Psychological Research (2011) 75:279–289
DOI 10.1007/s00426-010-0306-3

ORIGINAL ARTICLE

Contextual remapping in visual search after predictable target-location changes

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Received: 31 March 2010 / Accepted: 12 August 2010 / Published online: 20 August 2010

Abstract Invariant spatial context can facilitate visual search. For instance, detection of a target is faster if it is presented within a repeatedly encountered, as compared to a novel, layout of nontargets, demonstrating a role of contextual learning for attentional guidance ('contextual cueing'). Here, we investigated how context-based learning adapts to target location (and identity) changes. Three experiments were performed in which, in an initial learning phase, observers learned to associate a given context with a given target location. A subsequent test phase then introduced identity and/or location changes to the target. The results showed that contextual cueing could not compensate for target changes that were not 'predictable' (i.e. learnable). However, for predictable changes, contextual cueing remained effective even immediately after the change. These findings demonstrate that contextual cueing is adaptive to predictable target location changes. Under these conditions, learned contextual associations can be effectively 'remapped' to accommodate new task requirements.

Introduction

Everyday scenes typically consist of multiple, complex objects and events that the visual system needs to deal with. Often, this large amount of available information is not helpful in realizing the current behavioral goals. Therefore, mechanisms of visual attention select potentially relevant objects, while suppressing other irrelevant items. However, these 'other items' (in other words, the context in a given scene) may nevertheless be useful in guiding behavior. For example, it has been shown that a loaf of bread is identified more accurately within the context of a kitchen compared to that of a front yard surround (Palmer, 1975). This suggests that contextual information can support object selection and identification in complex environments.

More recently, Chun and Jiang (1998; see also Chun, 2000, for review) developed a paradigm that permits examining how invariant contextual information may influence visual search processes. In their prototypical contextual-cueing experiments, search arrays consisted of 1 target T and 11 nontarget Ls (see Fig. 1a for example displays). Importantly, search arrays differed in that targets could appear within either an 'old' or a 'new' configuration of items: for old configurations, the target was always embedded within the same contextual arrangement of nontarget items, and this arrangement was repeatedly presented over the course of the experiment. This was compared to a baseline (new) condition in which targets were always presented within novel nontarget arrangements that were created randomly on each trial. Thus, the performance difference between old and new configurations indicates whether there is an influence of invariant spatial (target–nontarget) layout. The results, in fact, showed that repetition of spatial layout (old displays) gave rise to a benefit in the mean reaction time (RT) compared to new spatial arrangements (the 'contextual-cueing' effect). Since observers were not able to explicitly discern repeated displays from novel arrangements in a subsequent recognition test, this finding was taken as evidence for mechanisms that implicitly encode the spatial associations between display items. Contextual cueing was interpreted as being the result of spatial associations formed between the target location and the locations of nontargets. Based on these learned

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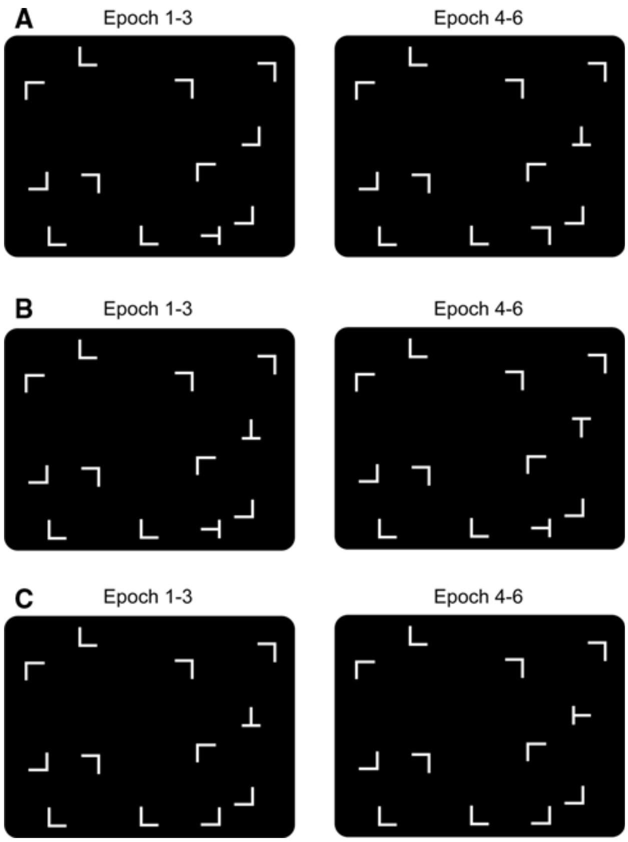


