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Contextual learning of multiple target locations in visual search

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In visual search, detection of a target is faster when a layout of nontarget items is repeatedly encountered, suggesting that contextual invariances can guide attention. Moreover, contextual cueing can also adapt to environmental changes. For instance, when the target undergoes a predictable (i.e., learnable) location change, then contextual cueing remains effective even after the change, suggesting that a learned context is "remapped" and adjusted to novel requirements. Here, we explored the stability of contextual remapping: Four experiments demonstrated that target location changes are only effectively remapped when both the initial and the future target positions remain predictable across the entire experiment. Otherwise, contextual remapping fails. In sum, this pattern of results suggests that multiple, predictable target locations can be associated with a given repeated context, allowing the flexible adaptation of previously learned contingencies to novel task demands.

Keywords: Contextual cueing; Implicit learning; Visual search.

Dynamic adaptation of behavioural goals to a constantly changing environment requires organisms to learn from past experience. For instance, visual statistical learning has been shown to provide a valuable basis for guiding attention to task-relevant aspects of a scene (see Oliva & Torralba, 2007, for review). In the real world, objects almost never occur in isolation,

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but are typically situated amongst other, related objects. The relations among objects form a "context" of common associations, which can support the guidance of attention. For example, Biederman, Mezzanote, and Rabinovitz (1982) have shown that detection of a target object (e.g., a car) is facilitated if presented within a probable context (e.g., a street scene), relative to an improbable context (e.g., a kitchen). This finding suggests that the typical co-occurrence of related objects can help to efficiently guide behaviour.

Contextual relations between objects may not only facilitate target detection on the basis of object identities, but can also occur for spatial relations between objects in visual search. For instance, search is facilitated when a spatial layout of nontargets is repeatedly paired with a given target location (Chun & Jiang, 1998), a finding referred to as "contextual cueing". In Chun and Jiang's (1998) paradigm, observers are required to search for a target T among a set of 11 nontarget Ls, and indicate the orientation (i.e., the pointing direction) of the target shape (to either the left or the right). Displays differ in that targets either appear within "old" or "new" layouts: Old configurations always present the target within the same layout of nontargets, whereas new configurations present novel nontarget arrangements on each trial. Consequently, comparisons between old and new context conditions indicate whether invariant spatial layout (i.e., the repetition of a given search layout throughout the experiment) influences target detection. Indeed, the results showed that repeated spatial arrangements (i.e., old configurations) led to a benefit in mean reaction time (RT), as compared to when the spatial layout was new—the contextual-cueing effect. Since observers were not able to explicitly discern repeated displays from novel arrangements (in a recognition test at the end of the experiment), this finding was interpreted as evidence for a mechanism that implicitly encodes the spatial associations between display items, thus, guiding attention and facilitating visual search (but see Smyth & Shanks, 2008).

One account of contextual cueing is that associative links are established (learned) between the target location and its surrounding context of nontarget items. In fact, it has been suggested that only two to three such associative links between a given target and its local context of nontargets are sufficient to support contextual cueing (see Brady & Chun, 2007, for a computational model; see also Song & Jiang, 2005). That is, contextual cueing may be based on relatively few learned associations between the locations of neighbouring nontargets and the target. With repeated presentation of the invariant display layouts, search performance is facilitated due to acquired associative (context) links providing an effective cue for guiding attention to the target location.

In terms of ecological relevance, contextual cueing can be regarded as a form of (contextual) scene memory that can facilitate attentional orienting.

In fact, contextual cueing has been shown to facilitate search not only for (relatively artificial) search arrays, but also for real-world natural scenes (e.g., Brockmole & Henderson, 2006). However, to cope with the demands posed by the relatively complex and dynamically changing natural environment, contextual cueing should be (at least to some extent) adaptive. For instance, targets (such as the car in the earlier example) might change location from time to time (e.g., the car might be parked in a different place), and contextual memory should be capable of updating such changes.

A number of studies have investigated whether contextual cueing can adapt to changes of the context–target relations. For instance, Manginelli and Pollmann (2009) trained observers on a set of invariant search displays, but relocated the target to a novel (previously empty) location in a subsequent test phase. The results showed reliable contextual cueing during training; however, after target relocation, the contextual-cueing effect was no longer evident (note, though, that there were no sustained costs either). Moreover, across 10 blocks of trials (in the test phase), observers were not able to readapt the previously learned context to the novel target location. A comparable lack of adaptation was also found when a learned target–context relation was changed such that the target swapped its location with a nontarget (Conci, Sun, & Müller, 2011; Makovski & Jiang, 2010), or when target locations were presented in alternating order across blocks (in order to facilitate the simultaneous learning of multiple target locations; Zellin, Conci, von Mühlenen, & Müller, 2011). Moreover, Makovski and Jiang (2010); see also Zellin et al., 2011) showed that adaptation decreased as the spatial distance between the initially learned target and the relocated target increased. Thus, a number of studies indicate that contextual cueing cannot effectively adapt to changes of the target location: Once a given target is associated with its repeated, invariant context, an unpredictable change of the target location cannot be compensated for and contextual learning fails to support search.

Importantly, the lack of contextual adaptation after an unpredictable location change is unlikely to be due to restrictions in memory capacity: A study by Jiang, Song, and Rigas (2005); see also Mednick, Makovski, Cai, & Jiang, 2009) demonstrated successive learning of novel, previously unseen display configurations on five consecutive days; note that contextual cueing remained effective for previously learned display configurations even though new learning occurred in the meantime. This pattern of results suggests that contextual memory has a high capacity for acquiring and retaining spatial layouts.

Despite this high capacity, contextual cueing cannot compensate for *unpredictable* target location changes in previously learned display layouts. On the other hand, in a recent study, we were able to demonstrate that adaptation may occur for changes that are *predictable* (Conci et al., 2011): In a variant of the contextual-cueing paradigm, displays were presented that consisted of 10 nontarget Ls among two target Ts (one pointing left/right and the other pointing up/down; see Figure 1 for example display layouts), and observers were required to search for one target (e.g., the target pointing left/right) in the first half of the experiment and for the other target (e.g., the target pointing up/down) in the second half. In contrast to previous studies on contextual adaptation (summarized earlier), both targets were entirely predictable (or learnable) as they were present simultaneously throughout the entire experiment. Under these conditions, contextual cueing was reliably obtained in both halves of the experiment (even though there was a numerical reduction of the contextual-cueing effect from 181 ms to 80 ms after the change of the task-relevant target). This finding suggests that a learned target–context relation can be transferred from one target to another (at minor costs) as long as both targets are simultaneously available during the initial learning phase. Our results therefore indicate that a context can be remapped from one target location to the other.

