Contextual cueing in preview search

Yi Ni Toh¹ · Caitlin A. Sisk¹ · Yuhong V. Jiang¹

Published online: 1 June 2020

© The Psychonomic Society, Inc. 2020

Abstract

Frequently finding a target in the same location within a familiar context reduces search time, relative to search for objects appearing in novel contexts. This learned association between a context and a target location requires several blocks of training and has long-term effects. Short-term selection history also influences search, where previewing a subset of a search context shortly before the appearance of the target and remaining distractors speeds search. Here we explored the interactions between contextual cueing and preview benefit using a modified version of a paradigm from Hodson and Humphreys (*Journal of Experimental Psychology: Human Perception and Performance*, 31(6), 1346–1358, 2005). Participants searched for a T target among L distractors. Half of the distractors appeared 800 ms before the addition of the other distractors and the target. We independently manipulated the repetition of the previewed distractors and the newly added distractors. Though the previewed set never contained the target, repetition of either the previewed or the newly added context yielded contextual cueing, and the effect was greater when the previewed context repeated. Another experiment trained participants to associate the previewed context with a target location, then disrupted the association in a testing phase. This disruption eliminated contextual cueing, suggesting that learning of the previewed context was associative. These findings demonstrate an important interaction between distinct kinds of selection history effects.

Keywords Visual search · Selective attention · Memory

Introduction

Many ordinary activities implicate visual search, such as the act of looking for a friend in a crowded space or searching for a pen on a cluttered desk. When engaging in these tasks, we only actively search a subset of the locations in the search space. The selection of locations to search depends not only

on task goals and perceptual salience, but also on our previous experience with that search environment. For example, when looking for a friend, we may search locations where we have often found our friend in the past, whereas we are unlikely to search improbable locations like the sky. Current goals, physical salience, and selection history constitute major sources of selective attention. They collectively determine which locations will be prioritized in processing (Awh et al., 2012). This view of selection as an integration of multiple sources has led to recent investigation of various selection history effects (Ferrante et al., 2018; Todd & Manaligod, 2018). Few studies, however, have examined how selection history effects interact. The current study aimed to test one such relationship: the interaction between long-term contextual cueing and short-term preview benefit.

Contextual cueing refers to the observation that individuals are faster in finding visual search targets when searching within familiar, repeated contexts. In the standard paradigm (Chun & Jiang, 1998), participants searched for a letter T among an array of letter Ls and reported the orientation of the T. Unbeknownst to them, some search displays were repeated several times in the course of the experiment. Response time on these repeated displays was faster than on unrepeated displays. Multiple mechanisms may contribute to contextual

Significance statement

Previewing part of a search display speeds search, demonstrating short-term selection history effects. Long-term selection history also influences search, as in contextual cueing, where repeated exposures to search context across blocks speeds search. Both short-term and long-term selection history influence attentional selection, though little is known about the interaction between these temporally distinct effects. We combined preview search and contextual cueing – the context of previewed displays and subsequent displays sometimes repeated. Context repetition always speeded search, but the effect size for the previewed set was larger, demonstrating modulation of long-term statistical learning by short-term selection effects.

✉ Yi Ni Toh
tohxx011@umn.edu

¹ Department of Psychology, University of Minnesota, 75 East River Road, Minneapolis, MN 55455, USA

cueing, with the repeated context expediting search, facilitating response, or both (Kunar et al., 2007; Schankin et al., 2011; Sisk et al., 2019). Contextual cueing exemplifies long-term selection history effects. It emerges after several presentations of the same array across blocks. Once acquired, it continues to speed up search 1 week after training (Chun & Jiang, 2003). Thus, repeated exposure to the same search array creates an enduring change in attention.

Selection history effects need not be acquired over repeated exposures, however, and may instead reflect very recent experience. An example of a short-term selection history effect is the preview benefit. In Watson and Humphreys (1997), a subset of distractors was presented several hundred milliseconds before the target and the remaining distractors were added. The “preview” of the first subset facilitated search relative to the standard condition in which all items were presented concurrently. A 1-s difference in onset time between the previewed and newly added items is sufficient for filtering out the previewed items.

Differences between contextual cueing and preview benefit, in terms of time scales and experimental manipulations, suggest that selection history effects represent a collection of distinct mechanisms (Fig. 1). Although they are distinct, different selection history effects may interact with one another. Hodsoll and Humphreys (2005) demonstrated an interaction between contextual cueing and preview benefit. They repeated the spatial arrangement of either the previewed or the newly added subset of items across blocks of trials. Even though previewing the first set enhanced filtering of that set, Hodsoll and Humphreys (2005) observed contextual cueing when the previewed set repeated. In contrast, despite participants’ active search through the newly added set, there was no contextual cueing when only the newly added set repeated. This finding suggests that the repetition of a spatial context had different effects depending on whether or not it was previewed.

Besides demonstrating an interaction between distinct selection history effects, Hodsoll and Humphreys’ (2005) findings raised an important question regarding the dependence of contextual cueing on attention. If participants conducted search primarily among the newly added set, why did they not benefit from the repetition of this set? Furthermore, if they could filter out the previewed set, why did that set induce contextual cueing?

Hodsoll and Humphreys’ (2005) findings are perplexing in light of other studies on the role of selective attention in contextual cueing. These studies showed that the attended, rather than ignored, context was the primary driver of contextual cueing. In Jiang and Chun (2001), participants searched for a black T among white Ls and black Ls. Owing to their similarity in color to the target, the black Ls constituted the attended subset. The white Ls were the ignored subset. Jiang and Chun (2001) found that repeating the attended subset facilitated search, but repeating the ignored subset did not. If the attended context is the main driver of contextual cueing, why then, did the preview paradigm show the opposite?

One explanation for Hodsoll and Humphreys’ (2005) findings is that contextual cueing does not scale with the amount of attention devoted to the search context. For example, Rausei, Makovski, and Jiang (2007) measured contextual cueing from two types of distractors: easy distractors were dissimilar to the target, and difficult distractors were highly similar to the target. Repeating the locations of either the easy or the difficult distractors yielded contextual cueing. The size of the effect was comparable between these two types of contexts, even though the difficult distractors took longer to reject and presumably received greater attention. Rausei et al. suggested that “beyond a threshold amount, additional increase in attentional dwell time does not further contribute to contextual cueing” (p. 1327).

Additionally, although active search is mainly restricted to the newly added items, the previewed subset is also attended

Fig. 1 An illustration of attentional selection that emphasizes (1) the presence of multiple types of selection history effects, and (2) the interaction between short-term and long-term selection history effects

to some extent, likely both before and after presentation of the newly added items. The visual marking account of the preview benefit suggests that the previewed subset receives active inhibition, which requires attention (Watson & Humphreys, 1997; Watson et al., 2003). Other studies have found that participants are imperfect in filtering out the previewed subset because they sometimes lose the temporal segregation between the previewed and the newly added items (the temporal asynchrony account), performing some search among the previewed subset (Jiang et al., 2002a, 2002b). A third account postulates that the preview benefit derives from the capture of attention by abrupt onset of the newly added items. This account also assumes that the previewed subset was attended during the preview (Donk & Theeuwes, 2001; Donk & Verburg, 2004). By all these accounts, the previewed subset is partially attended, and this may explain why repetition of this set induces contextual cueing. Repeated contexts within the previewed set may induce contextual cueing that is analogous to “inter-trial contextual cueing,” in which the search context on one trial is predictive of the target’s location on the next trial (Ono et al., 2005; Thomas et al., 2018).

