two groups – recognized-old were the ones that participants classified as “old” in the recognition task, and unrecognized-old were the ones they falsely claimed to be “new” in the recognition task. If awareness of individual configurations had contributed to contextual cueing, then search RT should be faster for recognized-old than unrecognized-old. Of the 96 participants, 9 did not have trials in both the recognized-old and unrecognized-old conditions (e.g., some of them responded “new” to all the repeated displays), leaving us with 87 participants’ data for this analysis. In Epoch 5, across all 87 participants, mean RT was 2,449 ms, 2,499 ms, and 2,573 ms for the recognized-old, unrecognized-old, and novel displays, respectively. The two types of old displays did not differ from each other, $F(1, 86) = 0.009, p = .927, \eta_p^2 < .001$. Similarly, in Epoch 6, across all valid participants, RT was comparable between recognized old (mean = 1,536 ms, SE = 52.1 ms) and unrecognized old (mean = 1,602 ms, SE = 60.8 ms), $F(1, 86) = 2.121, p = .149, \eta_p^2 = .024$. This finding held in Experiment 2 (recognized old mean = 1,490 ms, unrecognized-old new = 1,635 ms, $F(1, 42) = 2.77, p = .103, \eta_p^2 = .062$) and in Experiment 3 (recognized old mean = 1,581 ms, unrecognized-old new = 1,570 ms, $F(1, 43) = 0.10, p = .755, \eta_p^2 = .002$).

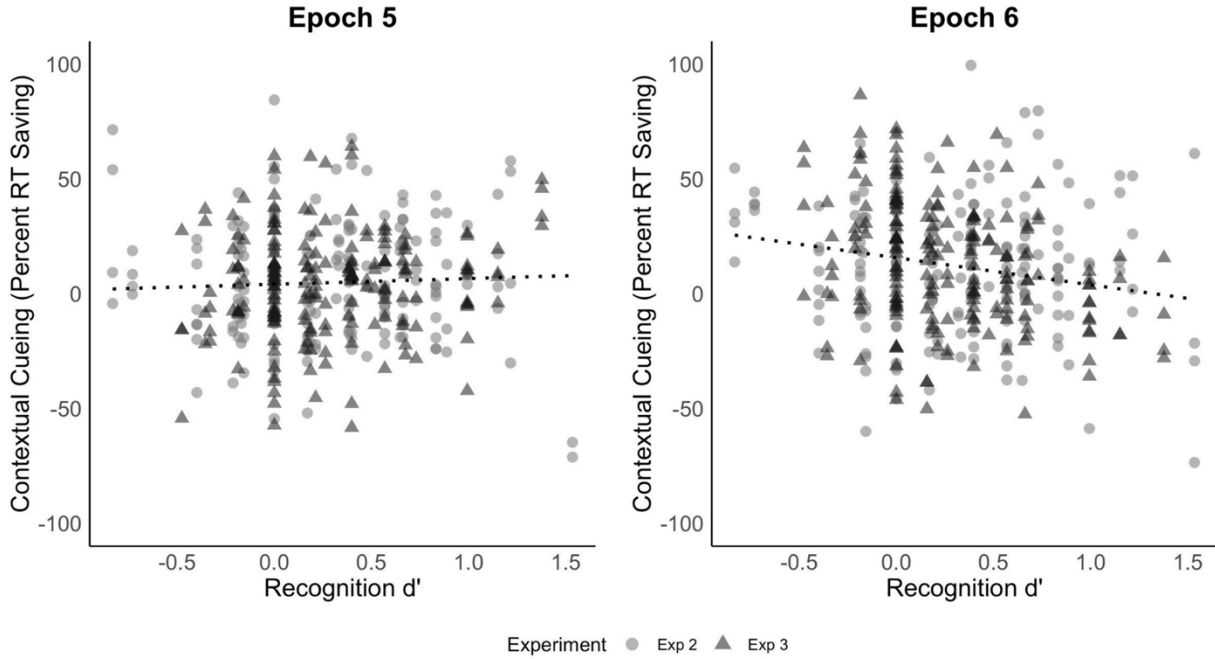


Figure 5. A scatterplot illustrating the relationship between explicit recognition of configurations (d' in discriminating repeated from novel displays) and the percent RT savings in the repeated condition relative to the novel condition in the visual search task. A. The correlation between recognition d' and Epoch 5's contextual cueing. B. The correlation between recognition d' and Epoch 6's contextual cueing. Each triangle or circle symbolizes one participant's data.