The aim of the current study was to investigate further how multiple targets can be associated with an invariant representation of context items. In particular, we examined the adaptive properties by which a learned context can be remapped, and whether remapping can overcome interference. Four experiments were conducted that always presented two target Ts together with a set of ten nontarget Ls (see Figure 1 for example displays), and observers were required to search for one type of target in the initial, learning phase, and for the other type of target in the second, "remapping" phase (as in Conci et al., 2011). Importantly, the change of the target (between learning and remapping) was always accompanied by an additional change to a single search item (see also Figure 1; changes are highlighted by grey circles). These changes were inserted to systematically examine the robustness of contextual remapping, and to gain insight into the adaptation of learned, associative links between search items in multiple-target contextual cueing.

EXPERIMENT 1

Experiment 1 was performed to examine whether contextual remapping can occur under conditions in which parts of a previously learned context undergo an unpredictable change. To this end, we employed a variant of the contextual-cueing paradigm in which search displays were presented that always contained two targets (Ts) within old and new arrangements of nontargets (Ls; see Figure 1A). In the first half of the experiment, observers were instructed to search for one of the two targets and report its identity (e.g., the T pointing left- or rightwards). Then, in the second half, the

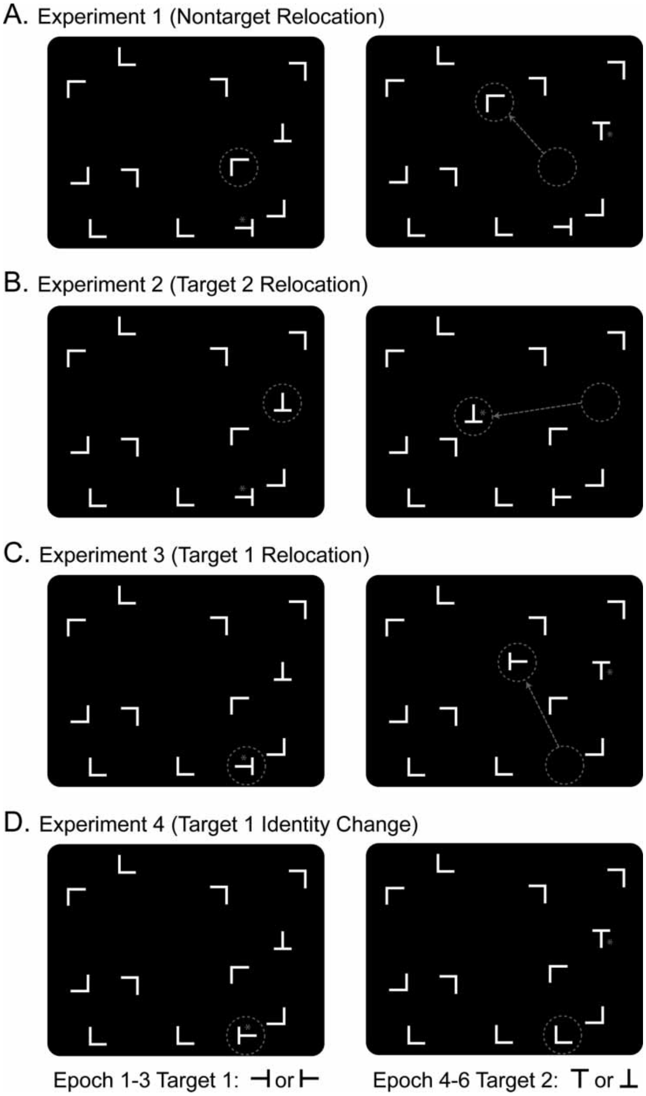

Figure 1. Example displays: All experiments presented search displays that contained two target Ts (among 10 nontarget Ls), but only one target was response-relevant in one half of the experiment (e.g., the T pointing left or right), whereas the other was relevant in the other half (e.g., the T pointing up or down). In Experiment 1 (A), a task-irrelevant nontarget changed its location after Epoch 4 (Part 2). In Experiment 2 (B), the target relevant in the second half changed its location. Experiment 3 (C) introduced a change of the target relevant in the first half (i.e., when this target was no longer response-relevant). Finally, in Experiment 4 (D), the target relevant in the (previous) first half was replaced by a nontarget. The dashed, grey circles and arrows denote the item that changed, and the grey asterisks mark the target that was task-relevant in the two consecutive parts in each experiment (not shown in the actual experiments).

task-relevant target switched and observers were now asked to report the identity of the other target (e.g., the T pointing up- or downwards). Importantly, the change of the task-relevant target was accompanied by a location change of a task-irrelevant nontarget item (e.g., for old-context displays one nontarget L was relocated and presented at a new, previously empty display position; see Figure 1A for example displays). On the basis of our previous study (Conci et al., 2011), we expected that observers are able to adapt the context to predictable changes of the task-relevant target (i.e., they would show contextual cueing in both parts of the experiment). Moreover, contextual learning should be relatively resistant against noise, such as the unpredictable location change of a nontarget within the repeated context (see Brady & Chun, 2007; Olson & Chun, 2002; Song & Jiang, 2005).

Methods

Participants. Ten students (5 male; mean age: 26.9 years) volunteered for course credit or payment of 8 Euro per hour. All participants reported normal or corrected-to-normal vision. As in our previous study (Conci et al., 2011), only observers who exhibited a positive (above-zero) contextual-cueing effect in the first half of the experiment were included in the further analyses. This precondition was set because we wanted to investigate how changes to display items affect already learned contextual memory representations (by definition, observers who failed to learn the repeated contextual layouts in the first half of the experiment cannot contribute to answering this question). Participants were tested until a total of $N=10$ observers were found that showed a positive contextual-cueing effect in the first half of the experiment. The same procedure was adopted in all the other experiments, reported later (for comparable approaches, see also Albouy et al., 2006; Kunar & Wolfe, 2011; Olson, Chun, & Allison, 2001).

Apparatus and stimuli. Participants were seated in a dimly lit, soundproof experimental booth. The experiment was controlled by an IBM PC-compatible computer using Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). A standard mouse was used as response device. The viewing distance was approximately 57 cm. Stimuli subtended $0.7^\circ \times 0.7^\circ$ of visual angle and were presented in grey (8.5 cd/m^2) against a black (0.02 cd/m^2) background of a 17-inch CRT monitor. A search display always consisted of 12 items, two targets and 10 nontargets. One of the two targets was the letter T rotated 90° to the left or right, and the other T pointed up- or downward. The pointing direction of the target "stem" (left/right or, respectively, up/down) was chosen randomly. Distractors were L-shaped letters rotated randomly in one of the four orthogonal orientations. Search displays were generated by placing two Ts and 10 Ls randomly within the cells of an 8 × 6 matrix (cell size 2.5°). Within each cell, the positions of the stimuli were randomly jittered horizontally and vertically in steps of 0.1° within a range of ±0.6°. Figure 1A presents example search displays.

