

Long-term adaptation to change in implicit contextual learning

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Abstract The visual world consists of spatial regularities that are acquired through experience in order to guide attentional orienting. For instance, in visual search, detection of a target is faster when a layout of nontarget items is encountered repeatedly, suggesting that learned contextual associations can guide attention (contextual cuing). However, scene layouts sometimes change, requiring observers to adapt previous memory representations. Here, we investigated the long-term dynamics of contextual adaptation after a permanent change of the target location. We observed fast and reliable learning of initial context–target associations after just three repetitions. However, adaptation of acquired contextual representations to relocated targets was slow and effortful, requiring 3 days of training with overall 80 repetitions. A final test 1 week later revealed equivalent effects of contextual cuing for both target locations, and these were comparable to the effects observed on day 1. That is, observers learned both initial target locations and relocated targets, given extensive training combined with extended periods of consolidation. Thus, while implicit contextual learning efficiently extracts statistical regularities of our environment at first, it is rather insensitive to change in the

longer term, especially when subtle changes in context–target associations need to be acquired.

Keywords Implicit learning · Attention · Visual search · Contextual cuing

Introduction

The visual world contains spatial regularities that can facilitate attentional orienting. For instance, objects in real-world scenes, such as computer monitors and keyboards, often co-occur or are likely positioned at recurrent locations within certain environments—for instance, on an office desk (see Oliva & Torralba, 2007, for a review). We learn such spatial regularities implicitly; that is, just by working in an office, a memory representation of the office’s spatial context is acquired, which then facilitates search for particular objects, such as a filing folder. However, familiar spatial layouts might also undergo changes, such as a permanent relocation of the folder to a different shelf in the office. Consequently, we would have to adapt existing memory representations to include the changed location, so as to maintain attentional guidance by the otherwise invariant context. The present study was designed to investigate the time course of such “relearning” after changes of previously acquired context–target relations.

Relearning an established association is clearly of ecological relevance, compensating for changes in dynamic environments. Such relearning has been investigated extensively in studies concerned with adapting memory representations of previously learned cue–word pairings (see, e.g., Anderson, 2003, for an overview). In these studies, observers explicitly learned to associate cue words (e.g., *fruit*) with particular target words (e.g., *banana*) in an initial learning phase. When the target words were replaced by new words (e.g., *orange*) in

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a subsequent phase, participants quickly learned the new associations—however, with cued recall of the initial target words being significantly inhibited as a result (retrieval-induced forgetting; Anderson, 2003). Thus, adaptation to changed associations occurs readily in explicit learning tasks but may cause interference with initially learned material.

Unlike cued word recall tasks, swift adaptation to changed target locations has not been observed in memory-guided visual search (e.g., Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). Typically, observers were required to search for a target “T” surrounded by a context of nontarget “Ls” (see Fig. 1 for example displays). Unknown to observers, some search displays were presented repeatedly throughout the experiment (old contexts), and search in these old contexts became faster, as compared with search in randomly generated configurations (new contexts), reflecting implicit attentional guidance to the target by the surrounding invariant context (contextual cuing; Chun & Jiang, 1998). To test effects of target location change on contextual cuing, each context was initially presented with a unique target location in a learning phase, after which the targets were relocated to new, previously empty positions within these contexts (Makovski & Jiang, 2010; Manginelli & Pollmann, 2009; Zellin, Conci, von Mühlennen, & Müller, 2013). While contextual cuing was reliably observed for initial target locations after a few repetitions, cuing failed to manifest for targets repeatedly presented at relocated positions—suggesting that implicit adaptation to novel target locations is rather ineffective.

Importantly, the lack of contextual cuing after target locations are changed is unlikely to be attributable to restrictions in memory capacity. For instance, Jiang, Song, and Rigas (2005) presented different old-context displays on 5 consecutive days. They observed successful contextual cuing for each set of old contexts on each day, indicating that learning of novel contexts is fairly unrestricted. Moreover, they found that contexts acquired on a later day of the experiment did not interfere with contextual cuing for contexts learned earlier on (see also Mednick, Makovski, Cai, & Jiang, 2009). In addition, acquired representations of invariant contexts continued to

facilitate search even after a week, suggesting that they undergo little decay. Taken together, these results show that, while contextual memory has in principle a high capacity for acquiring and retaining unique spatial layouts, there is little immediate adaptation of contextual cuing following a change of the target location in an otherwise invariant layout (Zellin, Conci, et al., 2013).

