Statistical learning in the past modulates contextual cueing in the future

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Observers' capability to extract statistical regularities from the visual world can facilitate attentional orienting. For instance, visual search benefits from the repetition of target locations by means of probability learning. Furthermore, repeated (old) contexts of nontargets contribute to faster visual search in comparison to random (new) arrangements of nontargets. Chun and Jiang (1998) called this effect "contextual cueing" because old contexts provide spatial cues to repeated target locations. In the present study, we investigated how probability learning modulates the adaptation of contextual cueing to a change in target location. After an initial learning phase, targets were relocated within their respective contexts to new positions that were, however, familiar from previous presentations in other spatial contexts. Contextual cueing was observed for relocated targets that originated from old contexts, but it turned into costs when relocated targets had previously been presented in new contexts. Thus, probability learning was not sufficient to observe adaptive contextual cueing for relocated targets. Instead, the contextual past of target locations—whether they had been cued or not—modulated the integration of relocated targets into a learned context. These findings imply that observers extract multiple levels of available statistical information and use them to infer hypotheses about future occurrences of familiar stimuli.

Introduction

In familiar visual scenes, like your own kitchen, statistical regularities contribute to efficient attentional orienting. For example, observers are sensitive to lower-order statistics, such as highly probable locations of target objects (e.g., chairs on the floor; Druker & Anderson, 2010; Fiser & Aslin, 2002; Geng & Behrmann, 2005; Jiang, Swallow, Rosenbaum, & Herzig, 2013; Neider & Zelinsky, 2006). Learning of repeated target locations as one type of statistical learning can be differentiated from the learning of higher-order statistics, such as the co-occurrence of objects with each other (e.g., pans and pots; see Fiser & Aslin, 2002; Oliva & Torralba, 2007, for reviews) and the location of objects in relation to their typical environment (e.g., a pan on the stove in the kitchen; see Bar, 2004, for review). Thus, observers extract both target location probabilities (*probability learning*) and invariant contextual relationships over time (*contextual learning*), which then facilitate the guidance of attention in visual search.

The contextual cueing effect reported by Chun and Jiang (1998) is an example of implicit statistical learning, which effectively involves both learning of location probabilities and invariant contextual relationships. In Chun and Jiang's paradigm, observers performed visual search for a target "T" surrounded by configurations of L-shaped nontargets and responded to the target's orientation (see Figure 1 for example displays). Unknown to observers, a set of displays was repeated throughout the experiment with invariant arrangements of nontargets and fixed target locations (old contexts) while a second set of displays presented arrangements of fixed target locations among randomly arranged nontargets (new contexts). Target locations were repeated in both old and new contexts to control for learning of location probabilities (e.g., Jiang et al.,

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2013). The repetition of target locations (probability learning) and general practice with the task (visual perceptual learning; see Sasaki, Nanez, & Watanabe, 2010, for review) both speeded the overall reaction times (RTs) across the experiment. In addition, visual search became faster for old-context in comparison to new-context displays. Thus, observers learned the associations between locations of target objects and their surrounding old contexts, which facilitated visual search (contextual learning; see Chun, 2000, for review). A final recognition test also showed that observers could not reliably discern old from new contexts, suggesting that contextual learning is mostly driven by implicit memory (Chun & Jiang, 1998).

While target locations are fixed for each old context in contextual cueing experiments, in everyday life, objects (e.g., a pan) are likely to change locations or to appear in several (recurring) places within their environments. Thus, ideally, statistical learning of contextual relationships should allow adaptation to changes and should include representations of multiple repeated target locations (Conci, Zellin, & Müller, 2012). However, several studies have reported that contextual cueing does not occur when targets are relocated within their otherwise invariant contexts (Chun & Jiang, 1998; Conci, Sun, & Müller, 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). For example, in the study by Manginelli and Pollmann, observers learned to associate old contexts with fixed target locations. After this initial learning phase, targets were relocated to new, previously empty positions within their otherwise invariant contexts. Target relocation to previously empty positions was found to cancel the contextual-cueing effect, which failed to recover after repeated encounters with the new target locations. Reliable contextual cueing was not even observed when target relocations to previously empty positions were fairly permanent with at least twice as many presentations of the relocated targets relative to the initial target locations (Zellin, Conci, von Mühlenen, & Müller, 2013). This pattern of results suggests, on the one hand, that contextual cueing is essentially limited to *single-target learning* (Zellin, Conci, von Mühlenen, & Müller, 2011); that is, each old-context display can be associated with only one repeated target location (and its immediate surround; see also Makovski & Jiang, 2010), meaning that visual search for other (new) repeated target locations will not be guided by the same old context. On the other hand, the observed lack of contextual cueing for relocated targets appearing at previously empty positions might be owing to the fact that, after having learned a particular context, observers did not expect targets to appear at previously empty positions (Jiang et al., 2013; see Clark, 2013, for a theoretical approach to cognitive prediction models). In other words, the positions of relocated targets in the studies mentioned above were not predictable, which could have prevented their integration into the old contexts. Indeed, Conci et al. (2011) reported successful contextual learning of two predictable target locations presented within one context (Experiment 2). In each trial, search displays contained two targets at two different locations simultaneously (one was oriented left/right, one was pointing upward/down-

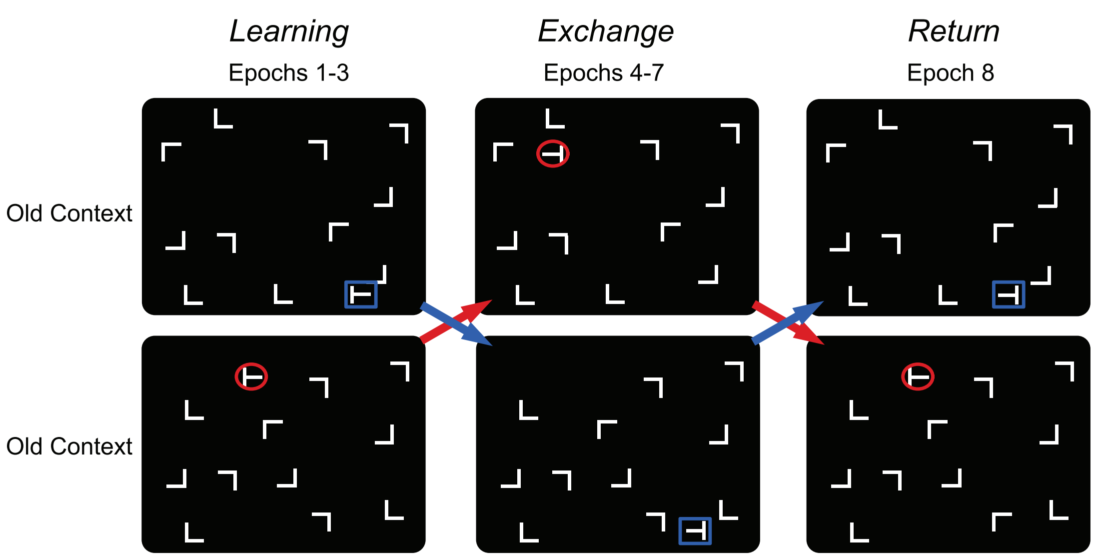

Figure 1. Two examples of old-context displays (top and bottom half) illustrating the exchange of target locations in Experiment 1: Search displays were initially paired with fixed, unique target locations in the learning phase (highlighted here by a square and a circle, which were not presented to observers). Subsequently, target locations were exchanged between old-context displays in the exchange phase (arrows). The final return phase again presented the initial context-target pairings.