Trial sequence. Each trial started with the presentation of a central fixation cross for 500 ms. The fixation cross was followed by the search display, to which participants reacted with a speeded response via mouse keys. The task was to search for one target (e.g., that pointing left or right) in the first 15 blocks, and for the other target from Block 16 onwards (e.g., that pointing up- or downwards), and to indicate the orientation of the target stem (either left/right or up/down) as quickly and accurately as possible. The mouse was placed in front of the observers, and they used their left- or right-hand index finger to press one or the other mouse button. Displays remained on-screen until a response was recorded. In case of an erroneous response, feedback was provided by an alerting signal ("–") presented for 1000 ms at the centre of the screen. The intertrial interval was 1000 ms.

Design and procedure. A three-factorial within-participant design was used with context, part, and epoch as independent variables. Context had two levels, old and new. For the old-context condition, the arrangement of nontarget items was the same on every presentation. In the new-context condition, a new, random arrangement of nontarget items was generated on the respective trials. To rule out location probability effects, all targets appeared equally often at the 48 possible matrix locations throughout the experiment. The orientation of the target was determined randomly for each trial, whereas the orientations (and identities) of the nontarget items were preserved for the old-context condition. The second variable, part, separated the experiment into two halves, which corresponded to the two task-relevant targets introduced in the experiment. The third variable, epoch, simply divided the experimental trials into consecutive bins (three epochs within each part), to permit possible learning effects to be assessed over the course of the experiment.

Importantly, in Part 2 of the experiment, not only the task-relevant target changed but also one nontarget was relocated to a previously empty position in the display (see Figure 1A; note that there were no constraints on the change of location, with random selection of the changed nontarget location among the available set of empty display positions). Relocation of a nontarget item was introduced in the experiment to examine whether observers could compensate for location changes of a task-irrelevant item within an old-context display. After the nontarget relocation in Block 16, the changed item remained at its new position (in old-context displays) for the remainder of the experiment.

At the beginning of the experiment, participants completed one block of 24 randomly generated practice trials to become familiar with the task. All subsequent experimental blocks contained the same 12 old context displays and 12 new context displays, presented in randomized order. After Block 16, the task-relevant target was changed (see Figure 1A). For instance, for observers instructed to search for a T pointing to either the left or the right in the first 15 blocks, from Block 16 onwards, the relevant target was the other T pointing up- or downwards. Note, that the two target locations in a display were kept constant for a given item arrangement (i.e., Target 1 was always located in Position A, and Target 2 in Position B—for both old and new context conditions in order to rule out location probability effects). The response-relevant target orientation in the two halves of the experiment (left/ right and up/down) was counterbalanced across observers (to rule out systematic effects of the stimulus–response mappings), and a detailed instruction regarding the task change was provided at the beginning of the experiment. An additional instruction message was presented on the screen after Block 15, reminding the observer of the impending change of the target and the response rule. There were 30 blocks in the experiment, with 720 experimental trials in total.

Recognition test. After completing the search task, participants were asked to perform a final recognition test. They were informed that certain display configurations had been repeated throughout the experiment and their task was to decide whether or not a given display had been shown previously. A total of 24 displays were presented to the participants. Half of them were old context displays that were used in the experiment (corresponding to the display layout presented in the second half of the experiment, i.e., with the relocated nontarget), the other half were newly generated displays. The trial sequence was identical to the search task, except that no error feedback was given. Nonspeeded responses were recorded via left (new) and right (old) mouse keys.

Results

Search task. Mean error rates were calculated for each independent-variable combination, separately for each participant. The overall error rate was relatively low (4.6%). A repeated-measures analysis of variance (ANOVA) with the factors context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6) revealed a significant main effect of epoch, $F(2, 18) = 5.16$, $p < .02$, owing to a decrease in errors across successive epochs (6.0%, 4.1%, and 3.9% in the first, second, and third epoch, respectively). No other significant effects were obtained.

Next, individual mean RTs were computed for each variable combination, excluding error responses and RTs 2.5 standard deviations below and above the grand RT mean of each participant. This outlier criterion (which was also applied in all subsequent experiments) led to the removal of 1.9% of all trials from the data proper (comparable exclusion rates of 1.8%–3.3% were obtained in all subsequent experiments). Figure 2 presents the mean correct RTs, averaged across participants, as a function of epoch, separately for old and new contexts. The mean RTs were subjected to a three-way ANOVA with main terms of context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6). This analysis revealed significant main effects of context, $F(1,\ 9) = 45.98$, $p < .001$, and epoch, $F(2,\ 18) = 14.48$, $p < .001$. Old-context displays were responded to 112 ms faster than new layouts. Furthermore, responses became faster with increasing epoch (1412 ms, 1359 ms, and 1273 ms in the first, second, and third epoch, respectively). Importantly, the Context × Part interaction was not significant, $F(1,\ 9) = 0.12$, $p = .73$, that is, there was effectively no difference in contextual cueing between both parts of the experiment (123 ms and 102 ms, respectively; note that all contextual-cueing effects reported refer to the difference in mean RTs between new- and old-context conditions, collapsed over the factor epoch). Instead, contextual cueing exhibited a significant difference between old and new contexts across all six epochs (see Figure 2).

To examine in more detail how contextual cueing develops across the course of the experiment, an additional RT analysis was performed that compared old and new contexts across blocks (see Figure 3). A three-way RT ANOVA with the factors context (old vs. new), part (first vs. second half of

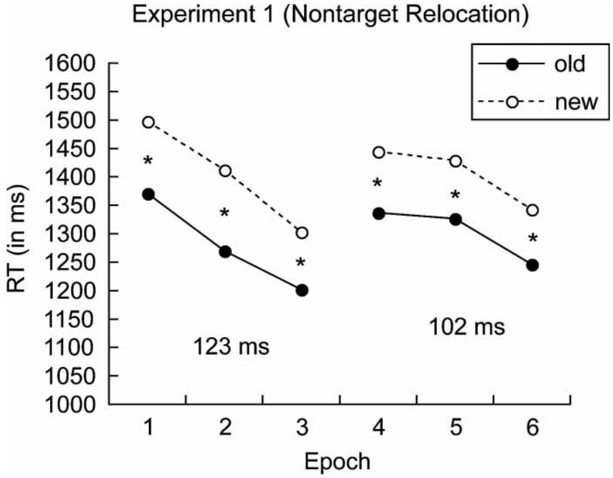

Figure 2. Mean reaction times (RTs) as a function of epoch in Experiment 1 (nontarget relocation). Filled and unfilled symbols represent old- and new-context conditions, respectively. Epochs 1 to 3 correspond to the initial learning phase, whereas the (task-relevant) target was switched for Epochs 4 to 6. The mean contextual-cueing effect is given (in ms) for each half of the experiment. Significant differences are indicated by an asterisk.