The present study was designed to investigate the long-term dynamics of contextual adaptation—that is, whether a learned association could be updated after a change when enough training is provided. Previous studies (summarized above) suggested that there is no immediate adaptation to change. Here, we performed an experiment with sessions on several days to test whether a larger number of repeated searches in changed contexts would promote adaptation of contextual associations. The study consisted of three phases performed on 6 separate days (comparable to Jiang et al., 2005): On day 1, contexts were presented with initial target locations (*learning phase*) to enable baseline learning. Subsequently, targets were relocated to new positions within their respective contexts, and the new context–target pairings were presented on 4 consecutive days (*relocation phase*) to provide extensive training with the relocated targets. Finally, to test whether both target locations were indeed associated with one old context, contextual cuing was examined again for both target locations (*return phase*) 5 days after the last session of the relocation phase.

Implementing overnight breaks should reduce interference while promoting memory consolidation. In general, active old memories impede the acquisition of new memories in implicit learning tasks (see Lustig & Hasher, 2001, for a review), but proactive interference is supposed to subside effectively during sleep (Jiang et al., 2005; Mednick et al., 2009). Hence, the restricting impact of old context–target associations (from day 1) on acquiring new associations (starting on day 2) should decrease after overnight breaks. In addition, overnight breaks after each relocation session should promote memory consolidation (Spencer, Sunm, & Ivry, 2006), increasing the chance for relearning to occur.

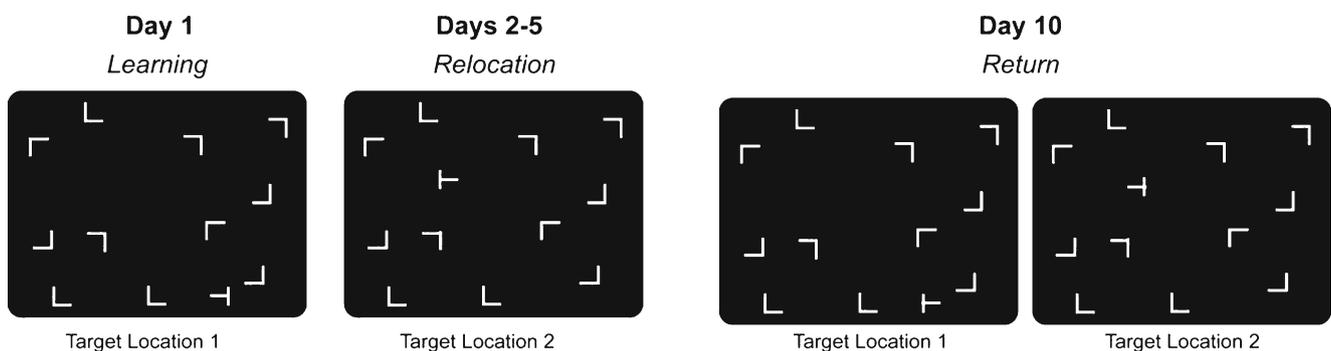


Fig. 1 Example old-context display illustrating the change of target locations across the experimental testing sessions: Displays were presented with initial target locations in the learning phase on day 1.

Subsequently, targets were relocated and repeatedly presented at their new locations on days 2–5 (relocation phase). On day 10, displays were presented with both the initial and the relocated targets (return phase)

Method

We tested a prespecified sample size of 14 adults (11 women; mean age, 24.4 years; range, 18–29 years). Informed consent was obtained from all participants. In order to examine for adaptation of existing contextual associations, observers performed all experimental sessions only if they showed above-zero contextual cuing on day 1 (for a comparable approach, see Conci, Sun, & Müller, 2011; Lustig & Hasher, 2001). We have previously reported that observers displaying a lack of initial learning exhibit effective learning of relocated targets, indicating that these participants simply acquired the invariant target–context associations existing later on (see Zellin, Conci, et al., 2013, for a detailed discussion). Thus, in order to examine “pure” adaptation of previously learned associations, rather than a form of “late learning,” such observers were excluded from the rest of the study (4 observers with mean—negative—contextual cuing of -139 ms on day 1). New observers subsequently replaced the excluded participants. Consequently, the findings reported below apply to the 14 observers who passed our initial selection criterion. Comparable sample sizes were used in previous studies to which our findings relate (Chun & Jiang, 1998; Jiang et al., 2005; Zellin, Conci, et al., 2013).