In sum, although participants achieved above-chance-level of recognition accuracy in Experiments 2 and 3, explicit awareness did not correlate with contextual cueing in the tunnel-vision training phase, and appeared counter-productive in the intact-vision testing phase. In addition, repeated configurations that were successfully recognized did not yield faster search time than the unrecognized ones. Explicit learning of repeated displays appears to be unconnected to implicit contextual cueing, unlike Chen and Lee (2024a; 2024b)'s finding on location probability learning.

Discussion

Experiment 3 replicated the observation that tunnel vision search diminished contextual cueing compared to search under unrestricted vision. However, tunnel vision did not eliminate contextual cueing. Contrary to findings from prior studies (Geringswald and Pollmann, 2015; Zang et al., 2015), our research demonstrated that significant contextual learning emerged during the training phase, exhibiting a small effect size. The small sample sizes used in previous investigations may not have yielded sufficient statistical power to detect this effect. In fact, when simulating studies with smaller sample sizes using our dataset, it became evident that we would not have reliably detected contextual cueing during the tunnel vision training phase had we included many fewer participants.

Experiment 3 further revealed that contextual cueing, acquired under tunnel vision conditions, persisted even when participants transitioned to full vision conditions. During the full-vision testing phase, both the trained and novel configurations were repeated across the four testing blocks, equating any additional learning for the two types of displays. As a result, the faster RT observed in the trained configurations compared to the novel ones could unequivocally be attributed to tunnel vision training. As far as we know, this finding is the first instance of a persisting contextual cueing effect following a change in viewing conditions. The persistence of contextual cueing may reflect the importance of the local context in learning. Tunnel vision search maintains the local context surrounding the target, thus preserving the learning associated with this context. This preservation could have enabled participants to persist in relying on the local context even when transitioning to full vision conditions.

Although contextual cueing was diminished during the training phase under tunnel vision conditions in Experiment 3 (or 2) compared to the full vision training of Experiment 1, the effect

was not weaker in Experiment 3 than in Experiment 1 in the subsequent testing phase. As participants regained full vision during testing, their overall search RT significantly improved, reaching the same level as that of Experiment 1's testing phase. Importantly, the magnitude of contextual cueing in the testing phase was consistent across all three experiments: 174 ms in Experiment 1, 170 ms in Experiment 2, and 209 ms in Experiment 3. While the effect observed in Experiment 2 might have stemmed from additional learning during the testing phase, contextual cueing in Experiment 3's testing phase could be attributed only to a persisting effect from the training phase. Consistent with Zang et al. 's (2015), our data suggested that tunnel vision search may have impaired the expression of contextual cueing but does not undermine implicit learning itself. Unlike Zang et al. (2015), however, we also demonstrated a significant contextual cueing effect during the training phase. Therefore, the persisting effect observed during testing was not a sudden rebound but rather an effect that could be better expressed once the restricted view was removed.

General Discussion

Mounting evidence shows that peripheral vision plays a pivotal role not only in scene perception and spatial navigation but also in efficiently directing visual attention (Larson & Loschky, 2009; Rosenholtz, 2016; Barhorst-Cates et al., 2016; Chen & Lee, 2024a, 2024b). The rapid extraction of global image statistics guides attention to important regions of the image through a nonselective attentional pathway (Wolfe, 2021). However, the role of peripheral vision in guiding attention implicitly remains unclear. In this study, using a “mouse-eye” paradigm, we found that implicit spatial contextual cueing was reduced, although not eliminated, under conditions of reduced peripheral vision. Upon regaining full vision, participants were able to use

previously encountered repeated spatial contexts to expedite search. Our research not only represents a methodological advancement but also resolves inconclusive findings from previous studies on the role of peripheral vision in implicit contextual cueing (Geringswald and Pollmann, 2015; Zang et al., 2015).

The “mouse-eye” paradigm finds its roots in computer vision research, where researchers use the mouse cursor as a stand-in for eye fixation. Through algorithms, image properties surrounding the cursor, as well as regions at varying distances from it, can be manipulated. This paradigm has proven successful in characterizing the perceptual salience of visual displays, generating attentional saliency maps akin to those derived from gaze-contingent eye tracking (Jiang et al., 2015).