What existing theories of the preview benefit cannot explain, however, is the lack of contextual cueing when the newly added subset repeats. This subset constitutes half of the items on the display, which should be sufficient to produce contextual cueing (Olson & Chun, 2002). Because the newly added subset was actively searched, it should have provided a useful spatial context for finding the target. The lack of learning suggests several possibilities.

One possibility is that the previewed subset may have interfered with the learning of the newly added subset. The interference may take two forms: a primacy effect and reduced attentional resources. First, because the previewed items appear early, they may have exerted a disproportionately strong effect on context processing. Jungé, Scholl, and Chun (2007) showed a primacy effect in contextual cueing. One group of participants in Jungé et al. encountered repeated displays immediately as the experiment started, whereas a second group first searched several hundred trials of unrepeated displays before encountering repeated ones. Contextual cueing was found in the first group but not in the second, suggesting that early trials of an experiment were more important than later ones in producing learning. If primacy effects apply not just across trials but also within a trial, then the temporally early context in the preview search paradigm may produce greater learning than the temporally late context. Second, competition for limited attentional resources may interfere with context learning. The visual marking account suggests that the previewed items receive active inhibition (Watson & Humphreys, 1997). When participants devote resources to inhibit those items, fewer resources are available for other aspects of the task. Just as secondary working-memory tasks may disrupt contextual cueing

(Annac et al., 2013; Manginelli et al., 2013; Travis et al., 2013), inhibition of the previewed items may also disrupt context learning of the newly added items.

A second, non-mutually exclusive, possibility is that the new set could produce contextual cueing, but the effect was weakened by the experimental design, so Hodsoll and Humphreys (2005) did not have sufficient statistical power to detect it. The experimental design used in Hodsoll and Humphreys included several features that weakened contextual cueing. First, the design involved a between-experiment comparison: one experiment repeated the previewed subset, and a second experiment repeated the newly added subset. This prevented within-subject comparisons of contextual cueing of the two types of context. Second, Hodsoll and Humphreys (2005) used a full range of English letters as the stimuli. “Although the spatial arrangement of the search displays was repeated, the particular letter at each location was assigned randomly in each block” (p. 1348). A recent study suggests that this design may disrupt contextual cueing. Using photographs of objects as stimuli, Makovski (2016) found that changing distractor identities across spatial repetitions abolished contextual cueing. Similarly, changing letter identities across blocks may have weakened contextual cueing in Hodsoll and Humphreys (2005). In fact, even with a sample size of 26, Hodsoll and Humphreys did not observe significant contextual cueing in their control experiment in which all items were presented concurrently and all distractor locations repeated, suggesting that their experimental design may be under-powered.

To understand the interaction between contextual cueing and preview search, and to clarify the roles of attention and temporal order in contextual cueing, we conducted three experiments using the preview search procedure. Participants in these experiments searched for a target T among distractor Ls and reported the orientation of the T. Half of the distractors were presented for 800 ms before the addition of the target and the remaining distractors to the display (Fig. 2). To reduce confusion in terminology (e.g., “old” for the previewed subset, but also “old” for the repeated condition), we will refer to the previewed items as “set 1,” and the newly added items as “set 2.”

The first experiment aimed to establish the preview benefit in the T-among-L search task. To this end, participants were tested in three conditions without context repetition: preview search (set 1 preceded set 2), half-element baseline (only set 2 was presented), and full-element baseline (set 1 and set 2 occurred concurrently). The next two experiments introduced repetition of either set 1 or set 2 across blocks.

After establishing a preview effect and quantifying the efficiency of filtering of previewed items in Experiment 1, we addressed the following questions. First, how does the preview benefit interact with contextual cueing? To address this question, Experiment 2 provides a conceptual replication of

Fig. 2 Trial sequence used in the preview search condition of this study

Hodsoll and Humphreys (2005). We manipulated the repetition of set 1 and set 2 orthogonally to produce four conditions: only set 1 repeated across blocks (“set-1-repeated”), only set 2 repeated (“set-2-repeated”), both sets repeated (“both-repeated”), or neither set repeated (“neither-repeated”). In addition to using a within-subject design, we used distractors of a uniform identity (all distractors were Ls) to minimize the disruption of contextual cueing. We examined whether, with the improved design, contextual cueing occurred with set 1 repetition, set 2 repetition, or both.

Second, what did people learn from the repetition of set 1? Did they learn which locations did not contain the target and could be excluded from search, or did they learn where the target was based on its association with set 1? To address this question, in Experiment 3, we changed the pairing between the repeated context and the associated target’s location after participants had acquired contextual cueing from set 1 repetition. If participants learned which locations could be excluded from search (i.e., the locations occupied by set 1), contextual cueing should be maintained as long as set 1 was repeated. But if participants learned the association between a specific repeated context and the target’s location, then contextual cueing should be disrupted when the pairing between the context and the target’s location changed.

Together, these experiments clarified the nature of contextual cueing in preview search and facilitated an understanding of how a short-term selection history effect modulated long-term statistical learning.

Experiment 1

To minimize letter identity as a source of context learning, we used a T-among-L search task in the current study. Participants searched for a white T target presented among 15 white L distractors. Although these stimuli have yielded preview benefit in previous studies (Kunar et al., 2003; Kunar & Humphreys, 2006; von Mühlenen et al., 2013; Watson, 2001), they differ from those of Hodsoll and Humphreys (2005). It is therefore important to confirm that previewing a

subset of the distractors could speed response time (RT) in our task.

Experiment 1 also served to estimate the efficiency with which participants filtered out the previewed items. Previous studies have shown that visual marking may have a capacity limit (Jiang et al., 2002a; Watson & Kunar, 2012). For example, using a paradigm in which participants selected all the new items rather than responding to just the target, Watson and Kunar (2002) found that participants could prioritize approximately six to seven new items, but not more. This finding suggests that participants may not be able to filter out all of the previewed items when the set size is high.

Participants in Experiment 1 performed visual search in three types of trials, administered in different blocks. In the preview condition, half of the distractors were presented for 800 ms before the addition of the remaining distractors and the target. In the full-element baseline condition, all items were presented concurrently. In the half-element baseline condition, only the target and half of the distractors were presented concurrently. We compared search RT in the preview condition with the full-element and half-element conditions to estimate the efficiency with which participants filtered out the previewed items. If RT was equivalent between the preview search and the half-element condition, it would indicate that participants were 100% efficient in filtering out the previewed items. Conversely, if RT was equivalent between the preview search and the full-element condition, it would indicate that participants were completely unable to filter out the previewed items. Because visual search RT is typically linearly related to the number of searched items (Wolfe, 1998), it is possible to estimate the effective set size in the preview condition based on its RT relative to the full-element and half-element conditions.

Method

Participants All participants in this study were college students between the ages of 18 and 36 years. All participants had normal or corrected-to-normal visual acuity, normal color vision, and were naïve to the purpose of the study. They

provided informed consent prior to participation and received extra course credit for their time.

The 24 participants in Experiment 1 included 15 females and nine males, with a mean age of 20 years ($SD = 2.0$). The sample size was pre-determined to be comparable to or larger than previous studies that used the preview search task (Watson & Humphreys, 1997).

Materials Participants were tested individually in a room with normal interior lighting. Stimuli were generated using Psychtoolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (www.mathworks.com) and displayed on a 19-in. CRT monitor ($1,024 \times 768$ pixels; 75 Hz vertical refresh rate). Viewing distance was approximately 40 cm.

The search items were white T or L, each subtending $2^\circ \times 2^\circ$, presented against a gray background. The target was a T tilted 90° to the left or right. The distractors were Ls; their orientations could be 0° , 90° , 180° , or 270° , randomly determined for each distractor on each trial. There was a small offset of 0.1° at the junction of the Ls to make search inefficient.