ward). While both targets were present in each trial, observers only searched for one of the targets in one half of the experiment and for the other target in the other half. Reliable contextual cueing was observed for both target locations due to the continuous presence of the two targets, making both target locations predictable within their respective context (*multiple-target learning*; see also Brady & Chun, 2007; Conci & Müller, 2012; Kunar & Wolfe, 2011). This finding suggests that predictability might be a key factor for successful adaptation to change in contextual learning.

In statistical learning, observers often form implicit expectations about future occurrences of familiar visual events based on their predictability (Beesley & Le Pelley, 2010; Dale, Duran, & Morehead, 2012; Reder, Weber, Shang, & Vanyukov, 2003; Turk-Browne, Scholl, Johnson, & Chun, 2010; see also Neider & Zelinsky, 2006, for more naturalistic scenes). For example, when observers implicitly expected fixed target locations not to be predicted by surrounding context information (new contexts), they were unable to learn actual old (i.e., repeated) contexts when they were presented (Jungé, Scholl, & Chun, 2007). In this study, old-context and new-context displays were presented separately in sequential order. When old contexts preceded the presentation of new (i.e., never repeated) contexts, reliable contextual cueing was observed. However, when new contexts were presented before old contexts, observers did not show a contextual-cueing effect for the old-context displays. In the latter case, observers probably "noticed" the absence of statistical regularities in the first half of the experiment, leading to implicit expectations that modulated subsequent statistical learning.

Given this, the present study was designed to further investigate the role of past statistical learning on observers' expectations that could modulate future statistical learning. In particular, we examined the role of predictability in adaptive contextual cueing by testing whether old contexts could become associated with changed target locations when these are predictable (instead of being completely new). In a typical contextual cueing experiment, a limited number of target locations are repeated in both old- and new-context displays (lower-order statistics; e.g., Chun & Jiang, 1998). This means that, in a given display, target locations are predictable independently of the surrounding context (in old and new contexts), which enables a progressive reduction in RTs through probability learning (Brady & Chun, 2007; Chun & Jiang, 1998; Jiang et al., 2013; see also Myers & Gray, 2010, for eye movement data). In the present study, we made use of this (lower-order) probability learning to achieve adaptation to relocated targets in (higher-order) contextual learning. Specifically, after an initial learning phase, targets were relocated to predictable locations that were previously occupied by a target in other displays, instead of introducing completely new target locations as in previous studies (e.g., Manginelli & Pollmann, 2009). In the initial learning phase, old and new contexts were presented with fixed target locations (comparable to, e.g., Chun & Jiang, 1998). Subsequently, target locations of old-context displays were exchanged once or, in other words, transferred between old contexts (Experiment 1; see Figure 1). For example, the predictable target location in old context A became the predictable target location in old context B (e.g., the location of the toaster in your kitchen would now be "transposed" to your parents' kitchen) and vice versa (e.g., the toaster in your kitchen would now be located at the toaster's position in your parents' kitchen). In Experiment 2, target locations were exchanged once between old- and new-context displays (see Figure 3). This means predictable target locations of random contexts were transferred to old contexts while predictable target locations of old contexts appeared in randomly arranged (new) contexts. By using repeated target locations from new contexts as relocated targets in old contexts, we investigated whether initial probability learning generally enables subsequent adaptation to change in contextual learning (as initial probability learning should make repeated target locations predictable; Conci et al., 2011).

Similar to the design of Conci et al. (2011), all target locations, including relocated targets, were predictable through repeated presentations in the initial learning phase, and location probabilities were constant throughout the experiments. But, in the present study, old contextual relationships were varied, that is, the actual context-target location pairings after target exchange were new (as in Manginelli & Pollmann, 2009), requiring observers to adapt old contextual relationships. If predictability of relocated targets is a necessary and sufficient premise for adaptation of old contextual relationships to change, we expected to observe contextual-cueing effects for target locations in the exchange phases.

After the exchange phases, initial context-target location pairings (from the learning phases) were presented again to test whether relocated targets interfere with initially acquired contextual relationships (adapted from Zellin et al., 2013). Furthermore, if contextual cueing occurs in both the exchange and return phases, the study would provide evidence for multiple-target learning (as originally proposed by Chun & Jiang, 1998; see also Conci et al., 2011; Kunar & Wolfe, 2011).

Experiment 1

Experiment 1 was designed to investigate whether adaptation of old contextual relationships to relocated targets would be facilitated if the positions of the relocated targets were predictable due to probability learning. After an initial learning phase, repeated target locations were exchanged between old-context displays once (exchange phase; see Figure 1). In the return phase, target locations were presented in their original contexts. If predictability of target locations facilitates adaptation to changed contextual relationships (Conci & Müller, 2012; Conci et al., 2011), contextual cueing should occur for relocated targets in the exchange phase.

Methods

Observers

Thirteen adults took part in the experiment (11 women; mean age: 24 years; age range: 19–30 years). All observers had normal or corrected-to-normal visual acuity, and one observer was left-handed. They received either payment (8€) or one course credit for their participation. In order to test adaptation of existing contextual associations to change, we only report results of observers who showed contextual-cueing effects (RT[new] minus RT[old]) larger than zero for old contexts in the initial learning phase (adapted from Conci et al., 2011; see also Albouy et al., 2006; Conci & Müller, 2012; Kunar & Wolfe, 2011; Olson, Chun, & Allison, 2001; Zellin et al., 2013, for a comparable approach). We have previously shown that observers who fail to display contextual learning initially tend to develop reliable contextual learning in later parts of the experiment (Zellin et al., 2013). Because the inclusion of these "late" learners would distort our results concerning the adaptation of previously learned contextual relationships, such observers were excluded from the data proper in the present study.[1] Consequently, experimental results and interpretations reported below apply in particular to the selected sample of observers.