Leveraging the flexibility of the “mouse-eye” paradigm and its potential for online testing, Chen and Lee (2024b) effectively applied this approach to studies involving peripheral vision. In their study, participants performed a T-among-L search task, with visual information limited to the central 6.7-degree diameter around the mouse cursor. Unbeknownst to the participants, the target disproportionately appeared in one visual quadrant, allowing for potential location probability learning. Chen and Lee (2024b) found that participants acquired location probability learning, as evidenced by faster search RT in locating the target in the high-probability quadrant compared to the low-probability ones. However, this learning was only evident in participants who became aware of the target's location probability. Those lacking explicit awareness—meaning they could not identify the high-probability target quadrant - showed no evidence of learning. Conversely, under full-vision search conditions, both aware and unaware participants demonstrated location probability learning.

Chen and Lee (2024b) suggested that peripheral vision is important in implicit location probability learning. When visual input is confined to the central visual field, only explicit learning of the target's location probability occurs. This finding represents a successful extension of an earlier study by the same authors employing gaze-contingent eye tracking (Chen & Lee, 2024a). Therefore, Chen and Lee (2024b) offer compelling evidence that the mouse-eye paradigm effectively mimics gaze-contingent eye tracking. Furthermore, their findings prompt a broader question about whether peripheral vision is indispensable for all forms of implicit attentional guidance, beyond implicit location probability learning. In discussing their findings, Chen and Lee (2024b) considered the possibility that explicit search strategies had interfered with implicit learning. In previous implicit learning research, explicit strategies sometimes, but not always, interfere with implicit learning (Stadler & Frensch, 1998). Being a more complex implicit learning mechanism, contextual cueing may be more likely preserved even with a deliberate search strategy, as demonstrated in the current study.

Spatial contextual cueing, a well-established form of implicitly guided attention, refers to the faster visual search on displays that participants have previously searched, relative to novel displays (Chun & Jiang, 1998; Goujon et al., 2015; Sisk et al., 2019). While studies initially conceptualized contextual cueing as configural, suggesting that participants learned from the repeated spatial layout of distractors to find the target (Chun & Jiang, 1998), later evidence indicates that the local context of distractor locations near the target drives contextual learning (Brady & Chun, 2007; Jiang & Wagner, 2004; Olson & Chun, 2001). For instance, Brady and Chun (2007) showed that repeating distractor locations in the same quadrant as the target induced as much learning as repeating all distractor locations. This localized feature of contextual cueing may allow implicit context learning even in the absence of peripheral vision.

When participants locate and fixate on the target, the local context surrounding it is captured by central vision, preserving crucial spatial cues for learning.

However, two previous studies directly examining the impact of peripheral vision loss have found markedly impaired contextual cueing (Geringswald and Pollmann, 2015; Zang et al., 2015). In both studies, participants were initially trained under a “tunnel vision” condition, limiting their view to items within around the central 7 degrees of their current fixation. Under this condition, participants did not exhibit faster target detection in repeated displays compared to novel ones, indicating a lack of contextual cueing. The two studies diverged on whether they found evidence for latent learning. To discern whether tunnel vision eradicated learning or simply prevented its expression, both studies included a testing phase where participants could see all items. While Zang et al. (2015) observed a rebound of contextual cueing, Geringswald and Pollmann (2015) did not. Unfortunately, these two studies used small sample sizes – 25 in Geringswald and Pollmann and 13 in Zang et al. – which may have contributed to the discrepancy. Thus far, no other studies have attempted a replication to reconcile these findings.

This unresolved issue may, in part, stem from the technical complexity and time-consuming nature of administering gaze-contingent eye tracking. The current study represents our first attempt at testing a large sample of participants in a simulated tunnel vision search task. In Experiment 1, we conducted an online study involving 24 participants under standard full-vision search conditions. We used the same stimulus parameters as in the subsequent tunnel-vision search experiments, facilitating direct comparisons. This experiment demonstrated the viability of obtaining high-quality data through online testing. Contextual cueing was highly significant, generating a large effect size comparable to previous in-person studies (Chun & Jiang, 2003; Jiang & Sisk, 2019). For Experiments 2 and 3, we employed the

mouse-eye setup to restrict visible information to a circular area 6.7-degrees in diameter around the mouse cursor. Given that foveation is necessary to identify each item within this visible area, this setup greatly limited input to the visual periphery, enabling us to gauge the extent of contextual cueing under tunnel vision conditions. With a high-powered design involving a total of 96 participants across the two experiments, we observed a significant contextual cueing effect in the tunnel-vision training phase. Moderate in size, this effect would not have been reliably detected using the smaller sample sizes implemented in previous studies.