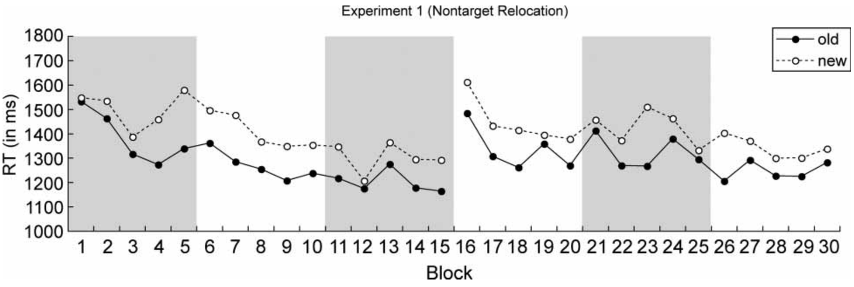

Figure 3. Mean reaction times (RTs) as a function of block in Experiment 1 (nontarget relocation). Filled and unfilled symbols correspond to old- and new-context conditions, respectively. Blocks 1 to 15 represent the initial learning phase; the (task-relevant) target was switched from Block 16 onwards. The grey and white background shading depicts consecutive blocks that were combined into epochs for separate analyses, yielding more robust measures than the mean RTs for a given block.

the experiment), and block (1/16 to 15/30) revealed significant main effects of context, $F(1, 9) = 49.84$, $p < .001$, and block, $F(14, 126) = 5.62$, $p < .001$. Importantly there was again no significant difference in contextual cueing between the two experimental parts (ps $> .7$), mirroring the results of the above epoch-based analysis. Subsequent pairwise comparisons revealed a quick onset of contextual cueing, which was evident already in the fourth block. A series of t-tests revealed [marginally] significant differences between old and new contexts in blocks: 4, 5, 6, 7, [8], 9, 11, 15, [16], 17, 18, 23, and 26. Note that the mean values per condition are based on only 12 observations per participant, which is the likely reason why not all comparisons were significant, despite a consistent numerical trend across all blocks. In general, this outcome is comparable to findings of fast contextual learning in previous studies (e.g., Conci et al., 2011, and in all subsequent experiments reported here).

Between-target distance analysis. An additional analysis was performed to examine whether the spatial distance between the two target locations influenced the degree of adaptation from the first to the second half of the experiment. First, the between-target distance was computed per participant for each old display (range: 2.5°–28°). Next, this measure of distance was correlated with contextual cueing in the second half of the experiment. This analysis revealed a moderate, but nevertheless significant negative correlation, $r = -.21$, $p < .03$, indicating that the contextual-cueing effect for the second target decreased with an increase in the distance between the two targets. Moreover, as illustrated in Figure 4, a median split of the intertarget distances (with target displacements smaller vs. larger than 14°) showed a significantly larger contextual-cueing effect for the small- (127 ms) relative to the large- (39 ms) target displacements, $t(56) = 1.93$, $p < .03$. This finding

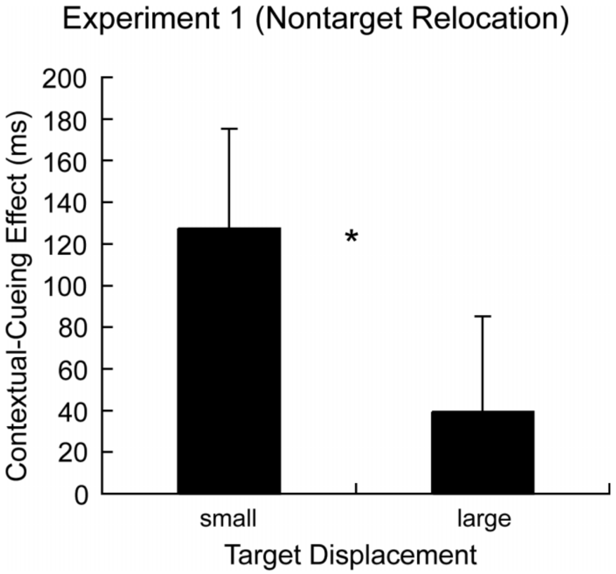

Figure 4. Effects of target displacement on contextual adaptation in Experiment 1. The mean contextual-cueing effect for the second half of the experiment (Epochs 4 to 6) is given for small versus large displacements between the two target locations ($p < .03$).

demonstrates that contextual adaptation occurs more reliably for the smaller separations between targets.

Recognition test. Overall mean accuracy in the recognition test was 51.6%. Participants correctly identified old patterns in 54.2% of all trials (hit rate), but this difference did not differ from the false alarm rate of 50.1%, $t(9) = 0.45$, $p = .67$. Thus, observers could not explicitly distinguish old contextual layouts from new displays above chance level.

Discussion

Experiment 1 replicated previous findings on contextual cueing in showing that repeated contextual information can have a beneficial influence on visual search: Observers were significantly faster in detecting the target within old-context displays than within novel contextual layouts (alongside a general decrease in RTs with epoch, probably reflecting unspecific learning processes within each half of the experiment; see Chun & Jiang, 1998). Moreover, the repeated displays were not explicitly recognized in a final recognition test, which supports the view that contextual cueing is based on an implicit memory that can guide spatial attention to the target location.

During the first three epochs of the experiment, observers were on average 123 ms faster in detecting the target within old, as compared to novel, displays. Importantly, subsequent to the switch of the relevant target in Part 2 of the experiment, observers still showed a cueing benefit of 102 ms for repeated layouts (which was statistically not reduced relative to the contextual-cueing effect in Part 1 of the experiment, i.e., the part by context interaction was nowhere near significance in both epoch- and block-analyses). An additional analysis showed that contextual cueing in Part 2 was larger when the target was located closer to the (initial) target position in Part 1. This outcome suggests that observers were able to "remap", or adapt, the context to the novel target, despite a location change of a potentially relevant contextual (nontarget) item. Although remapping was observable in general, it was found to be particularly effective for relatively close targets. In agreement with our previous study (Conci et al., 2011), this pattern of results suggests that contextual information can be adapted relatively efficiently (i.e., with negligible costs) to novel task requirements as long as the target change is predictable. Moreover, contextual remapping appears to be resistant against interference, as the location change of the nontarget did not affect the magnitude of contextual cueing. It thus appears that contextual learning can accommodate partially inconsistent subsets of a display layout—suggesting that not the entire (global) configuration, but only a (local) subset of the context is learned and used to guide attention (see also Brady & Chun, 2007, and Song & Jiang, 2005, who suggested that about three local target–nontarget associations are sufficient to establish a reliable contextual-cueing effect).