Example search displays are presented in Fig. 1. Displays consisted of 12 items, one of which was a T-shaped target rotated randomly by 90° to either the left or the right. The 11 remaining nontargets were L-shapes rotated randomly in one of the four orthogonal orientations. Search displays were generated by placing the target and nontargets randomly in the cells of an invisible 6×8 matrix (see Zellin, Conci, et al., 2013, for further details concerning stimulus presentation).

Each trial started with a centrally presented fixation cross, followed by a search display presented until observers responded via mouse keys. The task was to search for the target “T” and indicate its orientation (left- or right-tilted) as quickly and accurately as possible.

A repeated measures design was implemented with the (within-subjects) factors of *context* (old, new) and *epoch* (1–6) for each of the first 5 days of the experiment. With respect to context, a set of 12 old-context displays was generated individually for each observer and repeated throughout the experiment, with an invariant arrangement of nontarget items on every presentation. For new contexts, the configuration of nontarget items was generated randomly on each trial. Each old- and new-context display was paired with two repeated target locations. Different sets of target locations were selected for old and new contexts, such that, overall, 48 different target locations were assigned to the displays. The orientation of the target was random on each trial, whereas those of the nontargets were held constant for old contexts. The second factor, epoch, divided the experiment into six consecutive bins (each bin consisting of 120 trials), to examine the course of learning effects on the basis of aggregated and, thus, more robust values.

On each testing day, the experiment started with a practice block of 24 randomly generated displays. All subsequent 30 experimental blocks consisted of 24 trials, 12 with old and 12 with new context displays, presented in random order. After each block, observers continued with the experiment at their own pace. Overall, observers completed 744 trials on each day in the learning (day 1) and relocation (days 2–5) phases. During initial *learning*, 24 distinct, initial target locations were presented, whereas the subsequent *relocation* phase presented a second set of 24 distinct target locations for both old- and new-context displays (Fig. 1).

After a 5-day break, on day 10 (return phase), observers completed 10 further blocks (2 epochs; 264 trials in total) presenting the old-context displays from day 1 and days 2–5 intermixed with randomly generated new-context displays. Both the first and the second target locations were presented in half of the blocks (five consecutive blocks each; Fig. 1), with order of target presentation counterbalanced across observers. Each session was conducted at approximately the same time of day, with approximately 24-h breaks between sessions.

After the last search trial, 12 old contexts and 12 randomly generated contexts were presented with the target locations from day 1 in a final (“old”-vs.-“new”) recognition test. Displays were presented with initial target locations because one would expect explicit recognition of a given old context—if existent at all—to be stronger for more reliably learned context–target relations.

Results

Across all days, observers made few errors (range = 1.4%–2.3%); a repeated measures analysis of variance (ANOVA) with context (old, new) and day (1–5, 10) as factors revealed no significant effects ($ps > .2$).

Individual mean reaction times (RTs) were calculated for old and new contexts separately for each day and epoch. Error trials and RTs exceeding an individual’s mean RT by ± 2.5 standard deviations were excluded from RT analyses. The number of outliers was comparable between experimental sessions (range: 2.3%–2.8%).

Figure 2 displays the mean RTs for old- and new-context displays across epochs for days 1–5, and Fig. 3 shows RTs for old and new contexts separately for each target location on day 10. In a first step, an overall ANOVA with the within-subjects factors of *context* (old, new) and *day* (1–5, 10) yielded main effects of context, $F(1,13) = 13.50$, $p < .01$, $\eta^2 = .51$, and day, $F(1.42,18.51) = 4.99$, $p < .001$, $\eta^2 = .58$ (for this analysis, contextual cuing of initial and relocated targets on day 10 were collapsed). Importantly, the interaction between context and day was significant, $F(2.14,27.85) = 8.80$, $p < .01$, $\eta^2 = .40$, indicating that contextual cuing was significantly affected by the changes in target location (see Figs. 2 and 3). To further explore the interaction, separate analyses were performed for each phase.