Upon restoring full vision in a subsequent testing phase, we found a persistent contextual cueing effect. Notably, this effect was evident across two somewhat different experimental designs. In Experiment 2, novel configurations were generated anew for each of the 4 testing blocks, potentially allowing for new learning. In contrast, in Experiment 3, the same novel configurations were repeatedly used in all four testing blocks, thus equating new learning. Despite this design variance, both experiments demonstrated a significant contextual cueing effect during the testing phase. Furthermore, we conducted additional analyses to explore the correlation between explicit awareness of the repeated configurations and the size of contextual cueing. The correlation was statistically negligible. Moreover, configurations correctly identified as repeated did not result in faster search time compared to configurations falsely identified as novel. Thus, while peripheral vision may be essential for implicit location probability learning (Chen & Lee, 2024a; 2024b), it is unnecessary for implicit contextual cueing.

Our data provide insights into the role of peripheral vision in the acquisition and expression of implicit contextual cueing. Specifically, our findings suggest that although tunnel vision search did reduce contextual cueing during training, the effect remained significant. Furthermore, it persisted during a subsequent testing phase when participants had full vision

restored. Although contextual cueing was weaker during the training phase of the tunnel vision experiments compared to the intact vision experiment, once the restricted view was removed, participants in all three experiments showed similar levels of contextual cueing. Thus, while peripheral vision may enhance the expression of contextual cueing, it is not necessary for its acquisition. Importantly, this observation held regardless of participants' awareness of the repeated displays. Central vision alone appears sufficient to support implicit contextual cueing, likely because of its reliance on the local context.

While we have emphasized the persistence of contextual cueing under tunnel vision conditions, it is important to note that the effect was significantly diminished compared to intact vision conditions during the training phase. In fact, this small effect might have been overlooked with the more conventional sample sizes of 16-24 participants. This reduced effect suggests that peripheral vision indeed plays a role in the expression of contextual cueing. The accessibility of the global layout may have aided in spatially registering the local context (Brady & Chun, 2007). In addition, when participants have full vision, they can access the relevant local context at any time. In contrast, under tunnel vision conditions, the relevant local context becomes available only when participants have moved the mouse to that specific area. This may have limited the usefulness of the repeated context. However, once participants have navigated to the relevant region, they learn the local context around the target, explaining why tunnel vision does not reduce implicit learning itself.

Our study shows that although peripheral vision plays a crucial role in certain forms of implicitly guided attention, such as location probability learning (Chen & Lee, 2024a; 2024b), it is not necessary for others, like spatial contextual cueing. Thus, rather than treating all forms of implicitly guided attention as a single system dependent on peripheral visual input, it is

important to consider the specific nature of each type of learning. Spatial contextual cueing, which relies on local visual context, may proceed unimpeded because tunnel vision alone is adequate for associating repeated contexts with the target's location. Our finding does not support Geringswald and Pollmann (2015)'s conclusion that peripheral vision is essential for spatial context learning. The absence of learning in their study likely stemmed from a small sample size and insufficient statistical power to detect a significant effect.

While our conclusion aligns more closely with that of Zang et al. (2015) regarding the role of tunnel vision search in impairing the expression of learning, our data diverged from Zang et al. (2015) in important ways. Specifically, the small sample size in Zang et al. (2015) likely hindered their ability to detect a significant contextual cueing effect during the training phase. The rebound shown in their full-vision testing phase was puzzling given the complete absence of contextual cueing in the training phase. In contrast, our study, with a much larger sample size, revealed a diminished yet significant contextual cueing effect during tunnel vision training. This effect offered a logical explanation for the persistent contextual cueing observed in the testing phase.

Three factors may have contributed to the stronger training effect found in our study, relative to previous studies: increased sample size, the amount of visible stimuli inside the tunnel, and differences in methodology. First, statistical power was higher in our study due to the substantially larger sample size. If we had used a similar sample size as previous studies, such as a sample of 13, the estimated power for observing contextual cueing in the training phase would have been .277. In fact, resampling our data over 1,000 iterations, using a sample size of 13, found a significant training effect only 25.2% of the time. Second, although we restricted the visible region to a similar size as in previous studies (6.7° in diameter), our displays differed in