All the items were presented in randomly selected locations from an invisible 10×10 matrix ($30^\circ \times 30^\circ$), with the constraint that there were the same number of items in each quadrant. The target was equally likely to appear in any quadrant. To avoid collinearity between search items, the center location of each cell of the matrix was jittered by a random value between 0 and 0.76° .

Design Each participant encountered three types of trials: full-element baseline, half-element baseline, and preview search. The experiment was divided into ten epochs of 72 trials each. Each epoch was further divided into three blocks of 24 trials. The full-element, half-element, and preview search conditions were tested in separate blocks, each appearing in one block per epoch. The order of block type was counterbalanced within each participant. A different counterbalance order was used for different participants.

In the full-element baseline condition, participants searched for one T among 15 Ls, all presented concurrently. In the half-element baseline condition, participants searched for one T among seven Ls, again presented concurrently. In the preview search condition, participants searched for one T among 15 Ls. However, a subset of eight Ls was presented first (two Ls per quadrant appeared in this preview set). Eight-hundred milliseconds later the T and the other seven Ls were added to the display (Fig. 2).

Before each block, participants were informed of the nature of the upcoming block type. In the full-element and half-element conditions, they were told that the T would appear immediately with the Ls. In the preview condition, they were told that the first display would be all Ls, and that the T would only appear in the newly added set.

Procedure Participants first completed eight trials of practice under each of the three search conditions. They were asked to respond as accurately and as quickly as possible and received accuracy feedback after each trial. This was then followed by 720 experimental trials, divided into ten epochs. Each trial of the visual search task began with the presentation of a white central fixation point (size 0.5°) for 500 ms. This was followed by either the search display (in the full-baseline or half-baseline condition), or the preview display and then the rest of the search display 800 ms later (in the preview condition). Participants searched for the T and reported the direction of its tip by pressing either the left or the right arrow key. The target's orientation and associated keypress response was randomized on each trial, with the constraint that there was an equal number of left- and right-oriented Ts in each block. The distractor orientations were randomly selected on each trial. The display was erased upon a keypress response. A chirp followed each correct response and a low buzz along with a 2-s blank interval followed each incorrect response. The next trial started 500 ms later. Participants could take a break every 24 trials.

Results

Mean accuracy in the search task was 98.8% ($SE = 0.2\%$), which did not differ significantly across the three types of search, $F(2, 46) = .15$, $p = .863$. Figure 3 displays the mean RT across the ten epochs, excluding incorrect trials and trials with an outlier RT, defined as those shorter than 200 ms (0.006% of trials) or longer than 4 standard deviations of a given individual's mean (0.9% of trials). The same outlier removal criterion was used in subsequent experiments.

An ANOVA using search type (full-element, half-element, and preview search) and epoch as factors revealed a significant main effect of search type, $F(2, 46) = 179.17$, $p < .001$, $\eta_p^2 = .886$, demonstrating a preview benefit. The main effect of epoch was significant, $F(9, 207) = 23.43$, $p < .001$, $\eta_p^2 = .505$, with faster RT in later epochs. The interaction between search type and epoch was significant, $F(18, 414) < 3.70$, $p = .001$, $\eta_p^2 = .139$, as differences among the three search types became smaller in later epochs. Planned contrasts showed that preview search was faster than the full-element baseline, $t(23) = 9.59$, $p < .001$, Cohen's $d = 1.96$, but slower than the half-element baseline, $t(23) = 11.92$, $p < .001$, Cohen's $d = 2.43$.

Because search RT is typically a linear function of set size (Wolfe, 1998), we used linear interpolation to estimate the effective set size in the preview search condition. The mean RT in the half-element condition, with a set size of 8, was 1,270 ms. The mean RT in the full-element condition, with a set size of 16, was 2,206 ms. Using these measurements, we calculated the slope (117 ms/item) and y-intercept (334 ms) of the linear function relating RT to set size. Based on this

Fig. 3 Results from Experiment 1. Error bars show ± 1 SE of the mean

function, an RT of 1,713 ms, measured in the preview search condition, corresponded to an effective set size of 11.8. The newly added subset comprised eight of the 11.8 items in this effective set size, leaving 3.8 as the estimated number of previewed items that participants searched. Thus, participants effectively filtered out about half of the previewed distractors.

Discussion

Using the T-among-L search task, Experiment 1 confirmed that previewing a subset of search items facilitated search RT, relative to when all the items were presented concurrently (Watson & Humphreys, 1997). However, the preview search condition was slower than the half-element baseline, suggesting that filtering of the previewed items was imperfect. A previous study that independently manipulated the number of previewed items and newly added items showed that previewing became less effective when there were more new items to search from (Jiang et al., 2002a). Watson and Kunar (2012) estimated that participants could prioritize at most six to seven new items. Experiment 1 was consistent with these previous findings. Although previewing a subset of the distractors enhanced speed in the T-among-L search task, participants did not effectively filter out all of the previewed items.

Experiment 2

Experiment 1 showed that participants could partially filter out the previewed set from search, raising the possibility that repeating the previewed subset (set 1) may yield less contextual cueing than repeating the newly added subset (set 2). Alternatively, if the temporally earlier context within a trial is more important for contextual cueing, as Jungé et al. (2007)

found to be the case on a larger time scale, then repeating set 1 should yield more contextual cueing than repeating set 2.

To determine how contextual cueing developed in the preview search paradigm, in Experiment 2 we used the T-among-L search task and implemented several design features to strengthen statistical power. First, we reduced noise by matching the target's eccentricity across conditions (Carrasco et al., 1995). Second, we limited the variability in the distractor items' identities by using only Ls as distractors. Third, instead of testing set 1 repetition and set 2 repetition in different experiments, we used a within-subject, factorial design. Finally, sample size in our study – 32 – was twice as large as is needed to obtain a standard contextual cueing at a power of .80 (Jiang & Sisk, 2019), increasing the chance of detecting the effects of set 1 or set 2 repetition.

With this improved design, we examined whether previewing a subset of the distractors modulated contextual cueing. Several predictions can be made. First, if the main context for search is the actively searched set, then repeating set 2 should yield contextual cueing, whereas repeating set 1 should produce less benefit. Alternatively, if the main context for search is the temporally earlier set, then repeating set 1 should yield contextual cueing, but repeating set 2 should not. This pattern is what Hodsoll and Humphreys (2005) found. Third, it is possible that both the actively searched set and the temporally earlier set can serve as useful search context. In this case, repeating either set 1 or set 2 should induce contextual cueing.

Method

Sample size determination We aimed to test 32 participants in Experiment 2. As reported previously, a within-subject design testing contextual cueing can reach a power of .80 with a sample size of 14 and a power of .95 with a sample size of 21 (Jiang & Sisk, 2019). Sample size used in previous studies

was in this range: 13–26 participants in Hodsoll and Humphreys (2005), 16–17 participants in Jiang and Chun (2001), and 20 participants in Jiang and Leung (2005).

Participants Thirty-two new participants completed Experiment 2. There were 26 females and six males, with a mean age of 20 years ($SD = 3.2$).

Material and equipment These were the same as in Experiment 1.

Procedure Participants completed 12 trials of practice, followed by 640 experimental trials, divided into 20 blocks of 32 trials each. To reduce noise in the data, we binned sets of five adjacent blocks to form an epoch. Trial procedure was the same as the preview search condition of Experiment 1. Participants then completed a configuration recognition task (Appendix A).