The experimental procedure was designed according to the guidelines of the Declaration of Helsinki. Observers were comprehensively informed about the study and their rights and provided informed consent before any experiment started. Because the study was noninvasive and all data were processed anonymously, observers were asked to only give verbal consent.

Apparatus and stimuli

Stimulus presentation and response collection was controlled by an IBM-PC compatible computer using Matlab Routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Stimuli subtended $0.7° \times 0.7°$ of the visual angle and were presented in gray (8.5 cd/m^2) against a black background (0.02 cd/m^2) on a 17-in. CRT monitor. Search displays consisted of 12 items, one of which was a T-shaped target rotated randomly by 90° either to the left or the right. The 11 remaining items were L-shaped nontargets rotated randomly in one of the four orthogonal orientations. Search displays were generated by placing the target and nontargets randomly in the cells of a 6×8 matrix with an individual cell size of $2.5° \times 2.5°$. Nontargets were jittered horizontally and vertically in steps of 0.1° within a range of $\pm 0.6°$. Example search displays are shown in Figure 1. Observers were seated in a dimly lit room with a viewing distance of approximately 57 cm (unrestrained).

Trial sequence

At the beginning of each trial, observers fixated a cross presented at the center of the screen for 500 ms. Then, a search display was presented until observers made a speeded response by pressing one of two mouse buttons (with either the left- or right-hand index finger). Observers were instructed to search for the target "T" and decide as quickly and accurately as possible whether the stem of the "T" was pointing to the left or the right. Eye movements were not restricted. In case of a response error, a minus sign appeared on the screen for 1000 ms. An interstimulus interval of 1000 ms separated one trial from the next.

Design and procedure

Experiment 1 implemented a 2×8 repeated-measures design with the (within-observer) factors context" (old, new) and "epoch" (1–8).[2] With respect to context, for old contexts, a set of 12 search displays was generated for each observer and repeated throughout the experiment (with an invariant arrangement of nontarget items and one target item on every presentation). For new contexts, the configuration of nontarget items was generated randomly from trial to trial. In order to rule out location-probability effects, different sets of target locations were selected for old and new contexts, and each target location was assigned to one context in the initial learning phase. Overall, 24 equally probable target locations were assigned to the displays. The orientation of the targets was random on each trial whereas those of the nontargets were held constant for old contexts. Figure 1 depicts example search displays with invariant configurations of nontargets. The second factor, epoch, divided the experiment into eight equally sized consecutive bins (each bin consisted of 120 trials), which permitted the examination of possible learning effects over the course of the experiment by using aggregated, more robust values.

The experiment started with a practice block of 24 randomly generated displays to familiarize observers with the task. All subsequent 40 experimental blocks consisted of 24 trials, 12 with old- and 12 with new-context displays. New-context layouts were generated randomly for each trial. Old- and new-context displays were presented in random order in each block. After an initial learning phase of three epochs (blocks 1–15), repeated target locations were exchanged once between old-context displays. That is, each old-context display was again repeatedly presented with a fixed target location originating from another old-context display in epochs 4 to 7 (exchange phase; blocks 16–35). In the last, eighth epoch of the experiment, target locations returned to their original old-context displays (return phase; blocks 36–40; see Figure 1). After each block, observers took a short break and continued with the experiment at their own pace. Overall, observers completed 984 trials.

Recognition test

After the last search trial, a final test was applied to examine whether contextual cueing occurred implicitly during the previous experimental phases (see Chun & Jiang, 1998). Observers were asked to distinguish between old and new contexts via mouse-button responses. The 12 old-context displays and another 12 randomly generated new contexts were presented in random order (24 trials in total). Displays were presented with their original target locations from the initial learning phase because the explicit recognition of a given old context—if present at all—should be stronger for reliably learned context-target relationships (see preconditions above and Zellin et al., 2011, 2013). The response was nonspeeded, and no error feedback was provided.

Results

Search task

Individual mean error rates were calculated for each variable combination. The overall error rate was low (3.4%) and a 2×8 repeated-measures analysis of variance (ANOVA) with the factors context (old, new) and epoch (1–8) revealed no significant effects (all ps > 0.1).

Next, individual mean RTs were calculated for old and new contexts separately for each epoch. Error trials and RTs exceeding the individual's mean RT by ± 2.5 standard deviations were excluded from the analysis. This outlier criterion led to the removal of 2.5% of all trials; the same outlier procedure was applied in Experiment 2, resulting in a comparable exclusion rate (2.2%). Greenhouse-Geisser corrected values are reported in case Mauchley's test of sphericity was significant ($p < 0.05$).

Mean RTs for old and new contexts across epochs are presented in Figure 2 (top panel) with the corresponding mean contextual-cueing effects (RT[new] minus RT[old]) presented in the bottom panel of Figure 2. In a first analysis, individual mean RTs were computed for old and new contexts in each phase (learning, exchange, return). An overall 2×3 ANOVA with the factors context (old, new) and phase (learning, exchange, return) was performed to investigate whether contextual cueing changed in the different phases of the experiment. This analysis yielded main effects of context, $F(1, 12) = 15.68$, $p < 0.01$, and of epoch, $F(1.24, 14.89) = 11.44$, $p < 0.01$, but the interaction between context and phase was not significant ($p > 0.2$), indicating that target-location exchange and target-location return did not significantly affect contextual cueing (see also Figure 2). Contextual-cueing effects were comparable across the learning (50 ms), exchange (70 ms), and return (82 ms) phases.

Because RT distributions are often skewed, median RTs were additionally computed for each observer and each variable combination. An analogous overall ANOVA on the median RTs with the factors context (old, new) and phase (learning, exchange, return) was computed, which yielded similar main and interaction effects as the previous analysis: context, $F(1, 12) = 15.68$, $p < 0.01$; phase, $F(1.43, 17.16) = 11.49$, $p < 0.001$; context $\times$ phase, $F(1.37, 15.81) = 2.41$, $p > 0.1$. The median contextual-cueing effects were comparable across the learning (45 ms), exchange (64 ms), and return (105 ms) phases. Note also that mean contextual-cueing effects derived from either mean or median RTs were highly correlated in each phase of the experiment (rs $> .7$, ps < 0.01). In what follows, separate analyses based on mean RTs for each phase will be presented to examine the process of adaptation more closely.