Fig. 1 Examples of the search displays: In Experiment 1 **a**, observers searched for a target (*T*) among 11 nontargets (*Ls*), and the location and response-relevant identity of the target was changed from *epoch 4* (block 16) onwards. In Experiment 2 **b**, there were always two 'targets' (among 10 nontarget Ls), but only one target was response-relevant in one half of the experiment, while the other was relevant in the other half. In Experiment 3 **c** there was again only one target that changed its response-relevant identity (but not its location) after *epoch 4* in the second half of the experiment

associations, search performance was facilitated with repeated presentation.

Real-world scenes typically consist of a relatively fixed and stable collection of objects that co-occur with a certain degree of statistical covariation (Oliva & Torralba, 2007, for review). Given this, guidance by contextual memory may provide an adaptive advantage in supporting orienting in natural scenes. For example, in a real-world environment such as a supermarket, a given target object (e.g., milk) is typically located at a consistent place in relation to the surrounding nontarget items (e.g., butter, cheese), providing a relatively stable set of contextual-associative links that have the potential to guide search to the target item. In fact, contextual cueing has also been shown to operate in real-world scenes, supporting search via the repeated association of a given target with its surround (e.g., Brockmole & Henderson, 2006a). Thus, (relatively) invariant context may support the efficient orienting of attention in natural environments.

However, an ecologically valid mechanism that detects and exploits consistent target-to-context relations should also be adaptive, that is, contextual cueing should be modifiable in line with environmental changes. For instance, in the above example of a supermarket, contextual information should not be fixed but provide a flexible source of associative cues that adapt to new goals; for example, when the target object changes location (e.g., when the milk is suddenly placed at some other location) or when the target itself changes (e.g., when searching for a new target, say, a loaf of bread, after having found the milk, i.e., the recent target). In the laboratory, such adaptive changes in contextual cueing have thus far not been found consistently. For instance, when the context of nontarget configurations was kept constant, but the target location changed from trial to trial, no benefit in search RTs was obtained for old relative to new configurations (Chun & Jiang, 1998; Wolfe, Klempen, & Dahlen, 2000). Similarly, Chua and Chun (2003) trained observers on a set of invariant (three-dimensional) search displays which were subsequently also presented in the test phase, this time, however, with a rotational change (i.e., viewpoints were systematically varied between training and testing). Contextual cueing was found to decrease with increasing angular rotation between training and test displays, suggesting that (rotational) changes are not compensated for adaptively. Likewise, contextual cueing was not found to be adaptive following sudden changes in target location, after an initial training phase (Manginelli & Pollmann, 2009). Rather, such changes led to costs, presumably due to a tendency to orient towards the old, originally learned target location. While this bias disappeared after several repetitions, learning of the new target location (within the same configuration of nontarget items) was not effective (across ten blocks of trials), suggesting that contextual cueing is relatively fixed towards a given target location. A more detailed analysis of how contextual cueing adapts to relocated targets at various distances from the initial, previously learned target location has recently been provided by Makovski & Jiang, (2010). They found that contextual cueing decreased as the target appeared further away from its 'expected' location, eventually turning the typical facilitation effect into a contextual cost. Thus, in summary, these studies suggest that contextual learning is not adaptive to sudden changes in the environment, but persists at least to a certain degree.

Despite findings suggesting that contextual cueing is rather inflexible, other results provide some evidence for flexible adaptation in context-based learning. For instance, while contextual cueing depends on the association of a given target with a given spatial configuration of nontargets, more than one (specifically: two) potential target locations may be learned for a given old display (Chun & Jiang, 1998). In addition, sudden changes of the target and nontarget identities leave contextual cueing unaffected (Chun &

Jiang, 1998). Moreover, Jiang and Wagner (2004) reported evidence for adaptation to global changes: contextual cueing was found to occur even after the entire display had been rescaled or resized. Similarly, contextual cueing in natural scenes has been shown to overcome large-scale (i.e., global) changes in scenes (such as mirror reversals) at relatively small, transient costs (Brockmole & Henderson, 2006b). Thus, while changes in the target-to-context relation appear to disrupt contextual cueing, other (global) changes can be dynamically adapted to and compensated for.