EXPERIMENT 2

Experiment 1 showed, as expected, preserved contextual remapping even when an unpredictable location change of a nontarget item occurred between successive parts of the experiment. Experiment 2 was performed to further investigate whether an unpredictable location change could also be compensated for under conditions in which the change is potentially relevant for the current task. To this end, in Experiment 2, we introduced a change of the task-relevant target location. In the first part, observers again searched for one of two possible target types within old and new arrangements of nontargets. Then, in the second part, the task-relevant target was changed, that is, the second target, defined by a different axis of orientation, became relevant; and additionally, this second target was relocated to a novel, previously empty position (see Figure 1B for example displays; this is in contrast to Experiment 1 in which a nontarget was relocated). Thus, after the change of the task-relevant target location, the context learned in the first half of the experiment should now, in the second half, be misleading (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009); accordingly, contextual cueing should be abolished.

Methods

Apparatus, stimuli, design, and procedure were identical to Experiment 1, except that the unpredictable location change in Part 2 of the experiment was now assigned to the second, task-relevant target (rather than to a nontarget item, as in Experiment 1). Thus, for example, if observers were required to search for the horizontally oriented T in the first half of the experiment, they would be asked to switch and report the orientation of the vertical T in Part 2 of the experiment. However, this second target would now be relocated to a novel, previously unoccupied display location (see Figure 1B for examples), where it would then be presented throughout the second half of the experiment. Ten volunteers (four male; mean age: 27.1 years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of 8 Euro per hour or for course credits. All other details were identical to Experiment 1.

Results

Search task. Erroneous responses were again relatively rare (4.2%, which is comparable to Experiment 1), and a repeated-measures ANOVA with the factors context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6) revealed no significant effects.

Individual mean RTs were computed excluding error responses and outliers. Figure 5 presents the mean correct RTs, averaged across participants, as a function of epoch, separately for old and new contexts. The mean RTs were again subjected to a three-way ANOVA with main terms of context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6). This analysis revealed significant main effects for context, $F(1, 9) = 13.11$, $p < .007$, and epoch, $F(2, 18) = 6.72$, $p < .008$, together with a marginally significant main effect for part, $F(1, 9) = 5.06$, $p = .051$. Responses to old-context displays were, on average, 73 ms faster than responses to new contexts, and search became faster (by 34 ms) from the first to the third epoch. In addition, RTs in the second part of the experiment were 141 ms slower than responses in the first part. Importantly, the Context × Part interaction was also significant, $F(1, 9) = 8.68$, $p < .02$, illustrating that contextual cueing was strong and reliable in the first half of the experiment (165 ms), but no longer evident in the second half (-20 ms). Thus, contextual cueing vanished (or turned into a cost) when observers were required to switch the target definition (identity) and respond to the (second) target that underwent an unpredictable location change in Epoch 4.

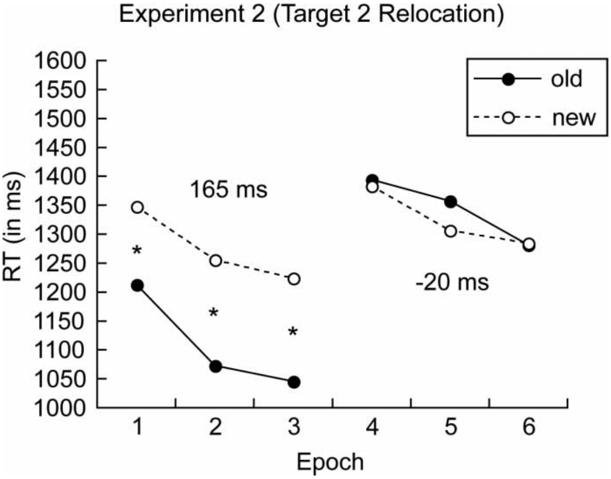

Figure 5. Mean reaction times (RTs) as a function of epoch in Experiment 2 (Target 2 relocation). Filled and unfilled symbols represent old- and new-context conditions, respectively. Epochs 1 to 3 correspond to the initial learning phase, whereas the (task-relevant) target was switched for Epochs 4 to 6. The mean contextual-cueing effect is given (in ms) for each half of the experiment. Significant differences are indicated by an asterisk.

Recognition test. Overall mean accuracy in the recognition test was 48.5%. Participants correctly identified old patterns in 46.8% of all trials (hit rate), but this difference did not differ from the false alarm rate of 46.7%, $t(9) = 0.22$, $p = .98$. This outcome indicates that observers were unable to discern old contextual layouts from new ones.

Discussion

Experiment 2 again revealed a reliable contextual-cueing effect in the first half for Epochs 1 to 3, replicating Experiment 1 and previous studies. Search was 165 ms faster for old as compared to novel contextual layouts, which compares with 123 ms in Experiment 1, suggesting that contextual cueing was initially (at least) equally effective in both experiments. However, although the initial learning phase was comparable in both experiments, the pattern of results markedly diverged after the change of the task-relevant target in the second part. In Experiment 1, contextual cueing could be clearly adapted to the novel target location, yielding a reliable RT benefit of 102 ms after the target switch. By contrast, in Experiment 2, no contextual facilitation was evident anymore; if anything, repeated contexts led to a cost of -20 ms after the switch of the target. Thus, contextual cueing was completely abolished when the task-relevant target was relocated to a novel, unpredictable location; in fact, the cost would indicate that the originally learned context now led to a certain misguidance of search. In essence, this pattern of results is in line with other reports that investigated the effects of target relocation in single-target displays (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009; Zellin et al., 2011). Taken together, these results suggest that a learned association between a target and its context cannot be easily reconfigured to represent a novel target location, and this change is not updated even after 15 repetitions. Therefore, as shown previously, adaptation of contextual cueing to unpredictable changes appears to be rather limited and inefficient.

EXPERIMENT 3

The results thus far indicate that adaptation (or "contextual remapping") to a predictable change of the response-relevant target can occur even if a contextual nontarget item is relocated (Experiment 1), but not if the relocation is confined to a response-relevant aspect of the display (i.e., the relevant target, as in Experiment 2). In Experiment 3, we further investigated whether contextual remapping can occur for an item that was *previously* response-relevant. To this end, we now relocated the target, which was (previously) relevant in Part 1 of the experiment (i.e., before the target switch): For the initial three epochs, observers were required to search for one type of target (e.g., the T pointing to the left or the right) within old and new arrangements of nontargets. Subsequently, in Part 2 of the experiment, the task-relevant target changed (e.g., observers now responded to the T pointing up- or downwards), but together with this task switch, the previously relevant target (i.e., the T pointing left- or rightwards) was relocated to a previously empty position (see Figure 1C for example displays). The predictions were as follows: Contextual remapping should occur reliably if the previously relevant target is irrelevant for contextual learning in Part 2 of the experiment (just as the relocated nontarget in Experiment 1). By contrast, if contextual learning depends on all task-relevant aspects of the entire experiment, then contextual adaptation should be prevented (just as for the relevant target location change in Experiment 2).