First, a 2×3 repeated-measures ANOVA with the factors context (old, new) and epoch (1–3) was computed for the learning phase (initial target locations), which revealed significant main effects of context, $F(1, 12) = 11.16$, $p < 0.01$, and epoch, $F(2, 24) = 10.09$, $p < 0.01$. RTs were, on average, 50 ms faster for old contexts than for new contexts and decreased by 78 ms across epochs. The interaction between context and epoch was also significant, $F(2, 24) = 7.25$, $p < 0.01$, reflecting an increase in the contextual-cueing effect during the initial learning phase (from −2 ms in epoch 1 to 102 ms in epoch 3; see bottom panel of Figure 2 for significant contextual-cueing effects).

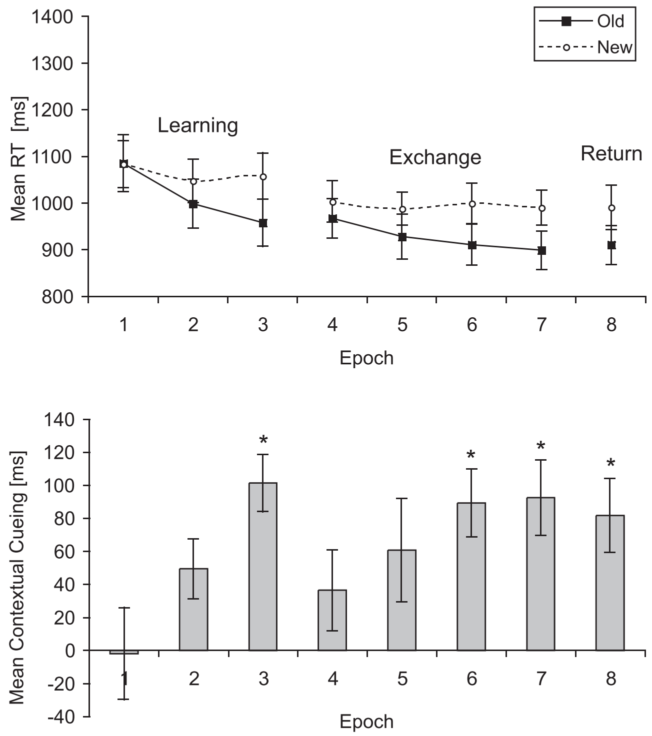

Figure 2. (Top panel) Mean RTs (in ms with associated standard errors) for old and new contexts across epochs in Experiment 1. (Bottom panel) Mean contextual-cueing effects (in ms with associated standard errors) across epochs; pairwise comparisons between RTs for old and new contexts were computed for each epoch with stars indicating significant contextual-cueing effects (Bonferroni-corrected significance level: $p < 0.0063$).

In order to explore the effect of exchanging target locations, the last epoch of the learning phase was directly compared with the first epoch of the exchange phase. A 2 × 2 ANOVA with the factors context (old, new) and epoch (3–4) yielded a significant interaction, $F(1, 12) = 17.52$, $p < 0.01$. Upon exchanging target locations, contextual cueing was significantly reduced from epoch 3 to epoch 4 (102 vs. 37 ms, respectively), without a reliable difference in RTs between old and new contexts in epoch 4, $t(12) = 1.49$, $p = 0.16$. However, contextual cueing recovered in the subsequent epochs of the exchange phase. A 2 × 4 ANOVA with the factors context (old, new) and epoch (4–7) revealed significant main effects of context, $F(1, 12) = 10.62$, $p < 0.01$, and epoch, $F(3, 36) = 3.28$, $p < 0.05$, and a significant interaction between context and epoch, $F(3, 36) = 3.08$, $p < 0.05$. On average, RTs were 70 ms faster for old contexts than for new contexts, RTs decreased by 41 ms from epoch 4 to epoch 7, and the RT-advantage for old contexts increased across epochs (from 37 ms in epoch 4 to 93 ms in epoch 7; see bottom panel of Figure 2 for significant contextual-cueing effects).

Returning target locations in epoch 8 did not affect mean RTs as evidenced by a 2 × 2 ANOVA with the factors context (old, new) and epoch (7–8, i.e., before and after the return of the initial target location), which revealed no significant interaction between context and epoch ($F < 1$). Overall, RTs were 82 ms faster for old contexts than for new contexts, $t(12) = -3.67$, $p = 0.00$, and contextual cueing in the return phase was comparable to contextual cueing in the initial learning phase, $t(12) = 1.63$, $p = 0.13$.

Recognition test

Overall, the mean accuracy in the recognition test was 45.8%. Observers recognized old contexts as old contexts on 45.5% of the trials (hit rate) and new contexts as old contexts on 53.9% of the trials (false alarms). The difference between hits and false alarms was not significant, $t(12) = -1.14$, $p = 0.28$. In a further step, the sensitivity measure d' was computed (z[hits] minus z[false alarms]) for each observer to represent individual recognition performance. Mean d' was relatively small (–.33) and did not differ significantly from zero, $t(12) = .79$, $p = 0.45$. Taken together, this pattern of results suggests that observers were largely unaware of the repetition of old contexts (see Chun & Jiang, 1998).

Discussion

The results of Experiment 1 showed that one old context can cue two different, repeated target locations (Chun & Jiang, 1998), provided they are predictable (see also Conci & Müller, 2012; Conci et al., 2011). In the learning phase, contextual cueing occurred for old-context displays paired with initial target locations. When target locations of old-context displays were exchanged, contextual cueing was temporarily reduced, but it fully recovered after two epochs. Toward the end of the exchange phase, the contextual-cueing effect for relocated targets was comparable to the effect observed in the initial learning phase. Moreover, contextual cueing for initial target locations was preserved throughout the exchange phase as indicated by robust contextual cueing in the final return phase. Thus, initially learned, implicit context-target associations were not affected by repeated presentations of relocated targets (see also Zellin et al., 2013, for a comparable finding).