Design This experiment used a within-subject design with the following factors: experimental epoch (1–4), set 1 repetition (repeated vs. novel), and set 2 repetition (repeated vs. novel). Each experimental block was divided randomly and evenly into four conditions: set-1-repeated, set-2-repeated, both-repeated, or neither-repeated (eight trials per condition per block).

To create these four conditions, at the beginning of the experiment we randomly selected 32 unique locations as target locations for the 32 trials of a block. There were eight target locations in each quadrant (two for each of the four conditions). We ensured that target locations were eccentricity-matched across the four conditions. For example, suppose (x, y) was the target location for a repeated set 1 array, with display center at $(0, 0)$. Locations $(-x, y)$, $(x, -y)$, and $(-x, -y)$ would be target locations for the both-repeated, set-2-repeated, and neither-repeated conditions, randomly assigned.

To create the both-repeated condition, for each display, we randomly chose eight locations for distractor set 1 (two per quadrant), and seven locations for distractor set 2 (two per quadrant, except for the target's quadrant which had one). These locations were generated before the first block and repeatedly used in subsequent blocks. Thus, both sets of the distractors repeated once per block, for a total of 20 repetitions for each both-repeated display. There were eight different displays in the both-repeated condition.

Set-1-repeated was generated in a similar manner, except that the seven locations for distractor set 2 were re-generated at the start of each block. This ensured that only set 1 repeated across blocks. The converse was true for set-2-repeated: the eight locations for distractor set 1 were re-generated at the start of each block whereas the seven locations for set 2 were maintained across blocks. Finally, both sets were re-generated at the beginning of each block in the neither-repeated condition.

Location randomization across all conditions was performed independently for each participant, producing repeated contexts that differed for different participants.

As in Experiment 1, the orientation of the T was randomly generated on each trial. Participants pressed an arrow key to indicate the orientation of the target.

Results

Mean accuracy in the search task was 98.9% ($SE = 0.2\%$). Accuracy was not affected by set 1 repetition, set 2 repetition, epoch, or their interactions (smallest p -value = .410). We used mean RT to assess contextual cueing, excluding incorrect trials and outliers (0.83% of trials were outliers). Figure 4 shows the group mean. Mean RT in the neither-repeated condition of Experiment 2 was comparable to that in the preview search condition of Experiment 1 ($t(54) = 1.25$, $p = .22$), and faster than RT in the full-element condition of Experiment 1 ($t(54) = 4.39$, $p < .001$). This suggests that preview benefit did occur in Experiment 2, even with the addition of repeated contexts.

An ANOVA using set 1 repetition (repeated vs. novel), set 2 repetition (repeated vs. novel), and epoch (1–4) as factors produced a significant main effect of set 1 repetition, $F(1, 31) = 11.13$, $p = .002$, $\eta_p^2 = .26$, along with a significant linear trend in the interaction between set 1 repetition and epoch, $F(1, 31) = 4.29$, $p = .047$, $\eta_p^2 = .12$. This finding shows that the repetition of the previewed subset induced contextual cueing. The main effect of set 2 repetition was not significant, $F(1, 31) = 2.72$, $p = .11$, $\eta_p^2 = .08$; however, the linear trend in the interaction between set 2 repetition and epoch was significant, $F(1, 31) = 5.22$, $p = .029$, $\eta_p^2 = .14$, demonstrating that the effect of set 2 repetition increased with training – a signature of contextual cueing. The main effect of epoch was significant, $F(3, 93) = 26.90$, $p < .001$, $\eta_p^2 = .47$, showing faster RT in later epochs. Set 1 and set 2 repetitions did not interact, $F < 1$, neither was there a three-way interaction, $F < 1$. In the last epoch, the neither-repeated condition was slower by 167 ms, 119 ms, and 94 ms relative to the both-repeated, set-1-repeated, and set-2-repeated conditions, respectively.

The overall ANOVA reported above provided some evidence for contextual cueing from both set 1 and set 2 repetitions, with stronger evidence for the former. However, it is not the most sensitive test of the effects. As a form of long-term visual statistical learning, contextual cueing emerges gradually with training. Instead of an overall ANOVA that combines both early and late trials, contextual cueing is more often assessed by examining data from the second half of the experiment, after learning has occurred (Chun & Jiang, 1998; Jiang & Sisk, 2019). Following this analysis tradition, we conducted a second ANOVA on data from the second half of the experiment, using set 1 repetition, set 2 repetition, and epoch (3 or 4) as within-subject factors.

Fig. 4 Results from Experiment 2. Error bars show ± 1 SE of the mean

This analysis revealed significant main effects of set 1 repetition, $F(1, 31) = 18.38$, $p < .001$, $\eta_p^2 = .37$, and set 2 repetition, $F(1, 31) = 5.89$, $p = .021$, $\eta_p^2 = .16$, with faster RT when either set 1 or set 2 repeated relative to when they did not repeat. The main effect of epoch showed that RT was faster in epoch 4 than in epoch 3, $F(1, 31) = 28.56$, $p < .001$, $\eta_p^2 = .48$. None of the interactions were significant, smallest p -value $> .25$. Thus, the repetition of either the previewed or the newly added set was sufficient to induce contextual cueing, and the two effects were additive. The effect size, indexed by the partial eta squared, was smaller for set 2 repetition than set 1 repetition, a pattern of results consistent with Hodsoll and Humphreys (2005).

Discussion

Experiment 2 showed that repeating either the previewed or the newly added set induced contextual cueing. In addition, there was no interaction between the two, showing additive effects of context repetition. This finding diverged somewhat from Hodsoll and Humphreys (2005), who concluded that “repeating the new items alone did not generate contextual learning, but repeating the previewed items alone did” (p. 1346). We replicated Hodsoll and Humphreys (2005) in finding significant contextual cueing from set 1 repetition. But contrary to that study, we also found significant contextual cueing from set 2 repetition. This latter finding may be attributed to several design features that reduced noise and increased statistical power. The stringent control of target eccentricity across conditions reduced one source of noise. In addition, whereas Hodsoll and Humphreys (2005) used a full range of English letters, we minimized the variability in distractor identity. This may be an important factor since changing distractor identities across spatial repetitions is disruptive of contextual cueing (Makovski, 2016). Finally, the

use of a within-subject factorial design further increased power.

The presence of contextual cueing from set 2 supports the idea that attended spatial context can induce learning. Nonetheless, the effect size associated with set 2 repetition ($\eta_p^2 = .16$) was smaller than that associated with set 1 repetition ($\eta_p^2 = .37$). This finding suggests that even though set 2 was the more actively searched set, the temporally earlier context played a larger role. That is, short-term search history altered context learning. The temporally earlier, rather than the more actively searched, context may be more significant in contextual cueing. But is a lead in presentation time sufficient to induce contextual cueing, or does set 1 need to be attended? Experiment 5 of Hodsoll and Humphreys (2005) suggests that a lead in presentation time is insufficient. In that experiment, set 1 items were all letter Os, whereas set 2 distractors and the target were other letters. Data showed that repeating the locations of letter Os did not induce contextual cueing, even though they were predictive of the target’s location. Thus, when set 1 was effectively filtered out, it no longer produced contextual cueing. In our study, set 1 was not completely filtered out. As demonstrated in Experiment 1, about half of the previewed items slipped into the search set. Thus, the presence of contextual cueing from either set 1 repetition or set 2 repetition supports the idea that attended contexts can facilitate visual search. However, the size of contextual cueing did not scale with the degree of active search. The less actively searched but temporally earlier context yielded more learning.