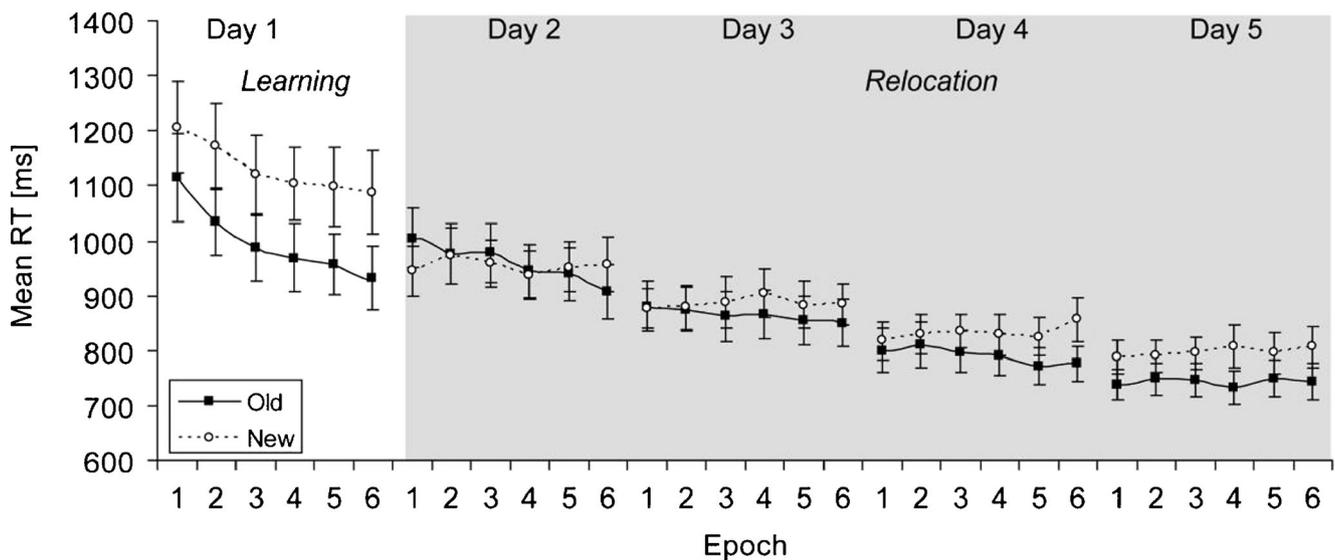


Fig. 2 Mean reaction times (RTs, in milliseconds; with associated standard error bars) for old and new contexts (solid and dashed lines, respectively) as a function of epoch on days 1–5

Day 1: Learning phase

A context (old, new) by epoch (1–6) repeated measures ANOVA of initial target locations revealed significant main effects of context, $F(1, 13) = 24.59, p < .001, \eta^2 = .65$, and of epoch, $F(2.18, 28.32) = 14.41, p < .001, \eta^2 = .53$, but no interaction ($p > .3$). RTs were 132 ms shorter for old than for new contexts, and RTs decreased by 150 ms across epochs. An additional analysis performed on individual blocks (rather than epochs) revealed the first significant difference between old and new contexts already in block 3, $t(13) = -2.46, p < .05$, which is comparable to findings of fast contextual learning in previous studies (e.g., Conci & von Mühlelen, 2009).

Days 2–5: Relocation phase

The adaptation of contextual cuing in the relocation phase was investigated by means of a repeated measures ANOVA with the factors of *context* (old, new), *epoch* (1–6), and *day* (2–5).

This analysis revealed a significant main effect of day, $F(1.83, 23.73) = 54.7, p < .001, \eta^2 = .81$, reflecting a reduction of RTs (by 186 ms) across the training days. In addition, significant interactions between context and epoch, $F(5, 65) = 6.01, p < .001, \eta^2 = .32$, and context and day, $F(1.65, 21.43) = 7.96, p < .001, \eta^2 = .38$, further revealed an increase in contextual cuing both across epochs within each training session and with the number of training days. Importantly, the three-way interaction was also significant [context \times epoch \times day, $F(15, 195) = 1.29, p < .05, \eta^2 = .13$]. Subsequent pairwise comparisons between RTs with old and new contexts in each epoch and day revealed a late development of contextual cuing: For the first 2 days, no significant differences between RTs for old and new contexts were evident, $t(13) < 2.08, ps > .06$. (Note that there was a single reliable difference on day 2 in epoch 6, $p = .02$, which is likely a nonsystematic effect.) Subsequently, as is illustrated in Fig. 2, reliable cuing effects were obtained toward the end of training on day 4, from epoch 5 onward, until the end of the relocation phase, $t(13) > 2.47, ps < .03$. (The comparison for day 5, epoch 3 revealed only a marginal difference, $p = .06$.)