Methods

Apparatus, stimuli, design, and procedure were identical to Experiment 1, except that the unpredictable location change in Part 2 of the experiment was assigned to the first, now task-irrelevant target (rather than a nontarget item, as in Experiment 1, or the relevant target, as in Experiment 2). Thus, for example, if observers were required to search for the vertical T in Part 2 of the experiment, the horizontal T (which was previously relevant) would be relocated to a novel, previously unoccupied display location from Epoch 4 onwards (see Figure 1C for examples). Ten volunteers (three male; mean age: 24.0 years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of 8 Euro per hour, or for course credit. All other details were identical to Experiment 1.

Results

Search task. In Experiment 3, response errors were rare (1.9%), and a repeated-measures ANOVA with the factors context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6) revealed again no significant effects.

Next, individual mean RTs were aggregated excluding error trials and outliers. Figure 6 presents the mean correct RTs, averaged across observers, as a function of epoch, separately for old and new contexts. In addition, the mean RTs were entered into a three-way ANOVA with main terms of context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6). This analysis yielded significant main effects for context, $F(1, 9) = 9.03$, $p < .02$, and for epoch, $F(2, 18) = 13.93$, $p < .001$, illustrating that RTs were influenced by a 64 ms contextual-cueing effect, together with a decrease of the response latencies (by 189 ms) from the first to the third epoch. Importantly, the Part × Context interaction was also significant,

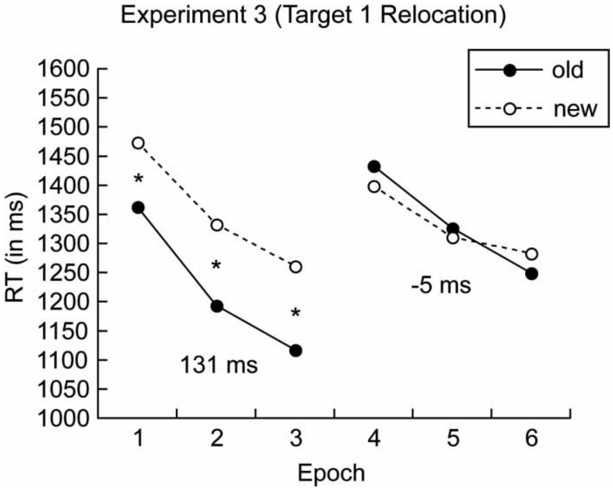

Figure 6. Mean reaction times (RTs) as a function of epoch in Experiment 3 (Target 1 relocation). Filled and unfilled symbols represent old- and new-context conditions, respectively. Epochs 1 to 3 correspond to the initial learning phase, whereas the (task-relevant) target was switched for Epochs 4 to 6. The mean contextual-cueing effect is given (in ms) for each half of the experiment. Significant differences are indicated by an asterisk.

$F(1, 9) = 25.69$, $p < .002$. As can be seen in Figure 6, contextual cueing was reliably obtained in Part 1 of the experiment (131 ms), but no difference between old and new contextual layouts was evident in Part 2 (−5 ms). This pattern shows that relocation of a (currently) nonrelevant (but previously relevant) target item has a considerable negative impact on observers' ability to adapt a contextual layout to a changed environment.

Recognition test. Overall mean accuracy in the recognition test was 59.5%. Participants correctly identified old patterns in 60.8% of all trials (hit rate), but this difference did not differ from the false alarm rate of 41.7%, $t(9) = 1.85$, $p = .1$, suggesting that observers showed no (or only little) awareness for repeated layouts in old displays.

Discussion

The first half of Experiment 3 (Epochs 1–3) rendered a reliable contextual-cueing effect of 131 ms, which is roughly comparable to the results obtained in Experiments 1 (123 ms) and 2 (165 ms). Thus, all three experiments showed reliable contextual learning initially, during the first three epochs. By contrast, when the task-irrelevant target was relocated in the second half of Experiment 3 (Epochs 4 to 6), contextual cueing was no longer evident (−5 ms), suggesting that the location change of a single, currently irrelevant (but previously relevant) item interfered with the adaptation of a learned context. This compares to Part 2 in Experiment 2, where the relocation of the task-relevant target distorted contextual cueing and lead to comparable costs of −20 ms. However, adaptation of a learned context was reliably observed when an item that was *never* relevant for a given task was relocated (e.g., a nontarget item such as in Experiment 1). Overall, this pattern of results may be taken to suggest that the two targets both depend on common associations with the learned contextual representation, and unpredictable changes interfere with contextual adaptation whenever the change affects a (currently or previously) task-relevant display item.

Another possible explanation for the lack of contextual cueing in the second half of Experiment 3 might be that the task-irrelevant target captured attention and interfered with contextual cueing. For instance, task-irrelevant singletons have been shown not only to influence search per se, but also to reduce contextual cueing (Conci & von Mühlenen, 2009). Note that a task-irrelevant singleton was also present in Part 1 of Experiment 3 (namely, the second target), but caused no interference with contextual cueing. Nevertheless, one possibility could be that a salient item (which was previously task-relevant) interferes with the ability to adapt to the novel task requirements. This might be interpreted as a form of task-contingent capture (e.g., Folk, Remington & Johnston, 1992)—which could have prevented efficient top-down control, making it hard to ignore a task-irrelevant singleton (von Mühlenen & Conci, 2009). On this view, contextual cueing would not be reduced after the target change in Epoch 4 because of a critical change within the learned contextual layout (as suggested earlier), but because attention is captured by the singleton (i.e., the target that was previously task-relevant), and this form of task-contingent capture could compromise the potential for contextual adaptation. Experiment 4 was performed to decide between these alternative explanations.

EXPERIMENT 4

In Experiment 3, the relocation of a response-irrelevant singleton interfered with the ability to adapt the context to novel task demands. Experiment 4 was designed to permit a decision whether this contextual interference occurred because of attentional capture by the task-irrelevant singleton (see also Conci & von Mühlenen, 2009), or because the relocation altered a critical part of a previously learned context. To decide between these alternatives, in Part 1 of Experiment 4, observers again were required to search for one type of target (e.g., the left-/rightward-pointing T) within old and new nontarget layouts. Then, in Part 2 of the experiment, the task-relevant target changed (e.g., observers now responded to the up-/downward-pointing T), but together with this change of task, the target that was previously relevant (i.e., the left-/rightward-pointing T) was replaced by a nontarget L shape (see Figure 1D for example displays). Thus, if attentional capture by the irrelevant singleton interfered with contextual adaptation, then the removal of the (interference-causing) singleton should enable contextual remapping. By contrast, no contextual adaptation should occur if a change-critical item within the learned context interferes with contextual cueing.