such a way that allowed more visible items inside that area. Specifically, because items could not appear in the central 6.8° in diameter or in the far corners, we had fewer possible locations to hold the search items. A frame-by-frame analysis found that, on average, 2.83 out of the 12 items were visible. This value was in between those of Zang et al. 's Experiment 1, which did not find contextual cuing in the training phase, and Experiment 2, which found contextual cueing. Third, the mouse-eye paradigm differed in how visible regions were controlled – by the mouse cursor rather than by eye-movements. This means that as long as the cursor was stationary, the visible area remained the same even when participants moved their eyes. Such eye movements may have facilitated learning (Damiano & Walther, 2019; Henderson et al., 2005). Nonetheless, contextual cueing in the training phase was clearly impaired under the mouse-eye paradigm, as compared with the intact vision condition, suggesting that the contribution from moving one's eyes inside the visible region was limited. Furthermore, in Chen and Lee (2024a; 2024b)'s studies that employed both methods, mouse-eye produced highly similar results to gaze-contingent eye-tracking in location probability learning. Future research is needed to further explore the similarities and differences between the two methodologies.

Our study leaves open the question about how full vision enhanced the expression of contextual cueing. Previous research has demonstrated that both the global configuration and the local item locations contribute to contextual cueing (Brady & Chun, 2007; Jiang & Wagner, 2004). In Brady and Chun (2007), although repeating just items in the target's quadrant induced as much contextual cueing as repeating all the items, the location of this quadrant must be maintained, suggesting that the repeated local context needs to appear in the same global context. However, the precise mechanism through which the global context enhances learning remains unclear. One promising avenue, using the mouse-eye setup, involves introducing various types of

visual degradation to peripheral locations. This could include blurring peripheral items to preserve their locations while concealing their identities, or spatially filtering them in different ways to retain either low- or high-spatial frequency information. Additionally, peripheral items could be relocated between repetitions, similar to the approach used by Brady and Chun (2007). The current study lays the groundwork for such future investigations.

Our study was administered online and therefore relied on participants' compliance with instructions, including the instructions to maintain the viewing distance measured at the beginning of the experiment. We cannot rule out the possibility that participants had deviated from this instruction, at least some of the time. Nonetheless, several factors alleviate concerns about deviation from the initial measured viewing distance. First, contextual cueing is relatively insensitive to viewing distance. Most in-person studies do not constrain viewing distance, and studies have reported viewing distances in the range comparable to our initial "virtual chinrest" measures (Zang et al., 2015; Schlagbauer et al., 2018). Second, the use of a within-subject design ensured that viewing distance was the same for repeated and novel displays. Third, a key part of our conclusion came from the testing phase, where participants searched with full vision. This phase was similar to standard contextual cueing studies, which as noted earlier, typically did not constrain viewing distance. Future efforts to increase compliance, including a second measure of viewing distance at the end of the experiment, will be needed.

Although our study only simulated peripheral vision loss, the findings may inform an understanding of attentional learning in individuals with actual physiological peripheral vision loss. It is possible that some forms of implicitly guided attention persist even in cases of peripheral vision loss. In addition to learning explicit search strategies using their central vision

(Chen & Lee, 2024a; 2024b), patients may continue to benefit from learning local context information extracted from their center of gaze.

Conclusion

Using a mouse-eye paradigm to simulate peripheral vision loss, this study demonstrates that contextual cueing, a form of implicit attentional guidance, remains robust despite the reduction of peripheral vision. Participants tasked with searching displays while restricted to viewing only the central 6.7-degree area around the mouse cursor exhibited faster target detection on repeated displays compared to novel ones. This effect persisted during the subsequent full-vision testing phase. Explicit awareness of the repeated display did not correlate with the magnitude of contextual cueing, indicating that learning was predominantly implicit. Although peripheral vision loss may interfere with certain forms of implicit attention, such as implicit location probability learning (Chen & Lee, 2024a; 2024b), it does not disrupt all forms of implicitly guided attention, particularly when learning relies primarily on local information gathered through central vision.

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Data and Code Availability Statement

Aggregated de-identified data, PsychoPy scripts, and videos confirming script accuracy can be accessed on the Open Science Framework (<https://osf.io/7s258/>).

Conflicts of interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

Shuchen Liu served as lead for data curation, formal analysis, project administration, validation, and visualization. Ke Zhou served as lead for supervision and served in a supporting role for formal analysis. Shuchen Liu and Ke Zhou contributed equally to conceptualization, writing-original draft, writing-review and editing, and methodology.

Ethics Approval and Consent to Participate

The experimental protocol was approved by the Institutional Review Board of Beijing Normal University. All participants provided informed consent online on Qualtrics.

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