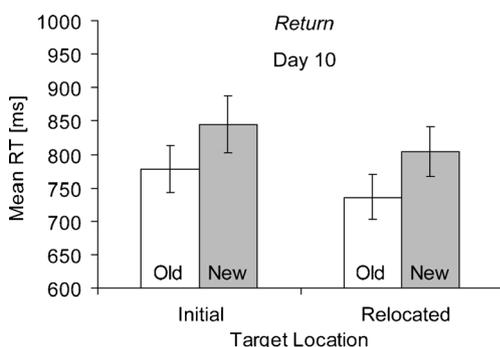


Fig. 3 Mean reaction times (RTs, in milliseconds; with associated standard error bars) for old and new contexts presented with initial and relocated target locations on day 10

Day 10: Return phase

Contextual cuing for initial and relocated targets (see Fig. 3) was compared by means of a mixed ANOVA with the within-subjects factors of *context* (old, new) and *target location* (TL 1, TL 2) and the between-subjects factor of *order* (TL 1 first, TL 2 first). This analysis revealed a significant main effect of context, $F(1, 12) = 18.78, p < .01, \eta^2 = .61$, reflecting shorter RTs (on average, 67 ms) for old than for new contexts. The main effect of target location was marginally significant, $F(1, 12) = 4.68, p = .051, \eta^2 = .28$, owing to longer RTs

Table 1 Planned contrasts between relative contextual cuing for initial target locations (TL 1) on day 1, for relocated targets (TL 2) on days 2–5, and for both initial (TL 1) and relocated (TL 2) targets on day 10

| | Day 1 | Day 2 | Day 3 | DDay 4 | Day 5 | Day 10 | |
|--|-------|-------|-------|--------|-------|--------|------|
| | TL 1 | TL 2 | | | | TL 1 | TL 2 |
| <i>M</i> relative contextual cuing (%) | 11.20 | −0.80 | 2.10 | 4.50 | 6.20 | 7.10 | 7.80 |
| <i>F</i> (1,13) | | 17.88 | 11.48 | 7.10 | 6.01 | 2.81 | 1.47 |
| <i>p</i> | | .00 | .01 | .02 | .03 | .12 | .25 |

(42 ms) for initial target locations, as compared with relocated targets in both old and new contexts. All other main and interaction effects were nonsignificant ($ps > .1$). Contextual cuing was comparable between initial and changed target locations (67 and 68 ms, respectively), $t(13) = -0.03$, $p = .97$.

Comparison between sessions

To further compare contextual-cuing effects for initial target locations on day 1 (baseline) with cuing effects on all other days, *relative* contextual-cuing effects were calculated for each day [(RT(new) − RT(old))/RT(new)]. By calculating relative contextual-cuing effects, we take into account that the general decrease in RTs across days reduces the absolute cuing effects (Jiang et al., 2005). Simple contrasts were computed between the relative contextual-cuing effect for initial target locations on day 1 and the relative cuing effects on all other days (Table 1). Contextual cuing was significantly smaller for relocated targets on days 2–5 than for initial target locations on day 1. However, the cuing effects for both target locations on day 10 were comparable to the effect observed on day 1. Thus, contextual cuing for relocated targets was comparable to cuing for initial target locations (baseline) only on day 10, while cuing for initial target locations was as effective on day 10 as on day 1.

Moreover, a comparison of relative contextual-cuing effects for individual participants revealed the contextual associations for the initial target locations to be relatively stable across days 1 and 10, as evidenced by a significant positive correlation, $r = .53$, $p < .03$. By contrast, no reliable correlation was obtained when contextual cuing for the relocated target on day 10 was compared with the effects for the initial target location on either day 1, $r = .17$, $p = .3$, or day 10, $r = .25$, $p = .2$. This pattern indicates that the initial associations were maintained across the duration of the experiment, while being independent of the learned associations for the second, relocated target.