Methods

Apparatus, stimuli, design, and procedure were identical to Experiment 3, except that in Part 2 of the experiment, the first, hitherto task-irrelevant target was replaced by a nontarget. Thus, for example, if observers were required to search for the vertical T in Part 2 of the experiment, the horizontal T (which was previously relevant) would be replaced by an L shape from Epoch 4 onwards (see Figure 1D for examples). Ten volunteers (four male; mean age: 25.8 years) with normal or corrected-to-normal visual acuity participated in the experiment for payment of 8 Euro per hour or course credit. All other details were identical to Experiment 1.

Results

Search task. Erroneous responses were again rare (1.1%), and a repeated-measures ANOVA with the factors context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6) revealed no significant effects.

In a subsequent step, individual mean RTs were computed excluding errors and outliers. Figure 7 presents the mean correct RTs, averaged across observers, as a function of epoch, separately for old and new contexts. The mean RTs were subjected to a three-way ANOVA with main terms of context (old vs. new), part (first vs. second half of the experiment), and epoch (1/4 vs. 2/5 vs. 3/6). This analysis revealed significant main effects of context, $F(1, 9) = 32.97$, $p < .001$, part, $F(1, 9) = 8.39$, $p < .02$, and epoch, $F(2, 18) = 22.95$, $p < .001$. Responses to old-contexts were (by 75 ms) faster than responses to new-contexts, and RTs in the first half of the experiment were 83 ms faster than responses in the second half. Moreover, RTs decreased by 130 ms from the first to the third epoch. Importantly, the Context × Part interaction was also significant, $F(1, 9) = 7.81$, $p < .03$. Although there was a robust contextual-cueing effect of 166 ms in Part 1 of the experiment, only a contextual cost, of −17 ms, was observed in the second half (see Figure 7). Finally, the Context × Epoch interaction was significant, $F(2, 18) = 3.61$, $p < .05$, reflecting a greater decrease of RTs from

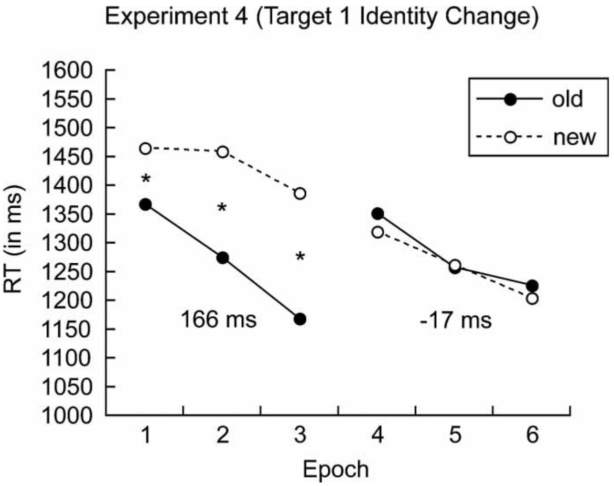

Figure 7. Mean reaction times (RTs) as a function of epoch in Experiment 4 (Target 1 identity change). Filled and unfilled symbols represent old- and new-context conditions, respectively. Epochs 1 to 3 correspond to the initial learning phase, whereas the (task-relevant) target was switched for Epochs 4 to 6. The mean contextual-cueing effect is given (in ms) for each half of the experiment. Significant differences are indicated by an asterisk.

the first to the third epoch for old contexts (163 ms) than for new contexts (98 ms). Thus, the results of Experiment 4 mirror the outcome from Experiment 3 in showing that a minor change to a contextually relevant item can interfere with the ability to adapt a context to novel task requirements.

Recognition test. Overall mean accuracy in the recognition test was 50.0%. Participants correctly identified old patterns in 45.8% of all trials (hit rate), which showed no difference to the false alarm rate of 45.8%, suggesting that observers were not aware of the repeated item arrangements in old displays.

Discussion

Experiment 4 rendered a pattern of results closely resembling the outcome of Experiment 3, namely, a robust and reliable contextual-cueing effect in the first half followed by contextual costs for the repeated displays in the second half (166 ms [131 ms] and −17 ms [−5 ms] contextual-cueing effects in Parts 1 and 2, respectively for Experiment 4 [3]). This suggests that the adaptation of a previously learned context fails if parts of the associated contextual items undergo a sudden change: In Experiment 3, the relocation of the target interfered with contextual cueing; but similarly, in Experiment 4, a change of the identity of a contextually relevant item led to contextual costs. Thus, this outcome suggests that an account based on attentional capture by the task-irrelevant singleton cannot explain the current results (as contextual cueing vanished in Part 2 of Experiment 4 even though no irrelevant singleton was present anymore). Instead, Experiment 4 lends support to the view that the two targets are both associated and linked to a single, learned context, and a (minor) change to parts of this contextual association will disrupt the ability to adapt a changing context during search.

GENERAL DISCUSSION

The present study, of four experiments, was designed to uncover the adaptive properties of contextual learning for multiple, predictable target locations. In all four experiments, observers were required to respond to one of two distinct targets (embedded within invariant or, respectively, random non-target layouts), with each target being task-relevant either during the first or second half of the experiment. Importantly, after the change of the task-relevant target, in the second half of the experiment, one search item also changed unpredictably either in location or identity. This unpredictable change was introduced to investigate the robustness of contextual remapping, that is, of adapting a given, learned context to a novel target.

Overall, our results suggest that the potential for remapping a given context depends largely on the type of item that undergoes an unpredictable change. Experiment 1 replicated our previous study (Conci et al., 2011) in demonstrating reliable contextual remapping when a (task-irrelevant) nontarget item was relocated (contextual-cueing effects were 123 [102] ms in the first [second] half of the experiment). Moreover, remapping was revealed to be more effective when the distance between two targets was small (i.e., $< 14°$ of visual angle), with some consistent reduction in contextual adaptation as the intertarget distance increased. This result confirms that a learned context can be transferred from one target to a second (predictable) target. In Experiment 2, the relocated item was the task-relevant (second) target. Consequently, there was no adaptive remapping of the learned context; rather, the repeated context caused costs (165 [−20] ms). Next, in Experiment 3, the task-irrelevant (first) target was relocated in the second half of the experiment. Although the changed item was not directly response-relevant (in the second half), the results showed again no contextual cueing in the second half, and consequently no evidence of contextual remapping (131 [−5] ms). Finally, in Experiment 4, the task-irrelevant (first) target changed its identity (i.e., the target was replaced by a nontarget, while remaining at its original location). Nevertheless, contextual remapping was not evident (166 [−17] ms) in this situation either, indicating that both the first and the second target are important “anchors” that need to be invariant for reliable adaptation to occur.