Experiment 2

Experiment 2 was the same as Experiment 1 except that repeated target locations of old-context displays were exchanged with repeated target locations of new-

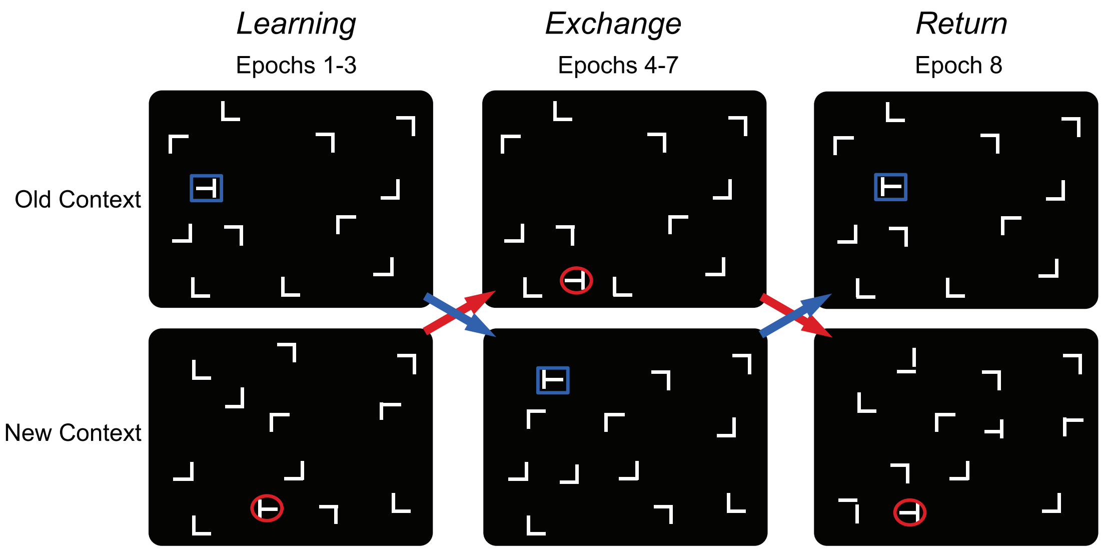

Figure 3. Examples of old- (top half) and new-context search displays (bottom half), illustrating the exchange of target locations in Experiment 2. Search displays were paired with unique target locations in the learning phase (highlighted here by a square and a circle, respectively, which were not presented to the observers). Subsequently, target locations were exchanged between old- and new-context displays in the exchange phase (arrows). The final return phase presented initial context-target pairings.

context displays. Probability learning typically occurs for all repeated target locations in both old- and new-context displays (Chun & Jiang, 1998; Jiang et al., 2013). Hence, target locations of new-context displays should be as predictable as the target locations of old contexts and also more predictable than completely new target locations presented as relocated targets in previous studies (e.g., Conci et al., 2011; Manginelli & Pollmann, 2009; Zellin et al., 2013). Therefore, contextual cueing should also occur for old contexts in the exchange phase of Experiment 2.

Methods

The methodological details were the same as in Experiment 1 except that repeated target locations were exchanged between old- and new-context displays after the initial learning phase (see Figure 3). Old- and new-context displays were presented with fixed target locations in the initial learning phase (epochs 1–3). The fixed target locations were surrounded by repeated contexts in old contexts while contexts varied in each trial in new contexts. In the subsequent exchange phase (epochs 4–7), repeated target locations of new contexts appeared in old contexts, and repeated target locations of old contexts appeared in new contexts. Finally, original context-target location pairings (from the learning phase) were again presented in the return phase (epoch 8).

Twelve adults took part in the experiment (eight women; mean age: 28.1 years, age range: 19–38 years). All observers had normal or corrected-to-normal visual acuity, and all were right-handed. They received either payment (8€) or course credit for their participation.

Results

Search task

Individual mean error rates were calculated for each variable combination. The overall error rate was low (2.2%), and a 2×8 repeated-measures ANOVA with the factors context (old, new) and epoch (1–8) revealed no significant effects (all ps > 0.1).

Individual mean RTs were calculated for old and new contexts separately for each epoch. Error trials and outliers were removed from the data. Mean RTs for old and new contexts across epochs are shown in Figure 4 (top panel). First, a 2×3 ANOVA with the factors context (old, new) and phase (learning, exchange, return) revealed significant main effects of context, $F(1, 11) = 20.79$, $p < 0.01$, and phase, $F(1.27, 13.94) = 7.30$, $p < 0.05$, as well as a significant interaction between context and phase, $F(2, 22) = 18.31$, $p < 0.001$. The interactions mean that target location exchange and return affected the contextual-cueing effects: The effects were, on average, 86 ms, −44 ms, and 112 ms in the learning, exchange, and return phases, respectively (see bottom panel of Figure 4 for the mean contextual-cueing effects across all epochs).

As in Experiment 1, median RTs were computed for each observer and each variable combination. The overall ANOVA with the factors context (old, new) and phase (learning, exchange, return) was again performed

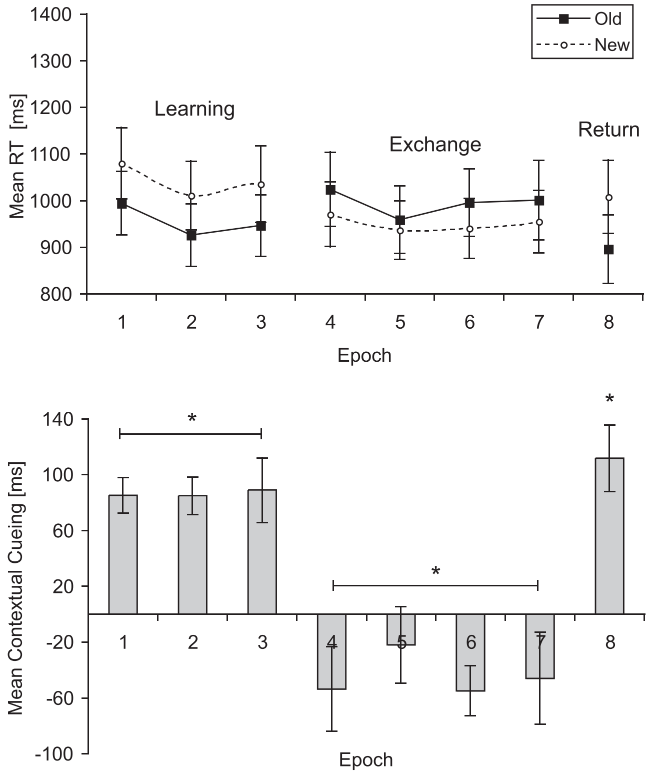

Figure 4. (Top panel) Mean RTs (in ms with associated standard errors) for old and new contexts across epochs in Experiment 2. (Bottom panel) Mean contextual cueing (in ms with associated standard errors) across epochs; stars represent significant contextual-cueing effects as indicated by main effects of context in the learning and exchange phases while the star in epoch 8 represents a significant pairwise comparison.

on median RTs, yielding a similar pattern of main and interaction effects as reported for mean RTs: context, $F(1, 11) = 15.43$, $p < 0.01$; phase, $F(2, 22) = 6.96$, $p < 0.01$, context × phase, $F(1.05, 11.52) = 17.40$, $p < 0.01$. Again, contextual-cueing effects (averaged across the epochs of a given phase) varied substantially across the different phases (97 ms, −62 ms, and 145 ms in the learning, exchange, and return phases, respectively). Furthermore, mean contextual-cueing effects computed based on either mean or median RTs were highly correlated in each phase of the experiment (rs > .9, ps < 0.001), suggesting that the possibly skewed RT distributions did not affect the overall pattern of RT effects. All subsequent analyses (reported below) were based on mean RTs.