Recognition test

Overall, mean accuracy was 52%. Observers correctly identified old contexts on 56% of trials (hit rate) and reported new contexts as old on 53% (false alarms); the hit and false alarm

rates did not differ significantly from each other, $t(13) = 0.73$, $p = .48$, suggesting that observers did not explicitly recognize old contexts.

Discussion

We examined whether established memory representations of spatial layouts are adapted to a change in target locations. Overall, observers took just 3 repetitions to acquire repeated context–target associations. However, adaptation of these learned contexts to changed target locations required 80 repetitions (presented over 3 days of training). This suggests that observers were rather inflexible in adapting to relocated targets, necessitating extensive training in the relocation phase to represent a permanent change in the search environment. Moreover, contextual cuing for relocated targets seemed to consolidate further during the 5-day break between days 5 and 10, which, however, did not interfere with contextual cuing of initial target locations. In other words, there was reliable contextual cuing for both target locations on the last day of the study, with effect sizes comparable to the cuing effects observed in the initial learning phase on day 1. Even though the same old contexts were presented on several days, observers were unable to distinguish old from new contexts in the recognition test, consistent with the memory underlying contextual cuing being implicit in nature (Chun & Jiang, 1998, 2003; although see Smyth & Shanks, 2008).

The results from the first 3 days resembled previous findings (Makovski & Jiang, 2010; Manginelli & Pollmann, 2009; Zellin, Conci, et al., 2013): While contextual cuing manifested after a few repetitions on day 1, for relocated targets reliable contextual cuing was not observed until day 4.¹ It thus seems that the repeated context consistently (mis-) guided attention to the initially learned target location, proactively interfering with the adaptation of contextual associations (see also Shiffrin & Schneider, 1977; Zellin, Conci, von Mühlénen, &

¹ It should be noted that contextual cuing after target relocation on days 2–5 (−5 to 54 ms) was much smaller than cuing on day 1, even when the entire sample of (18) observers is considered (72 ms; see the Method section). This suggests that the relocation costs were not due to a bias in participant selection.

Müller, 2011). In general, initial learning tends to (proactively) interfere with subsequent learning of new statistical relations, with interference being particularly marked when cues for memory retrieval are similar or entirely identical (as in the present study; Lustig & Hasher, 2001). Accordingly, the continued presentation of old contexts would have activated associations to initial target locations automatically, impeding adaptation after the change.

The negative effects of proactive interference may, nevertheless, be overcome effectively in some cases. For instance, previous studies demonstrated that adaptation occurs more readily when target location changes are predictable from the outset of the experiment (Conci et al., 2011; Conci & Müller, 2012; Zellin, von Mühlénen, Müller, & Conci, 2013) or when attention is guided to the relocated target by a salient, bottom-up signal (Zellin, Müller, & Conci, 2013). That is, learning can occur when alternative target locations are incorporated into the context initially or when the change is accompanied by a salient event guiding attention to the relocated target. However, when additional information about the target location change is not available, interference can be reduced only over a considerable amount of training and rest.

Despite sustained proactive interference in the present study, the (relative) contextual-cuing effect for initial target locations was unaffected, since it was as reliable in the return phase (day 10) as in the learning phase (day 1). This finding confirms that initially acquired contextual associations are resistant to retroactive interference (Jiang et al., 2005; Jungé, Scholl, & Chun, 2007; Zellin, Conci, et al., 2013), with contextual associations being stable over time (Chun & Jiang, 2003; Mednick et al., 2009) and representing multiple contexts with unlimited capacity (Jiang et al., 2005).