In summary, this pattern of results shows that a random variation of a nontarget does not compromise the ability to adapt a context to a novel target (as in Experiment 1). That is, contextual remapping is relatively stable, in particular, when the two targets share a common surround. Remapping can occur even if unexpected changes happen to task-irrelevant items. In contrast, a random target change nevertheless interferes with contextual remapping (Experiments 2 to 4). Such an alteration not only leads to contextual costs whenever it is the changed target itself that is currently task-relevant, but also when the changed target has been relevant previously and is currently no longer required for performing the task. This pattern may be taken to indicate that the two targets are linked and interrelated within a single contextual representation, thus causing mutual interference whenever one of the targets changes. A schematic illustration of possible learned associations is depicted in Figure 8. In this view, separate targets would come to be associated within a single network of learned associative links, and contextual remapping would critically depend on the common association of the two targets within one learned context. In addition, the small numerical reduction of contextual cueing after the change of the relevant target (e.g., from 123 ms to 102 ms in Experiment 1; see Figure 3) may reflect costs associated with changing the target location within the learned context, as a result of interference from the previously relevant target position. Despite these minor costs of switching the task-relevant targets, contextual

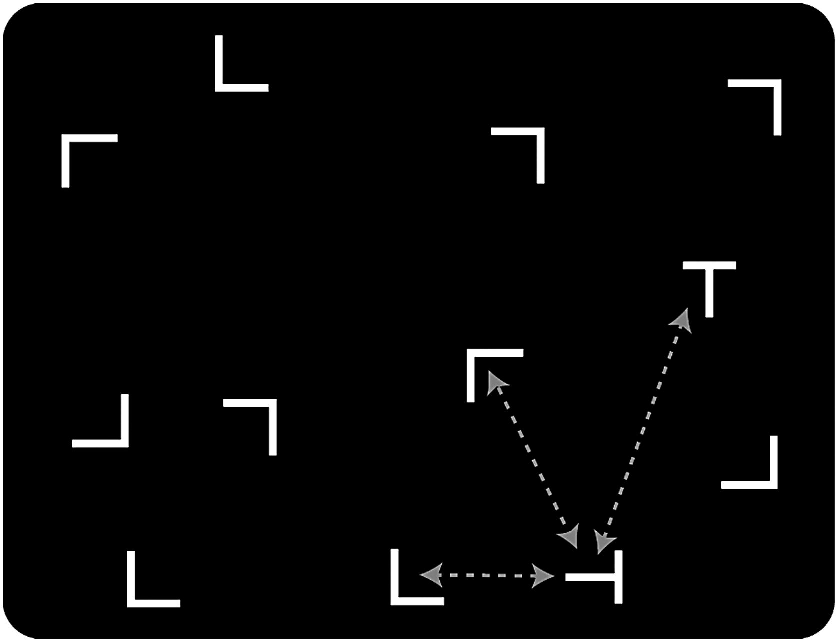

Figure 8. Example of a search display with schematic illustrations of possible learned contextual associations (as indicated by the grey arrows between search items). To enable contextual remapping, both targets are encoded and linked within a single representation of the local context.

adaptation nevertheless remains effective as long as the contextual associations remain intact. However, whenever a part of the learned contextual representation (or the association of the targets with their surrounding local context) changes, contextual remapping fails. Conversely, if the change occurs outside of the learned association, then contextual cueing (i.e., the adaptivity of the underlying contextual associations to a second target) remains effective.

In general agreement with previous studies that investigated the role of random spatial variations on contextual learning (Brady & Chun, 2007; Olson & Chun, 2002; Song & Jiang, 2005), Experiment 1 revealed that unpredictable location changes to a nontarget (within a repeated search layout) have no influence on the size of the contextual-cueing effect. For instance, Song and Jiang (2005) demonstrated that contextual cueing was efficient in guiding attention as long as a given display matched a (well-learned) representation in a subset of only three to four items. Similarly, Brady and Chun (2007) suggested a computational model according to which a given target location is primarily associated with the local context of some three nontarget items (and with all other, more distant nontarget items exhibiting little influence on contextual cueing). In line with these studies, our findings show that once a display has been learned, an irrelevant item may well change in an unpredictable fashion and yet leave contextual remapping unaffected. However, task-relevant items clearly interfere with contextual adaptation. For instance, when one of the two target items changes unpredictably in location, the learned association is critically weakened and contextual cueing fails. This indicates that any relevant item will be incorporated in the learned, contextual representation (made up of a relatively small subset of items).

In more general terms, Ono, Jiang, and Kawahara (2005) suggested that the strength of contextual cueing depends on two factors, referred to as noise and consistency: Whereas an increase in the amount of random variability in a given display (i.e., the amount of noise) reduces contextual cueing, the strength with which an association is learned (i.e., the consistency of a learned association) facilitates performance. Within this framework, our experiments demonstrate that the ability to remap a target depends primarily on reliable (or, consistent) target–context associations (for both targets). By contrast, contextual cueing was not influenced by the statistical noise embedded within task-irrelevant portions of a display (consistent with a learned context being relatively resistant against noise; see Song & Jiang, 2005). This pattern of results suggests that contextual remapping is principally driven by consistency, whereas noise may primarily exert an influence earlier during learning of contextual invariances (see also Jungé, Scholl, & Chun, 2007).

In spite of no influence of irrelevant nontargets on the adaptation of a learned context, converging evidence from a number of studies suggests that *unpredictable* target changes cannot be compensated for in contextual cueing (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). Rather, contextual learning is relatively limited and confined to only one spatial location (and its immediate surround; Zellin et al., 2011). Thus, contextual learning appears to facilitate primarily the region where the target is located. Conversely, nontarget locations are inhibited relative to empty positions, suggesting that both attended and ignored locations are modulated by learning (Ogawa, Takeda, & Kumada, 2007). Despite these limitations, our results show that *predictable* changes may well be compensated for in contextual cueing (Conci et al., 2011), suggesting that under specific circumstances, a given context might facilitate two distinct target locations. Importantly, though, this potential for remapping a context between distinct target locations appears confined to a single contextual association of both the current and future targets within one representation (see Figure 8, for an illustration). Moreover, contextual remapping is particularly effective when the two target locations share a common surround, further suggesting that both positions are embedded within a single contextual representation.

In summary, the present study shows that predicting the location of a target on the basis of implicit contextual memory depends largely on the stability of task-relevant aspects in a given scene (see also Enns & Lleras, 2008). Our results show that adaptation of a learned association to a changing task is, in general, relatively robust and resistant to random interference, but fragile whenever any aspects relevant to the task change.

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