The present study was designed to further investigate whether contextual cueing can—under certain conditions—be adaptive to changes of target location (and identity). Specifically, we examined whether the 'predictability' of a changed target would have an influence on the benefit deriving from contextual cueing for attentional guidance. To this end, we performed a series of three experiments that always contained two parts: initially during learning, observers learned to associate a given context with a given target location for a set of invariant displays (interspersed with random displays). In the second part of the experiment, observers were then presented with a change of the target location, coupled with an identity change—the key question being whether there would still be some advantage for previously learned contexts under conditions in which the changed target location was 'predictable', that is, learnable during the initial phase (Experiment 2), as compared to nonpredictable target changes (Experiment 1). (Experiment 3 was a control experiment designed to examine whether a predictable target identity change not accompanied by a location change would diminish contextual cueing).

In order to permit comparison of performance across all three experiments, target location changes were always linked with a change in target identity. For instance, in Experiment 1, observers learned to associate a given target (e.g., a T pointing to the left or the right) with a given context. Then, in the second half of the experiment, the target changed its location (i.e., swapping it with that of a nontarget) as well as its identity (i.e., it would now be an upward- or downward-pointing T). Essentially, the reason for this linked location and identity change was to make the experiment comparable to Experiment 2, in which both targets were presented simultaneously in all displays, thus making the change in response (from one to a target of type A to one to a target of type B) predictable. Finally, in Experiment 3, instead of there being a location change, there was only a change of the target type (see Fig. 1 for example displays).

Experiment 1

Experiment 1 examined whether contextual cueing can survive (unpredictable) changes of the target-to-context relations. In the first half of the experiment, observers searched for a target T amongst old and new arrangements of nontarget Ls. In the second half, from block 16 onwards, the target's identity (i.e., its horizontal or vertical orientation) was changed—such that a T pointing to the left or the right was replaced by a T pointing upwards or downwards, or vice versa—and its location was swapped with that of a nontarget item (see Fig. 1a). According to Manginelli and Pollmann (2009) and Makovski and Jiang (2010), sudden and unpredictable changes of the target location would be expected to disrupt contextual cueing (as long as the location change is not within the direct surround of the previous target); this disruption can occur with a target location change to a previously empty location or to a location previously occupied by a nontarget. Consequently, we expected that in the second half of the experiment, the location change would cancel the RT benefit for old displays, thus replicating Manginelli and Pollmann's finding, while the identity change should not have an influence on contextual cueing (see Chun & Jiang, 1998, and Experiment 3 below).

Methods

Participants

Ten students (mean age 24.8 years) volunteered for course credit or payment of 8 Euro per hour. All participants reported normal or corrected-to-normal vision. Only participants who exhibited a positive (above zero) contextual-cueing effect in the first half of the experiment were included in the further analyses. This pre-condition was set because we wanted to investigate how location and identity changes 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 other experiments reported below. Approximately, three observers had to be replaced based on this criterion per experiment, to ensure an equal number of ten observers for each experiment.

Apparatus and stimuli

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 the response device. The viewing distance was approximately 57 cm. Stimuli subtended $0.7° \times 0.7°$ of visual angle and were presented in gray

($8.5\ cd/m^2$) against a black ($0.02\ cd/m^2$) background of a 17-in. CRT monitor. A search display always consisted of 12 items, 1 target, and 11 nontargets. The target was either the letter T rotated 90° to the left or right, or a T that pointed upwards or downwards. 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 1 T and 11 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 $\pm 0.6°$. Figure 1a presents examples of the 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 responded with a speeded response via mouse keys. The task was to search for an oriented T among Ls 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 each observer, and the left-hand and right-hand index fingers were used 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 1,000 ms at the center of the screen. The inter-trial interval was 1,000 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, while 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 distinct target location and identity conditions introduced in the experiment. Finally, the third variable, epoch, simply divided the experiment into consecutive bins (three epochs within each part), permitting possible learning effects to be assessed over the course of the experiment.