For the learning phase, a 2 × 3 repeated-measures ANOVA with the factors context (old, new) and epoch (1–3) revealed significant main effects of context, $F(1, 11) = 36.56$, $p < 0.01$, and epoch, $F(2, 22) = 12.52$, $p < 0.01$. RTs were, on average, 86 ms faster for old contexts than for new contexts and decreased overall by 46 ms across epochs. The interaction between context and epoch was not significant ($p > 0.9$). To show that contextual cueing developed in the first epoch (rather than occurring in the first block by chance), additional pairwise comparisons between RTs for old and new contexts in the first five blocks were computed, which revealed the first significant difference already in block 2, $t(11) = -3.52$, $p = 0.005$ (Bonferroni-corrected significance level $p < 0.01$), which is in line with previous reports of early contextual-cueing effects (e.g., Conci & von Mühlenen, 2009).

The effect of exchanging target locations on contextual cueing was first analyzed with a 2 × 2 ANOVA with the factors context (old, new) and epoch (3–4, i.e., before and after target location exchange). The interaction between context and epoch was significant, $F(1, 11) = 8.71$, $p < 0.05$. Exchanging target locations turned contextual cueing of 89 ms in epoch 3 into contextual costs of −54 ms in epoch 4. Thus, the interaction between context and epoch also reflected an inversion of RTs for old and new contexts from epoch 3 to epoch 4. That is, RTs for new contexts in epoch 4 (with old-context target locations) were faster than RTs for new contexts in epoch 3 (by 65 ms), $t(11) = 2.27$, $p = 0.04$. Conversely, RTs for old contexts in epoch 4 (with new-context targets) were much slower than RTs for old contexts in epoch 3 (by 78 ms), $t(11) = 3.25$, $p = 0.01$. Another 2 × 4 ANOVA across the whole exchange phase with the factors context (old, new) and epoch (4–7) yielded a significant main effect of context, $F(1, 11) = 5.19$, $p < 0.05$, which, however, reflected faster RTs for new contexts in comparison to old contexts (contextual costs of −44 ms). The main effect of epoch was also significant, $F(3, 33) = 3.85$, $p < 0.05$, with decreasing RTs (by 20 ms) across epochs. The interaction between context and epoch was not significant ($p > 0.7$). Overall, visual search in new contexts was expedited by presenting old-context target locations in the exchange phase whereas search in old contexts was impaired by inserting new-context target locations.

When original target locations returned in epoch 8, contextual cueing recovered in comparison to epoch 7 as reflected by a 2 × 2 ANOVA with the factors context (old, new) and epoch (7–8, i.e., before and after the return of initial target locations), which revealed a significant interaction between context and epoch, $F(1, 11) = 18.06$, $p < 0.01$. Mean RTs were 112 ms faster for old than for new contexts in epoch 8, $t(11) = 4.70$, $p = 0.00$, and mean contextual cueing in epoch 8 was comparable to mean cueing effects in epoch 3, $t(11) = 1.47$, $p = 0.17$.

Recognition test

Overall, the mean accuracy of recognizing old and rejecting new contexts was 55.6%. Observers' hit rate of

56.9% differed significantly from the number of false alarms (45.8%), $t(11) = 2.29$, $p = 0.04$, which indicates that observers were, to some extent, aware of the repetition of parts of the contexts. However, mean d' (0) was not significantly different from zero ($p = 1$); that is, recognition performance was essentially at chance level. Furthermore, contextual cueing for initial target locations was not significantly correlated with d', $r = -.21$, $p = 0.50$, indicating that the explicit recognition of some old contexts did not influence contextual-cueing effects (see also Geyer, Shi, & Müller, 2010; Shanks, 2010; Westerberg, Miller, Reber, Cohen, & Paller, 2011).

Discussion

In Experiment 2, no adaptation to relocated targets was observed: Robust contextual cueing occurred for old-context displays paired with fixed target locations in the initial learning phase. However, when target locations were exchanged between old- and new-context displays, visual search was faster in new-context displays than in old-context displays. While the exchange of target locations in Experiment 1 affected contextual cueing only transiently, in Experiment 2, contextual cueing was reversed and did not occur in the entire exchange phase. At the same time, search in new contexts was expedited when they were paired with old-context target locations in the exchange phase (compared to performance in the learning phase). Thus, it appears that old-context target locations maintained their level of facilitation independently of the surrounding context. In the return phase, when old-context displays were presented with their initial target locations, contextual cueing was again as strong as in the learning phase (see also Experiment 1).

General discussion

We investigated whether probability learning (i.e., learning target location probabilities) would facilitate the adaptation of contextual learning to relocated targets. Old- and new-context displays were paired with fixed target locations and presented repeatedly in an initial learning phase. Subsequently, target locations were exchanged between either old-context displays (Experiment 1) or between old- and new-context displays (Experiment 2). Because exchanged (i.e., relocated) target locations were predictable based on having been repeated in the initial learning phase, contextual cueing was expected to continue in the exchange phases. In the final phase of the experiments, target locations returned to their original contexts. Overall, we found that exchanging such predictable target locations of old contexts continuously facilitated visual search in both old and new contexts whereas predictable target locations of new contexts impaired contextual cueing in the exchange phase.

More precisely, successful adaptation to relocated targets was observed when predictable target locations were exchanged between old-context displays (Experiment 1). In fact, contextual cueing for relocated targets was just as strong as contextual cueing for initial target locations in the learning phase. However, when predictable target locations were exchanged between old- and new-context displays, visual search became slower in old-context displays than in new-context displays (Experiment 2). In this case, adaptation to predictable relocated targets was not observed. Conversely, the presentation of old-context target locations in new contexts (exchange phase of Experiment 2) facilitated visual search significantly.

In both experiments of our study, the return of initial target locations to their original contexts elicited reliable contextual cueing comparable to results of the learning phases. Thus, the present study supports previous findings showing that implicit contextual associations are retained across inconsistencies and possible sources of retroactive interference (Chun & Jiang, 2003; Jiang, Song, & Rigas, 2005; Jungé et al., 2007; Mednick, Makovski, Cai, & Jiang, 2009; van Asselen & Castelo-Branco, 2009; Zellin et al., 2013). As for the results of Experiment 1, successful contextual cueing in both the exchange and return phases suggests that old contexts cue at least two (predictable) target locations equally efficiently with no evidence of interference between target locations (see also Conci & Müller, 2012; Conci et al., 2011). Thus, under specific circumstances may multiple target locations be integrated into one invariant context (as originally proposed by Chun & Jiang, 1998, and Brady & Chun, 2007).