Experiment 3

The fact that the size of contextual cueing did not scale with the degree of active search may suggest that the learning that

occurred when set 1 repeated was distinct from the associative learning that occurs in standard contextual cueing tasks. What is the nature of contextual cueing from set 1 repetition? Did participants learn the association between a repeated set 1 and a specific target location, or did they learn to avoid searching locations occupied by set 1? When the spatial configuration of a search array repeats, it may induce several types of learning, including perceptual learning of the repeated configuration (Chaumon et al., 2008), associative learning between the configuration and the target's location (Brady & Chun, 2007), and learning that speeds response selection processes (Kunar et al., 2007). Among these, associative learning plays an important role. Contextual cueing is disrupted if, following training, the target moves to a previously empty location (Manginelli & Pollmann, 2009). It may even reverse to a “contextual cost” if the target switches locations with a distractor (Makovski & Jiang, 2010). Contextual cueing also interferes with re-learning if the previously trained configuration is now paired with a different target location (Zellin et al., 2014). Furthermore, when a repeated display is consistently associated with a target “present/absent” response, contextual cueing appears primarily on target-present trials. Target-absent trials induce little to no learning (Beesley et al., 2015; Kunar & Wolfe, 2011; Schankin et al., 2011). These findings suggest that contextual cueing primarily reflects the predictive value of the repeated context for the target's location, although perceptual and response preparation factors may also contribute.

The associative nature of contextual cueing does not rule out the possibility that participants may also learn which locations are *not* target locations. In fact, Ogawa, Takeda, and Kumada (2007) found evidence that distractor locations were inhibited more on repeated displays than on novel displays. In that study, in addition to performing the T-among-L search task, participants were also required to report the occasional appearance of a small “probe” dot on top of a search item. When the probe fell on the search target, probe detection was faster on repeated than novel displays. Conversely, when the probe fell on a distractor, its detection was slower on repeated than novel displays. The latter finding suggests that distractors on repeated displays were more strongly inhibited than those on novel displays.

Previewing a subset of distractors may enhance the inhibition of the previewed items. With each repetition of set 1, which never contains the target, participants may learn to deprioritize those locations further (distractor learning). Alternatively, previewing set 1 may mainly induce learning about the target. That is, set 1 may become a predictive cue for where the target is likely to be (associative, target learning).

So does preview search induce associative (target) learning, or do people learn to deprioritize set 1? To address this question, in Experiment 6, Hodsoll and Humphreys (2005) repeated set 1 across blocks, but each time the target was in a new location. Results showed no contextual cueing,

suggesting that set 1 learning reflected associative target learning. However, factors that reduce the effect size and statistical power were also present in that experiment. For example, the letters changed from block to block, which may have introduced interference to spatial context learning (Makovski, 2016).

In Experiment 3, we further investigated the nature of contextual cueing from set 1 repetition by implementing several design features to enhance statistical power. In addition to controlling for the target's eccentricity and reducing the variability of distractor identity, we trained participants using repeated set 1 and a consistent target location. There were several such context-location associations. In a subsequent testing phase, we changed the pairing between the repeated context and the target location. With this design, we aimed to induce significant contextual cueing in the training phase, then test whether contextual cueing would decline significantly in the testing phase. Thus, instead of drawing conclusions on the basis of null results, our design probed the nature of contextual cueing by focusing on statistically significant effects. The associative (target) learning account predicts significant disruption from the training to the testing phase, whereas the deprioritization (distractor) learning account predicts significant contextual cueing in the testing phase.

Method

Participants Thirty-two new participants, 20 females and 12 males, completed Experiment 3. Their mean age was 20 years ($SD = 1.3$).

Design Participants performed 28 blocks of the visual search task, including 24 trials per block. The first 24 blocks were the training phase. There were two conditions in this phase: set-1-repeated and neither-repeated, each with 12 trials per block. These conditions had the same design as in Experiment 2; we did not test set-2-repeated or both-repeated as we were only interested in the nature of set 1 learning. Target eccentricity was controlled between the two conditions: if a target in set-1-repeated appeared at (x, y) , then there would be a matched target location in the neither-repeated condition at $(-x, -y)$.

Each of the 12 repeated set 1 arrays was paired with a specific target location in the training phase. In the testing phase (blocks 25–28), the 12 target locations of set-1-repeated were shuffled and randomly re-paired with different set 1 contexts. Thus, the target locations as well as the spatial configurations of set 1 continued to repeat in the testing phase, but the association between the two was disrupted. The 12 target locations of the neither-repeated condition were not associated with any consistent contexts in either the training or the testing phase.

The experiment ended with the configuration recognition task (Appendix A).

Results

Two participants had accuracy below 90% (one was 79%, the other 84%), which was more than 3 SDs below the mean accuracy of the other participants. Data from these two participants were removed, leaving us with a final sample size of 30. Including these participants would not have changed the pattern of results reported below.

Mean accuracy in the remaining participants was 98% (SD = 2.7%). It was unaffected by any of the experimental factors ($ps > .10$). In the RT analysis, we removed incorrect trials, as well as trials with an outlier RT (0.93% of trials). Data from four adjacent blocks were binned into a single experimental epoch. Figure 5 shows the results. Mean RT in the neither-repeated condition of Experiment 3 was comparable to that in the preview-search condition of Experiment 1 ($t(54) = 1.93$, $p = .059$), and faster than RT in the full-element baseline condition of Experiment 1 ($t(54) = 5.91$, $p < .001$). This suggests that preview benefit also occurred in Experiment 3.

Training phase Participants acquired contextual cueing in the training phase. An ANOVA on context condition (set 1 repeated vs. neither repeated) and epoch (1–6) yielded significant main effects of context, $F(1, 29) = 8.52$, $p = .007$, $\eta_p^2 = .23$, and epoch, $F(5, 145) = 77.40$, $p < .001$, $\eta_p^2 = .73$, but no interaction between the two. Owing to the gradual acquisition of contextual cueing, the omnibus F -test was insensitive to the interaction between context and epoch. Follow-up tests showed that context did not affect RT in the first epoch, $t(29) = 0.09$, $p > .90$. In epoch 6, RT was significantly faster in set-1-repeated than neither-repeated, $t(29) = 3.21$, $p = .003$. In epoch 6, the neither-repeated condition was 88 ms slower than the set-1-repeated condition.

Testing phase Once the consistent association between the repeated context and the target location was removed in the testing phase, participants no longer demonstrated contextual cueing. In epoch 7 (testing phase), participants were numerically slower in set-1-repeated than neither-repeated, $t(29) = 0.73$, $p = .47$. This is a substantial decline from the end of the training phase. An ANOVA using context condition (set 1 repeated vs. neither repeated) and epoch (6 vs. 7) as factors revealed a significant interaction between the two, $F(1, 29) = 7.77$, $p = .009$, $\eta_p^2 = .21$.

Discussion

Experiment 3 showed that the repetition of the previewed set was sufficient to induce contextual cueing. This replicated effects of set 1 repetition found in Experiment 2 and in Hodsoll and Humphreys (2005). The magnitude of the effect appeared smaller in Experiment 3 than in Experiment 2. This may be attributed to a reduction in the proportion of repeated displays. In Experiment 2, 75% of the trials included repeated contexts, and among these, some displays repeated in their entirety. In contrast, 50% of the trials in Experiment 3 included repeated contexts, and these displays were only ever partially repeated (i.e., set 2 was always novel). A previous study showed that contextual cueing was sensitive to the frequency or reliability with which the repeated contexts occurred (Zinchenko et al., 2018). This may have contributed to the smaller effect in Experiment 3 than in Experiment 2. Nonetheless, despite the smaller effect size, Experiment 3 showed once again, that repeating the previewed set facilitated search.