At the beginning of the experiment, participants completed 1 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. Importantly, after block 16, the target identity and location was changed (see Fig. 1a). For instance, for observers instructed to search for a T pointing either left or right in the first 15 blocks, from block 16 onwards, the target was a T pointing upwards or downwards; and the target's location was swapped with that of a (previous) nontarget location. Thus, after the location change, the previous target location was occupied by a nontarget, while a nontarget location now contained the target. Note that the two target locations in a display—that is, that before and that after the change in the middle of the experiment—were kept constant for a given item arrangement (i.e., the target was always located in position A in blocks 1–15, and in position B in blocks 16–30; 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 target and 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 a given display had been shown previously or not. A total of 24 displays was presented to the participants. Half of them were old context displays that were used in the experiment (with the target identity and location corresponding to the display layout presented in the second half of the experiment), the other half were newly generated displays. The trial sequence was identical to the search task, except that no error feedback was given. Non-speeded 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 very low (1.9%). A repeated-measures analysis of variance (ANOVA) with the factors context (old vs. new), part (first half vs. second half of the experiment) and epoch (1–3 vs. 4–6) revealed a significant main effect of epoch, $F(5.45) = 8.57$, $P < 0.03$, due to a decrease in errors with increasing epoch (2.9, 1.4 and 1.5% in the first, second and third epochs, respectively). Moreover, the context × part × epoch interaction was significant, $F(2.18) = 3.92$, $P < 0.04$, owing to a significant increase in errors immediately after the task switch in epoch 4 for the old-context condition relative to new layouts (4.7 vs. 2.6%, $P < 0.05$); there were no other significant differences between old and new contexts in other epochs (mean errors 1.6%; all $P > 0.11$).

Next, individual mean RTs were computed for each variable combination, excluding erroneous responses and RTs 2.5 standard deviations below and above the mean. This outlier criterion (which was also applied in all subsequent experiments) led to the removal of 3.75% of all trials from the data proper (comparable exclusion rates 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 half vs. second half of the experiment) and epoch (1–3 vs. 4–6). This analysis revealed significant main effects of context, $F(1.9) = 14.31$, $P < 0.005$, and epoch, $F(2.18) = 12.23$, $P < 0.001$, as well as a significant interaction between context and part, $F(1.9) = 9.63$, $P < 0.02$. Old-context displays were responded to 85 ms faster than new layouts. Furthermore, responses became faster with increasing epoch (127 ms speed-up between epoch 1/4 and epoch 3/6). Finally, the significant context × part interaction was due to contextual cueing showing a reliable difference between the two experimental halves: 184 ms in the first half, as compared to a non-significant effect of −13 ms in the second half.

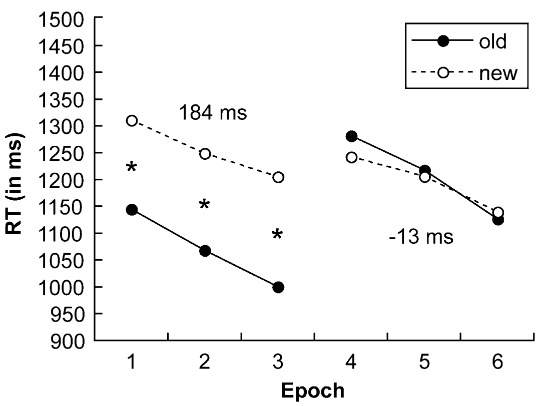


Fig. 2 Mean reaction times (*RTs*) as a function of epoch in Experiment 1. *Filled* and *unfilled symbols* represent old-context and new-context conditions, respectively. *Epochs 1–3* correspond to the initial learning phase, whereas a change of the target location was introduced in *epochs 4–6*. The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

In addition, to explore in detail the onset and development of contextual cueing, the mean RTs were analyzed separately for each block (note that these mean values are based on only 12 observations per participant). As can be seen from Fig. 3, the contextual-cueing effect emerged relatively early, becoming evident already in the second and fourth blocks (all P's <0.03, except for a marginal difference in block 6, $P = 0.054$, and no significant differences in blocks 3 and 7). By contrast, after the change of the target, the difference between old and new arrangements was no longer reliable (except for a significant difference in block 18, $P < 0.05$). This indicates that the target switch greatly deteriorated contextual cueing (i.e., the re-learning of the changed target-to-context relations).

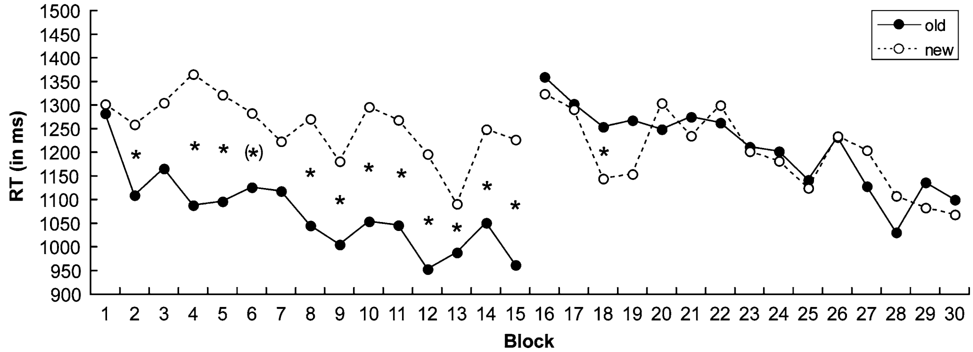
Recognition test

Overall mean accuracy in the recognition test was 46.3%. Participants correctly identified old patterns on 54.3% of all trials (hit rate), but this difference did not differ from the false alarm rate of 61.7%, $t(9) = 1.48$, $P = 0.17$. Thus, observers were not able to explicitly discern the old contextual layouts above chance level.