Adaptation to relocated targets has usually been tested with the introduction of completely new target locations at previously empty positions after a learning phase (Chun & Jiang, 1998; Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). In these cases, adaptation to relocated targets was not observed at all—not even when old contexts were rather permanently paired with relocated targets (Zellin et al., 2013), suggesting that only a single target location can be associated with an invariant context (Zellin et al., 2011). By contrast, here we observed contextual cueing for relocated targets when they were predictable from repeated encounters in the learning phase, specifically, when they were relocated from one old context to another old context (Experiment 1). Similarly, Conci et al. (2011) demonstrated that contextual cueing for multiple targets in one invariant context can be enabled by using predictable target locations. However, unlike the present study, they presented two target locations simultaneously within one context, and observers searched for one of them at a time (see also Conci & Müller, 2012). Hence, old contexts were each associated with two fixed target locations from the beginning of the experiment. In the present study, while all target locations were also predictable, old contexts were only presented with one target location at a time. Nevertheless, when those predictable target locations were transferred from their initial old contexts to different old contexts, they eventually facilitated visual search in the exchange phase even though they had not appeared in those old contexts before (Experiment 1).

In contrast to Experiment 1, relocated targets from new-context displays impaired contextual cueing in Experiment 2 although they were as predictable from the initial learning phase as relocated targets in Experiment 1. The detrimental impact of new-context target locations on contextual cueing exceeded the negative effects observed when targets were relocated to previously empty positions (Manginelli & Pollmann, 2009; Zellin et al., 2013). In fact, the observed contextual costs in the exchange phase of Experiment 2 resembled findings of impaired visual search when a target is presented at a nontarget position within one context (e.g., Makovski & Jiang, 2010). The impairment of search for targets placed at nontarget positions is thought to result from the inhibition of nontargets in contextual cueing (see also Ogawa, Takeda, & Kumada, 2007). In the current study, previously empty positions in old contexts were also inhibited because new-context target locations appearing in old contexts originated from nonpredictive contexts.

While all relocated targets were predictable from repeated presentations in the learning phase in Experiment 2, only target locations of old-context displays were previously predicted whereas target locations of new-context displays were not predicted by the surrounding context. This difference in past contextual relationships seemed to modulate target locations' transferability to another predictive context. Thus, observers extracted higher-order statistical information beyond our original expectations: Not only did observers learn target location probabilities (lower-order statistics) and contextual relationships (higher-order statistics; see Fiser & Aslin, 2002), but they additionally represented the "contextual past" of predictable target locations (see also Reder et al., 2003). The different contextual pasts of old- and new-context target locations might have resulted in opposing expectations (or hypotheses) about future associations with old or new contexts, and these expectations seemed to be coupled with the respective target locations in the exchange phases of the experiments (Conci et al., 2012; see also Clark, 2013). In particular, the previously predictive relationships of old-context target locations permitted the learning of further associations with another old context whereas new-context target locations caused detrimental effects due to their initial appearance in new, nonpredictive contexts.

If previous statistical learning of contextual relationships influences subsequent contextual learning of exchanged target locations, the presentation of old-context target locations in new contexts should also result in an impairment of visual search. However, in Experiment 2, search in new contexts benefitted from the presentation of old-context target locations. A potential explanation for this finding could be that contextual learning in the initial part of the experiment automatically prioritized all old-context target locations over new-context target locations. If, for example, search displays in contextual cueing are represented as activation maps, all search items would receive the same (low) activations at the beginning of the experiment (see Brady & Chun, 2007, for a typical model). Across the experiment, the activations of all repeated target locations (in both old and new contexts) increase through probability learning, reflected as peaks of activation in the maps relative to nontargets, which speeds target detection. Old contexts further increase the activations of old-context target locations, resulting in an advantage for visual search in comparison with new-context target locations. Higher activations of old-context targets might have contributed to fast visual search for old-context targets presented in new contexts—along with potentially reduced activations of new-context targets. Thus, in this view, old-context target locations were represented as high-priority peaks of activation in all displays due to their contextual past; that is, the representations of target locations in contextual cueing are highly influenced by their contextual past while also being somewhat decoupled from the surrounding context (see Jiang & Wagner, 2004, for a similar conclusion regarding the representation of nontargets).

Besides predictable target locations of old and new contexts, targets can also be relocated to previously empty positions with virtually no statistical past (e.g., Manginelli & Pollmann, 2009). These empty positions would not be represented in the activation map, and, hence, observers would not expect them to contain a target object. Thus, target relocation to previously empty positions should slow visual search in old contexts substantially, which was, indeed, observed in several studies (e.g., Manginelli & Pollmann, 2009; Zellin et al., 2013). However, because empty positions are not associated with a specific statistical past, observers should, in theory, be able to integrate relocated targets presented there. Thus far, only tendencies toward contextual learning of relocated targets at previously empty positions have been observed (e.g., with eye movement measures as in Manginelli & Pollmann, 2009). Because implicit learning is quite prone to effects of proactive interference (see Lustig & Hasher, 2001, for review), contextual learning of those relocated targets could be severely delayed (Zellin et al., 2013), necessitating a large number of presentations of relocated targets at previously empty positions in order to be associated with old contexts.

As a summary of our line of argumentation, Figure 5 provides a schematic illustration of the different contextual pasts of predictable old-context and new-context target locations. In the figure, old- and new-context target locations are represented as peaks in a general activation map (as, for example, in Brady & Chun, 2007) with higher activations for old-context targets relative to new-context targets (because invariant contexts further enhance activations of old-context target locations beyond basic probability learning). Most importantly, Figure 5 shows that old-context target locations are associated with surrounding nontargets and are, therefore, contextually bound whereas new-context target locations "stand alone". Because old-context target locations are associated with predictive contexts, they can be transferred to further predictive contexts. For example, after repeated search for toaster X in kitchen Y at the predictable location Z, observers might "assume" that Z is a legitimate location for any toaster in any invariant kitchen scene (see also Conci et al., 2011). By contrast, the lack of contextual associations for new-context target locations impairs later integration into an old context—simply