Importantly, Experiment 3 showed that contextual cueing was abolished when the pairing between the repeated context

Fig. 5 Results from Experiment 3. The first six epochs were the training phase. The last epoch was the testing phase, during which the consistent association between each set 1 display and a particular target location was disrupted. Error bars show ± 1 SE of the mean

and the target's location was disrupted in the testing phase, suggesting that participants learned the association between set 1 and the target's location. Although the repeated context could have facilitated search by informing participants where not to search, we found no persistence in the testing phase. Thus, repetition of set 1 did not serve to increase the efficiency of visual marking. Instead, context learning relied on the predictive value of set 1 for the target's location.

Our finding provided converging evidence for Hodsoll and Humphreys' (2005) conclusion that repeating the previewed set induced associative learning of the context and the target's location. Hodsoll and Humphreys (2005) repeated the spatial locations of the previewed items but presented the target at random locations across blocks. They did not find an effect of contextual cueing. This finding led them to conclude that learning was associative. The approach we took in Experiment 3 differed somewhat from that of Hodsoll and Humphreys (2005). In addition to the design modifications that increased statistical power, we first trained participants to acquire a significant contextual cueing effect before administering a testing phase to assess the nature of learning. These design features enabled us to observe a significant contextual cueing effect in the training phase, and to draw conclusions based on a significant decline of contextual cueing from the training to the testing phase. By not relying solely on null results, Experiment 3 provided compelling evidence that contextual cueing from the preview display was associative in nature.

General discussion

Selective attention is sensitive to both what happened a moment ago and more distant experience. Preview search is an example of a short-term selection history effect – a brief temporal lead in presentation time allows people to deprioritize the previewed distractors on that trial (Watson & Humphreys, 1997; Watson et al., 2003). Yet the previewed items, as well as items that appear later, provide visual contexts for finding the target. Contextual cueing from these items reflects a long-term selection history effect acquired through multiple repetitions. Once acquired, the effect can last for at least a week (Chun & Jiang, 2003). Although mechanistically different, the preview benefit and contextual cueing also shared similarities. For example, a distracting concurrent task – talking on the cell phone – increased overall response time in both contextual cueing and preview search tasks (Gunnell et al., 2019). This similarity presents the possibility that the two mechanisms may interact to influence visual selection (Hodsoll & Humphreys, 2005).

Using an improved experimental design, the current study re-evaluated the nature of contextual cueing using the preview search paradigm. Previewing a subset of items led participants to search primarily among the newly added items (Watson &

Humphreys, 1997). In Experiment 1, we replicated the preview benefit in a challenging T-among-L search task. We further showed that participants were imperfect in filtering out the previewed subset. This finding is consistent with previous reports that when set 2 contained a large number of items, participants would search some of the set 1 items (Jiang et al., 2002a). Still, RT was faster in the preview search condition relative to the full-element baseline condition, indicating that participants actively searched more of the items in set 2 than in set 1 when both were displayed. Experiment 2 showed that either the previewed or the newly added context was sufficient to produce learning. However, the effect size, reflected in partial eta-squared, was about twice as large when the previewed items (set 1) repeated as when the newly added items (set 2) repeated. Experiment 3 replicated contextual cueing from set 1 repetition, and further demonstrated that participants learned the association between a repeated set 1 display and the target location.

Our findings diverged from previous work in its observation of contextual cueing when the newly added items repeated. Previously, Hodsoll and Humphreys (2005) observed a numerical trend of faster RT when set 2 repeated, compared with the novel baseline. However, the effect was not statistically significant. This led to a puzzling finding in that actively searched context failed to induce contextual cueing. By using a within-subject factorial design, a larger sample size, and minimizing factors that might interfere with contextual cueing (e.g., changes in distractor identity), here we observed contextual cueing from repeating the actively searched set. This finding supports the idea that attended context can induce contextual learning (Jiang & Chun, 2001).

Stronger cueing from set 1 repetition than set 2 repetition suggests that active search is not the only factor that determines whether a search context induces associative learning. Several additional factors may heighten contextual cueing from set 1, relative to set 2. First, as the temporally leading array, set 1 may dominate learning, reflecting a primacy effect. This primacy effect might reflect overshadowing of set 2 learning when set 1 is predictive of the target's location (Kunar et al., 2014; Rosenbaum & Jiang, 2013). The primacy effect may also result from interference—when set 1 is novel, the noise it introduces may hamper the learning of set 2 (Jungé et al., 2007; Olson & Chun, 2002).

Second, because both preview search and contextual cueing depend, in part, on attentional resources (Gunnell et al., 2019; Jiang & Chun, 2001; Watson & Humphreys, 1997), context learning of set 2 may be reduced when resources are needed to inhibit set 1. Specifically, “marking” the locations of set 1 items requires visual short-term memory (Jiang & Wang, 2004). This may have interfered with set 2 learning given that secondary working memory tasks sometimes disrupt contextual cueing (Anzac et al., 2013; Manginelli et al., 2013; Travis et al., 2013; Vickery et al., 2010).

Third, because set 1 was previewed for 800 ms, its spatial layout could be accurately represented. In contrast, set 2 was added to set 1. At no point during the trial was set 2 presented on its own. This means that participants had to correctly segment set 2 from set 1 to extract the spatial context of set 2. Yet “visual marking” was imperfect: each time a repeated set 2 was presented, the actively searched set would include both set 2 and some number (e.g., about three to four) of set 1 items. This may introduce variability in the perceived spatial context of set 2, reducing learning. Thus, short-term selection history can alter long-term statistical learning.

Three accounts have been proposed to explain the preview benefit. The lead account, visual marking, proposes that preview enables set 1 to be effectively inhibited (Watson & Humphreys, 1997; Watson et al., 2003). Alternatively, the preview benefit has been attributed to the capture of attention by the newly added items (Donk & Theeuwes, 2001; Donk & Verburg, 2004), or to temporal segregation of the two sets (Jiang et al., 2002b). These accounts are not mutually exclusive. Inhibition of the previewed set, attentional capture by the new set, and temporal segregation between the two, may all contribute to the observed preview benefit. The current study was not designed to distinguish among the three accounts, but it clarifies one element of preview search. The observation of contextual cueing from set 1 repetition provides strong evidence that the previewed items were attended. If they had not been attended, as when set 1 was distinct from set 2 in color or shape (Hodsoll & Humphreys, 2005), repeating set 1 would not yield contextual cueing. Set 1 may be attended during preview and subsequently inhibited, as proposed by the visual marking account. Or it may be attended during the preview and partially attended during search, as implied by the attentional capture or temporal asynchrony accounts.

Experiment 3 showed that set 1 repetition facilitated performance mainly through its predictive value for the target’s location. This finding echoed the larger literature, which shows that contextual cueing is weak or absent when the repeated context is not predictive of the target (Chaumon et al., 2008; Chun & Jiang, 1998; Kunar & Wolfe, 2011; Schankin et al., 2011; Shen & Jiang, 2006; Wolfe et al., 2000). Some findings suggest that participants may also learn the distractor-distractor association (Beesley et al., 2015). The current study provides no evidence that participants benefited from the distractor-distractor association, even in a situation in which the distractor display was previewed on its own. The main advantage of repeating a search context lies in its predictive value – a repeated context guides attention to the associated target location.