Discussion

The results of Experiment 1 replicate previous findings on contextual cueing in visual search. Within the first three epochs, participants were significantly faster in detecting a target within an old context than within a novel arrangement,

Fig. 3 Mean reaction times (*RTs*) as a function of block in Experiment 1. *Filled* and *unfilled symbols* represent old-context and new-context conditions, respectively. *Blocks* 1–15 correspond to the initial learning phase, whereas a change of the target location was introduced from block 16 onwards. Significant differences are indicated by an *asterisk*



and this difference in performance stabilized within the first four blocks. In addition, in the final recognition test, observers were not able to distinguish the old, repeated contextual layouts from new displays, suggesting that the underlying processes are implicit. This pattern of results is in perfect accord with previous findings (e.g., Chun & Jiang, 1998), showing that search performance benefits from the (implicit) association of a given target location with its surrounding context.

How did the change of the target's identity and location (after block 15) affect performance? As illustrated in Fig. 2, in the second half of the experiment, the contextual-cueing effect was largely reduced. Immediately after the change in epoch 4, no contextual facilitation (−39 ms) was evident at all, and even after the repeated presentation of the relocated target within the old arrangement of nontargets, no substantial recovery of contextual cueing was observable (mean contextual-cueing effect: −13 ms for epochs 4–6, as opposed to 184 ms for epochs 1–3). Thus, in line with effects of contextual misguidance after target location changes (as reported by Manginelli & Pollmann, 2009; Makovski & Jiang, 2010), the current results show that contextual cueing is abolished when the target swaps its location (and changes its identity). Thus, all three studies show that the contextual cueing benefit not only disappears, but even turns into a cost if there is a substantial change of the target location (i.e., if the new target is not located within the direct surround of the previous target), whether to a previously empty location or a previous nontarget location. Moreover, our findings replicate and extend the results of Makovski and Jiang (2010) in revealing initially a contextual cost in particular for target–nontarget swaps, which then gradually disappeared after several blocks. Overall, these results imply that when the target-to-context relation undergoes a sudden change, re-tuning of contextual associations to the new target location is inefficient; that is, contextual associations once learned are rather fixed and not adapting to a (consistently) changed environment (in fact, the learned associations do not adapt even after 15 repetitions). Contextual re-learning therefore appears to be subject to proactive interference (see, e.g., Anderson & Neely, 1996, for review), as acquired contextual associations cannot easily be remapped to novel target locations. Probably, the target-to-context association, which was learned for a given display in the first half of the experiment, subsequently intrudes when the target location changes in the second half and the association to a repeated context would need to be updated.

Experiment 2

Experiment 1 demonstrated that unpredictable, sudden (location and identity) changes cannot be compensated for after initial contextual learning. However, it remains a possibility that contextual cueing can rather efficiently adapt to changes at least when these are predictable. In particular, adaption may be possible when observers, right from the beginning of an experiment, learn to associate not only the location of the task-relevant target in the first half of the experiment with the context, but also the location of the target relevant in the second half. Experiment 2 was designed to investigate whether such predictable target location changes would allow for contextual cueing to re-adapt. To this end, in Experiment 2, displays always contained two targets (Ts) within an arrangement of nontargets (see Fig. 1b), while the task remained the same as in Experiment 1. In the first half of Experiment 2, observers were instructed to respond to the pointing direction of one target (e.g., the T pointing left/right); in the second half, the response-relevant target was switched, that is, observers were to report the pointing direction of the second target (the other T pointing upwards/downwards). Since both targets were simultaneously present, and observers knew right from the start which target was relevant in the second half of the experiment, the change of target (location and identity) in the second half was perfectly predictable. Consequently, if the predictability is a key requirement to adapt the context to novel situations, then contextual cueing should remain effective throughout the entire experiment.