Of note, in the final testing phase on day 10, there was no evidence that the (manifest) contextual-cuing effects were adversely impacted by response competition arising from the same old context being associated with different target locations (see the correlation analysis and Conci & Müller, 2012; Conci et al., 2011)—similar to the absence of competition when observers learned two sets of old contexts consecutively (Zellin, Conci, et al., 2013). According to Brady and Chun (2007), the initial and changed target locations would be represented as two peaks within a single activation map retrieved in response to the same context, which compete to summon attention—translating into an, on average, reduced contextual-cuing effect. If so, the fact that contextual cuing for contexts associated with two target locations was not reduced under the conditions of the present study may then suggest that observers eventually came to encode the changed target location within a separate context representation (“activation map”) that coexisted with the initially established representation. Although the distractor configuration is globally the same for the two representations, they differ subtly in the *local* associations of the target with its surrounding distractors,

which are thought to be crucial for contextual cuing (Brady & Chun, 2007). Thus, depending on exactly where the target is located, the “same” configuration may come to activate one or the other (“local”) context representation, guiding attention to the respective target position—without interference from a potentially competing representation. However, given that the difference between the two contexts is subtle, it takes a considerable amount of training for a separate representation to develop that can reliably cue the changed target location.

In sum, the present study showed that observers were, at first, inflexible in adapting implicit contextual representations to sudden, but permanent, relocations of targets, while extended training, combined with periods of offline consolidation, eventually led to the integration of changed context–target relations. Furthermore, successfully adapting to changed target locations did not affect associative memory for initial target locations. Consequently, observers are able to associate one context with two target locations, without adverse effects of response competition on implicit contextual learning.

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References

- Anderson, M. C. (2003). Rethinking interference theory: Executive control and the mechanisms of forgetting. *Journal of Memory and Language*, *49*, 415–445.
- Brady, T. F., & Chun, M. M. (2007). Spatial constraints on learning in visual search: Modeling contextual cuing. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 798–815.
- Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology*, *36*, 28–71.
- Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 224–234.
- Conci, M., & Müller, H. J. (2012). Contextual learning of multiple target locations in visual search. *Visual Cognition*, *20*, 746–770.
- Conci, M., Sun, L., & Müller, H. J. (2011). Contextual remapping in visual search after predictable target-location changes. *Psychological Research*, *75*, 279–289.
- Conci, M., & von Mühlénen, A. (2009). Region segmentation and contextual cuing in visual search. *Attention, Perception, & Psychophysics*, *71*, 1514–1524.
- Jiang, Y., Song, J.-H., & Rigas, A. (2005). High-capacity spatial contextual memory. *Psychonomic Bulletin & Review*, *12*, 524–529.
- 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 cuing. *Visual Cognition*, *15*, 1–11.
- Lustig, C., & Hasher, L. (2001). Implicit memory is not immune to interference. *Psychological Bulletin*, *127*, 629–650.
- Makovski, T., & Jiang, Y. V. (2010). Contextual cost: When a visual-search target is not where it should be. *Quarterly Journal of Experimental Psychology*, *63*, 216–225.
- Manginelli, A. A., & Pollmann, S. (2009). Misleading contextual cues: How do they affect visual search? *Psychological Research*, *73*, 212–221.

- Mednick, S. C., Makovski, T., Cai, D. J., & Jiang, Y. V. (2009). Sleep and rest facilitate implicit memory in a visual search task. *Vision Research*, *49*, 2557–2565.
- Oliva, A., & Torralba, A. (2007). The role of context in object recognition. *Trends in Cognitive Sciences*, *11*, 520–527.
- Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing. II. Perceptual learning, automatic attending and a general theory. *Psychological Review*, *84*, 127–190.
- Smyth, A. C., & Shanks, D. R. (2008). Awareness in contextual cuing with extended and concurrent explicit tests. *Memory & Cognition*, *36*, 403–415.
- Spencer, R. M. C., Sunm, M., & Ivry, R. B. (2006). Sleep-dependent consolidation of contextual learning. *Current Biology*, *16*, 1001–1005.
- Zellin, M., Conci, M., von Mühlénen, A., & Müller, H. J. (2011). Two (or three) is one too many: testing the flexibility of contextual cueing with multiple target locations. *Attention, Perception, & Psychophysics*, *73*, 2065–2076.
- Zellin, M., Conci, M., von Mühlénen, A., & Müller, H. J. (2013a). Here today, gone tomorrow – adaptation to change in memory-guided visual search. *PLoS One*, *8*(3), e59466.
- Zellin, M., Müller, H. J., & Conci, M. (2013). Attention to change in memory-guided visual search. Manuscript in preparation.
- Zellin, M., von Mühlénen, A. Müller, H. J., & Conci, M. (2013). Statistical learning in the past modulates contextual cueing in the future. *Journal of Vision*, *13*(3):19, 1–14.