Our study shows that contextual cueing could be observed when a subset of the spatial context repeated. Nonetheless, regularities in visual spatial context were insufficient for learning in some conditions. Although the repetition of set 1 was

informative not only of where the target was, but also where it was *not*, repeating the context but not the context-target association disrupted contextual cueing. In addition, as Hodsoll and Humphreys (2005) showed, when set 1 was not attended (e.g., it contained all letter Os), it did not facilitate search even though the spatial layout of set 1 was predictable of the upcoming target’s location. Thus, only the attended and predictive context facilitates search, suggesting that unattended aspects of environmental regularities are poorly represented.

In proposing the integrated priority map theory, Awh et al. (2012) identified current goals, physical salience, and selection history as three major sources to determine attentional priority. The theory captures selection history as a single node in the model. Our study expands on the integrated priority map theory by suggesting that selection history contains a collection of effects (Fig. 1). In addition, short-term selection, such as the preview effect, introduces timing and attention differences that may modulate long-term statistical learning, such as contextual cueing.

Acknowledgements We thank Roger Remington, Melina Kunar, Thomas Geyer, and an anonymous reviewer for comments and suggestions. CAS was supported by an NSF graduate fellowship.

Open Practices Statement De-identified data in an aggregated format may be requested from the corresponding author. The experiments were not preregistered.

Configuration recognition test

We administered the configuration recognition test at the completion of Experiments 2 and 3. Because a sample size of 32 is inadequate for reliably detecting explicit awareness (Vadillo et al., 2016), the lack of a statistically significant effect needs not imply a lack of awareness. Nonetheless, we report the recognition data to facilitate future meta-analysis.

Procedure At the completion of the search task in Experiments 2 and 3, an experimenter provided instructions about the surprise recognition task. Participants were first asked whether they had noticed that some displays were repeatedly presented in the experiment. Regardless of their answers, they were shown a display and asked to judge whether they had seen a trial like this during the experiment. They pressed “s” if they thought the display was the same as what they saw before, or “d” if it was new. A chirp followed each response regardless of whether it was correct. Experiment 2 tested 32 trials, including 8 configurations from each of the 4 conditions. Experiment 3 tested 24 trials, 12 in each condition.

Results In Experiment 2, the mean proportion of trials that participants reported “old” was: both-repeated 53.9%, set-1-repeated 53.1%, set-2-repeated 55.9%, and neither-repeated

47.7%. These values did not differ significantly from one another, $F(3, 93) = 1.36$, $p = .26$. The mean hit rate across the three repeated conditions (54.3%) was marginally higher than the false alarm rate (47.7%), $t(31) = 1.94$, $p = .062$. In Experiment 3, recognition hit rate to set-1-repeated (55.8%) did not differ significantly from the false alarm rate to novel displays (56.4%), $t(29) = 0.14$, $p > .89$.

We next examined the correlation between the size of contextual cueing and explicit recognition rates. For each participant, an awareness index was calculated as recognition hits (averaged across the three repeated conditions in Experiment 2) minus false alarms. Normalized contextual cueing was calculated using data from the second half of training. It was the RT advantage in the repeated condition(s) relative to the novel condition, divided by the participant's mean RT. Pearson's correlation between awareness and contextual cueing was $r = -.12$, $p = .52$ in Experiment 2, and $r = 0.06$, $p = .76$ in Experiment 3.

References

- Annac, E., Manginelli, A. A., Pollmann, S., Shi, Z., Müller, H. J., & Geyer, T. (2013). Memory under pressure: Secondary-task effects on contextual cueing of visual search. *Journal of Vision*, 13(13), 6–6. <https://doi.org/10.1167/13.13.6>
- 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>
- Beesley, T., Vadillo, M. A., Pearson, D., & Shanks, D. R. (2015). Pre-exposure of repeated search configurations facilitates subsequent contextual cueing of visual search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 41(2), 348–362. <https://doi.org/10.1037/xlm0000033>
- Brady, T. F., & Chun, M. M. (2007). Spatial constraints on learning in visual search: Modeling contextual cueing. *Journal of Experimental Psychology: Human Perception and Performance*, 33(4), 798–815. <https://doi.org/10.1037/0096-1523.33.4.798>
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4), 433–436. <https://doi.org/10.1163/156856897X00357>
- Carrasco, M., Evert, D. L., Chang, I., & Katz, S. M. (1995). The eccentricity effect: Target eccentricity affects performance on conjunction searches. *Perception & Psychophysics*, 57(8), 1241–1261. <https://doi.org/10.3758/bf03208380>
- Chaumon, M., Drouet, V., & Tallon-Baudry, C. (2008). Unconscious associative memory affects visual processing before 100 ms. *Journal of Vision*, 8(3), 10–10. <https://doi.org/10.1167/8.3.10>
- Chun, 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>
- Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29(2), 224–234. <https://doi.org/10.1037/0278-7393.29.2.224>
- Donk, M., & Theeuwes, J. (2001). Visual marking beside the mark: Prioritizing selection by abrupt onsets. *Perception & Psychophysics*, 63(5), 891–900. <https://doi.org/10.3758/BF03194445>
- Donk, M., & Verburg, R. C. (2004). Prioritizing new elements with a brief preview period: Evidence against visual marking. *Psychonomic Bulletin & Review*, 11(2), 282–288. <https://doi.org/10.3758/BF03196571>
- Ferrante, O., Patacca, A., Di Caro, V., Della Libera, C., Santandrea, E., & Chelazzi, L. (2018). Altering spatial priority maps via statistical learning of target selection and distractor filtering. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 102, 67–95. <https://doi.org/10.1016/j.cortex.2017.09.027>
- Gunnell, D. O. A., Kunar, M. A., & Watson, D. G. (2019). Having a phone conversation delays but does not disrupt cognitive mechanisms. *Journal of Experimental Psychology Applied*. <https://doi.org/10.1037/xap0000239>
- Hodsoll, J. P., & Humphreys, G. W. (2005). Preview Search and Contextual Cueing. *Journal of Experimental Psychology: Human Perception and Performance*, 31(6), 1346–1358. <https://doi.org/10.1037/0096-1523.31.6.1346>
- Jiang, Y., & Chun, M. M. (2001). Selective attention modulates implicit learning. *The Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, 54(4), 1105–1124. <https://doi.org/10.1080/713756001>
- Jiang, Y., & Leung, A. W. (2005). Implicit learning of ignored visual context. *Psychonomic Bulletin & Review*, 12(1), 100–106. <https://doi.org/10.3758/BF03196353>
- Jiang, Y., & Wang, S. W. (2004). What Kind of Memory Supports Visual Marking? *Journal of Experimental Psychology: Human Perception and Performance*, 30(1), 79–91. <https://doi.org/10.1037/0096-1523.30.1.79>
- Jiang, Y., Chun, M. M., & Marks, L. E. (2002a). Visual marking: Dissociating effects of new and old set size. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(2), 293–302. <https://doi.org/10.1037/0278-7393.28.2.293>
- Jiang, Y., Chun, M. M., & Marks, L. E. (2002b). Visual marking: Selective attention to asynchronous temporal groups. *Journal of Experimental Psychology: Human Perception and Performance*, 28(3), 717–730. <https://doi.org/10.1037/0096-1523.28.3.717>
- Jiang, Y. V., & Sisk, C. A. (2019). Contextual Cueing. *Spatial Learning and Attention Guidance*, 59–72. https://doi.org/10.1007/7657_2019_19
- Jungé, J. A., Scholl, B. J., & Chun, M. M. (2007). How is spatial context learning integrated over signal versus noise? A primacy effect in contextual cueing. *Visual Cognition*, 15(1), 1–11. <https://doi.org/10.1080/13506280600859706>
- Kunar, M. A., & Humphreys, G. W. (2006). Object-based inhibitory priming in preview search: Evidence from the “top-up” procedure. *Memory & Cognition*, 34(3), 459–474. <https://doi.org/10.3758/BF03193571>
- Kunar, M. A., & Wolfe, J. M. (2011). Target absent trials in configural contextual cueing. *Attention, Perception & Psychophysics*, 73(7), 2077–2091. <https://doi.org/10.3758/s13414-011-0164-0>
- Kunar, M. A., Humphreys, G. W., Smith, K. J., & Hulleman, J. (2003). What is “marked” in visual marking? Evidence for effects of configuration in preview search. *Perception & Psychophysics*, 65(6), 982–996. <https://doi.org/10.3758/BF03194828>
- Kunar, M. A., Flusberg, S., Horowitz, T. S., & Wolfe, J. M. (2007). Does contextual cueing guide the deployment of attention? *Journal of Experimental Psychology: Human Perception and Performance*, 33(4), 816–828. <https://doi.org/10.1037/0096-1523.33.4.816>
- Kunar, M. A., John, R., & Sweetman, H. (2014). A Configural Dominant Account of Contextual Cueing: Configural Cues are Stronger than Colour Cues. *Quarterly Journal of Experimental Psychology*, 67(7), 1366–1382. <https://doi.org/10.1080/17470218.2013.863373>
- Makovski, T. (2016). What is the context of contextual cueing? *Psychonomic Bulletin & Review*, 23(6), 1982–1988. <https://doi.org/10.3758/s13423-016-1058-x>