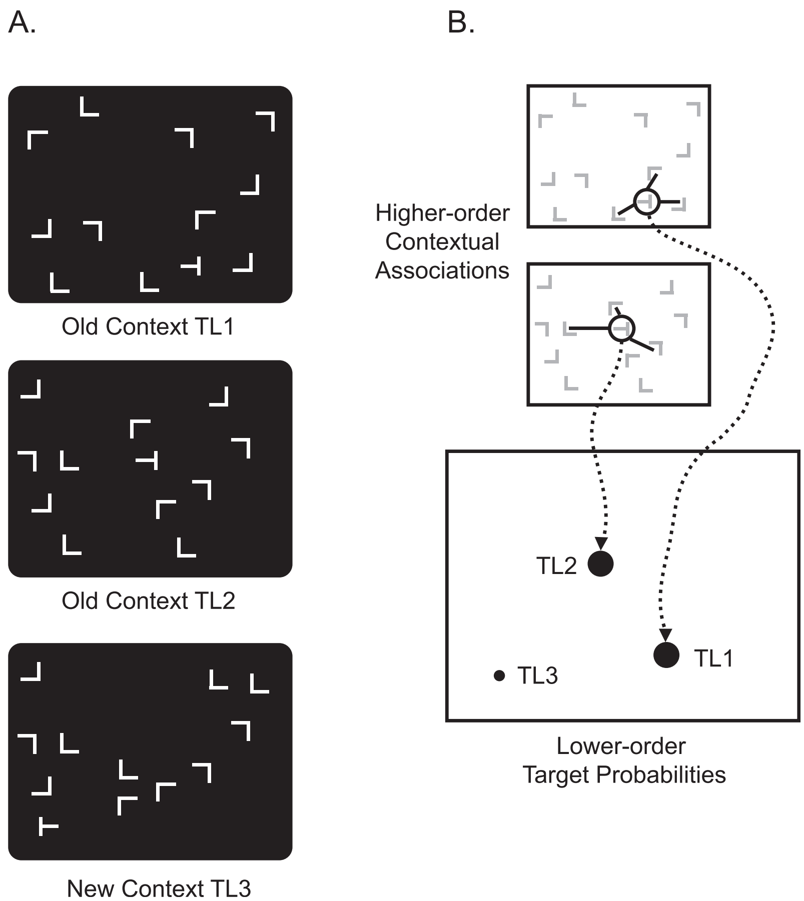

Figure 5. Schematic illustration of the influence of statistical learning in the past on contextual learning in the future. Panel A shows two examples of old-context displays, each with fixed target locations 1 (TL1) and 2 (TL2) and one example of a new-context display with a different fixed target location 3 (TL3). In panel B, different contextual pasts of old-context and new-context target locations are depicted. All three target locations are represented as predictable peaks on a general activation map (black circles) based on lower-order probability learning with the size of each circle scaling the rates of activation (i.e., representing some form of search priority; see Fecteau & Munoz, 2006, for review). Activations of old-context targets are further increased through higher-order contextual learning (dotted-line arrows). Because old-context target locations are contextually bound (solid lines connecting targets and nontargets), they can be matched with further old contexts. New-context target locations, on the other hand, lack predictive contextual associations. Their contextual past hinders the integration into old contexts in the future.

because it does not belong there. For example, if the predictable location Z of toaster X is never surrounded by an invariant kitchen scene or occurs in totally different, ever-changing scenes (kitchen, garage, etc.), observers might learn not to expect this target location to be predicted by an invariant context in the future (see Clark, 2013).[3]

In line with our conclusions regarding the influence of past statistical learning on future contextual learning, the statistical past of cues and their associated outcomes generally influences the success rate of adaptive processes in statistical learning. For example, Jungé et al. (2007) already pointed out that observers probably form (implicit) expectations about statistical regularities of the presented search displays. In their study, observers learned about the absence of statistical regularities in the first half of the experiment. Afterwards, statistical regularities were not expected, and, therefore, contextual cueing did not occur in the subsequent phase for the actual old contexts. Furthermore, Beesley and Le Pelley (2010) reported that the predictive past of a cue influenced the subsequent rate of learning of that particular cue. In a variant of the Serial Reaction Time task, observers were trained with good and poor predictors of subsequent outcomes. In a second stage, good and poor predictors were paired with new outcomes, and observers were faster to learn these new associations with previously good predictors as compared to previously poor predictors. In the present study, the statistical past of predictable target locations (target locations might be considered as outcomes) determined whether or not observers associated them with a further predictive cue. When target locations had a "poor" past of associations (i.e., target locations of new contexts), they were not associated with another predictive cue subsequently, but targets with a "good" past continued to facilitate search in other contexts (i.e., target locations of old contexts).

These findings have important implications for research on the adaptation to change in implicit (statistical) learning experiments. Specifically, change can be implemented in several different ways in contextual cueing: by starting a completely new experiment (Jiang et al., 2005), by swapping targets with nontargets (Makovski & Jiang, 2010), by presenting targets at previously empty positions (Manginelli & Pollmann, 2009), or by exchanging target locations between contexts as in Experiments 1 and 2 of our study. Differences between these variants of change in contextual cueing may seem subtle, but, as our results have shown, adaptation to each variant of change is modulated by different representations of the corresponding statistical past (see also Zellin et al., 2013). Thus, instead of equating different variants of, for example, changed target locations (e.g., Pollmann & Manginelli, 2009), the respective statistical past needs to be taken into account when experiments on adaptation to change are designed and interpreted.

Conclusion

The present study revealed that one invariant context can cue two target locations successfully. However, unlike our expectation, predictability of changed target locations as such was not sufficient for adaptive contextual learning. Instead, contextual learning of changed target locations depended on their contextual past: Contextual learning occurred for changed target locations when they were predictable *and* previously predicted by an invariant context. Likewise, visual search in new contexts benefited from the presentation of previously predicted target locations. Conversely, contextual costs were observed for changed target locations when they were predictable but previously not predicted by an invariant context. Overall, these findings suggest that observers extract multiple aspects of statistical information available in the environment interactively, resulting in implicit hypotheses about future occurrences of familiar stimuli, which modulate success rates of subsequent statistical learning.

Keywords: statistical learning, contextual cueing, visual search

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Footnotes

[1]Across both Experiments 1 and 2, a total of 14 observers were excluded with mean negative contextual cueing of −89 ms in the initial learning phase and mean contextual cueing of 105 ms in the exchange phase.

[2]Note that the factor "epoch" included separate experimental phases (learning, exchange, return; see below for further details).

[3]Note that examples of real-world objects and scenes are only used to illustrate our results and theoretical assumptions. Their validity as specific hypotheses for statistical learning in real-world scenes would require empirical testing.

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