- Makovski, T., & Jiang, Y. V. (2010). Contextual cost: When a visual-search target is not where it should be. *Quarterly Journal of Experimental Psychology* (2006), 63(2), 216–225. <https://doi.org/10.1080/17470210903281590>
- Manginelli, A. A., & Pollmann, S. (2009). Misleading contextual cues: How do they affect visual search? *Psychological Research*, 73(2), 212–221. <https://doi.org/10.1007/s00426-008-0211-1>
- Manginelli, A. A., Langer, N., Klose, D., & Pollmann, S. (2013). Contextual cueing under working memory load: Selective interference of visuospatial load with expression of learning. *Attention, Perception, & Psychophysics*, 75(6), 1103–1117. <https://doi.org/10.3758/s13414-013-0466-5>
- Ogawa, H., Takeda, Y., & Kumada, T. (2007). Probing attentional modulation of contextual cueing. *Visual Cognition*, 15(3), 276–289. <https://doi.org/10.1080/13506280600756977>
- Olson, I. R., & Chun, M. M. (2002). Perceptual constraints on implicit learning of spatial context. *Visual Cognition*, 9(3), 273–302. <https://doi.org/10.1080/13506280042000162>
- Ono, F., Jiang, Y., & Kawahara, J.-I. (2005). Intertrial temporal contextual cuing: Association across successive visual search trials guides spatial attention. *Journal of Experimental Psychology: Human Perception and Performance*, 31(4), 703–712. <https://doi.org/10.1037/0096-1523.31.4.703>
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10(4), 437–442.
- Rausei, V., Makovski, T., & Jiang, Y. V. (2007). Attention dependency in implicit learning of repeated search context. *Quarterly Journal of Experimental Psychology* (2006), 60(10), 1321–1328. <https://doi.org/10.1080/17470210701515744>
- 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>
- Schankin, A., Hagemann, D., & Schubö, A. (2011). Is contextual cueing more than the guidance of visual-spatial attention? *Biological Psychology*, 87(1), 58–65. <https://doi.org/10.1016/j.biopsycho.2011.02.003>
- Shen, Y. J., & Jiang, Y. V. (2006). Interrupted visual searches reveal volatile search memory. *Journal of Experimental Psychology: Human Perception and Performance*, 32(5), 1208–1220. <https://doi.org/10.1037/0096-1523.32.5.1208>
- Sisk, C. A., Remington, R. W., & Jiang, Y. V. (2019). Mechanisms of contextual cueing: A tutorial review. *Attention, Perception, & Psychophysics*, 81(8), 2571–2589. <https://doi.org/10.3758/s13414-019-01832-2>
- Thomas, C., Didierjean, A., Maquestiaux, F., & Goujon, A. (2018). On the limits of statistical learning: Intertrial contextual cueing is confined to temporally close contingencies. *Attention, Perception, & Psychophysics*, 80(6), 1420–1435. <https://doi.org/10.3758/s13414-018-1519-6>
- Todd, R. M., & Manaligod, M. G. M. (2018). Implicit guidance of attention: The priority state space framework. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior*, 102, 121–138. <https://doi.org/10.1016/j.cortex.2017.08.001>
- Travis, S. L., Mattingley, J. B., & Dux, P. E. (2013). On the role of working memory in spatial contextual cueing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(1), 208–219. <https://doi.org/10.1037/a0028644>
- Vadillo, M. A., Konstantinidis, E., & Shanks, D. R. (2016). Underpowered samples, false negatives, and unconscious learning. *Psychonomic Bulletin & Review*, 23(1), 87–102. <https://doi.org/10.3758/s13423-015-0892-6>
- Vickery, T. J., Sussman, R. S., & Jiang, Y. V. (2010). Spatial context learning survives interference from working memory load. *Journal of Experimental Psychology: Human Perception and Performance*, 36(6), 1358–1371. <https://doi.org/10.1037/a0020558>
- von Mühlenen, A., Watson, D., & Gunnell, D. O. A. (2013). Blink and you won't miss it: The preview benefit in visual marking survives internally generated eyeblinks. *Journal of Experimental Psychology: Human Perception and Performance*, 39(5), 1279–1290. <https://doi.org/10.1037/a0031537>
- Watson, D. G. (2001). Visual marking in moving displays: Feature-based inhibition is not necessary. *Perception & Psychophysics*, 63(1), 74–84. <https://doi.org/10.3758/BF03200504>
- Watson, D. G., & Humphreys, G. W. (1997). Visual marking: Prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychological Review*, 104(1), 90–122. <https://doi.org/10.1037/0033-295x.104.1.90>
- Watson, D. G., & Kunar, M. A. (2012). Determining the capacity of time-based selection. *Journal of Experimental Psychology: Human Perception and Performance*, 38(2), 350–366. <https://doi.org/10.1037/a0025794>
- Watson, D. G., Humphreys, G. W., & Olivers, C. N. L. (2003). Visual marking: Using time in visual selection. *Trends in Cognitive Sciences*, 7(4), 180–186. [https://doi.org/10.1016/S1364-6613\(03\)00033-0](https://doi.org/10.1016/S1364-6613(03)00033-0)
- Wolfe, J. M. (1998). What Can 1 Million Trials Tell Us about Visual Search? *Psychological Science*, 9(1), 33–39. JSTOR.
- Wolfe, J. M., Klempen, N., & Dahlen, K. (2000). Postattentive vision. *Journal of Experimental Psychology: Human Perception and Performance*, 26(2), 693–716. <https://doi.org/10.1037/0096-1523.26.2.693>
- Zellin, M., von Mühlenen, A., Müller, H. J., & Conci, M. (2014). Long-term adaptation to change in implicit contextual learning. *Psychonomic Bulletin & Review*, 21(4), 1073–1079. <https://doi.org/10.3758/s13423-013-0568-z>
- Zinchenko, A., Conci, M., Müller, H. J., & Geyer, T. (2018). Predictive visual search: Role of environmental regularities in the learning of context cues. *Attention, Perception, & Psychophysics*, 80(5), 1096–1109. <https://doi.org/10.3758/s13414-018-1500-4>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.