Methods

Apparatus, stimuli, design, and procedure were identical to Experiment 1, except that all search displays always contained two target Ts (one with the stem oriented left/right and one with the stem oriented upwards/downwards) and 10 nontarget Ls (see Fig. 1b for example displays). As in Experiment 1, 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 upwards or downwards). Note, that the two target locations were always the same for a given display, and observers were informed at the beginning of the experiment about the change of task. The order of the task-relevant target (upwards/downwards or left/right) was counterbalanced across observers. Figure 1b presents examples of the search displays. Ten volunteers (mean age 24.8 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 quite rare (2.5%), and an ANOVA with the factors context (old vs. new), part (first half vs. second half of the experiment) and epoch (1–3 vs. 4–6) revealed no significant effects.

Individual mean RTs were computed excluding erroneous responses and outliers. Figure 4 presents the mean correct RTs, averaged across participants, as a function of epoch, separately for old and for new contexts. In addition, the mean RTs were subjected to a three-way ANOVA with main terms of context (old vs. new), part (first half vs. second half of the experiment), and epoch (1–3 vs. 4–6). This analysis revealed significant main effects for context, $F(1.9) = 38.48$, $P < 0.001$, and epoch, $F(2.18) = 29.24$, $P < 0.001$. Responses were 130 ms faster, on average, on old-context compared to new-context trials, and search became faster from the first to the third epoch (by 142 ms). Moreover, a marginally significant main effect of part, $F(1.9) = 4.76$, $P = 0.06$, indicated that search was slowed (by 272 ms) when the target switched in epoch 4 relative to epoch 3. The context × part interaction was not significant, $F(1.9) = 2.17$, $P = 0.18$.

In summary, the target (and response) change led to an overall slowing of RTs; however, in contrast to Experiment 1, no significant reduction of the contextual-cueing effect was observable, despite the target change. Instead, contextual cueing showed a significant positive effect before and after the change of the relevant target (for comparisons of old and new contexts, all P's <0.05).

Recognition test

Overall mean accuracy in the recognition test was 45%. The hit rate (i.e., correct identifications of old trials) was 45%, but this did not differ from the false alarm rate of 55%, $t(9) = 1.45$, $P = 0.18$. Thus, as in Experiment 1, explicit recognition of repeated displays was essentially at chance in Experiment 2.

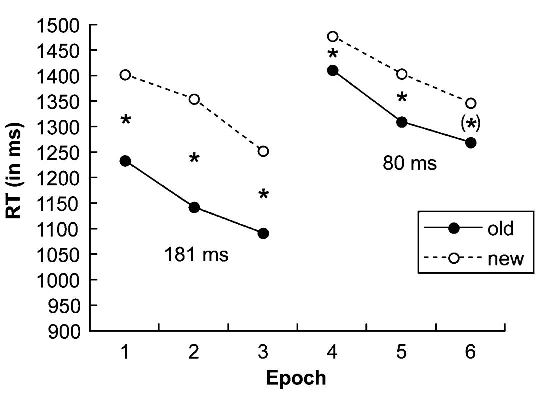


Fig. 4 Mean reaction times (*RTs*) as a function of epoch in Experiment 2. *Filled* and *unfilled symbols* represent old-context and new-context conditions, respectively. *Epochs 1–3* correspond to the initial learning phase, whereas the (task-relevant) target was switched for *epochs 4–6*. The mean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

Discussion

Experiment 2 replicated Experiment 1 (and previous studies) in showing a robust contextual-cueing effect for the first half of the experiment. Search was 181 ms faster for old relative to new contexts in Experiment 2 during the first three epochs, which compares with 184 ms in Experiment 1, suggesting that contextual cueing was initially equally effective in both experiments, $t(18) = 0.66$, $P = 0.94$. However, while the initial learning phase was comparable in Experiments 1 and 2, the pattern of results markedly diverged after epoch 4. In Experiment 1, contextual cueing was drastically reduced (numerically by ~106% to a non-significant, negative level) in the second half of the experiment; by contrast, while there was also a certain reduction in Experiment 2, this was much smaller (only some ~55%) and the cueing effect remained significant throughout the second half of the experiment. In addition, in epoch 4, immediately after the change of target, contextual cueing was completely abolished in Experiment 1 (cost of −39 ms), while it remained relatively intact in Experiment 2 (significant benefit of 66 ms). Thus, contextual cueing was still effective (albeit showing a certain numerical reduction together with a trend for an overall slowing of response latencies) after the target change in Experiment 2. In contrast, search was not assisted by contextual repetitions in Experiment 1 following the switch (in the middle of the experiment) of the target location and identity.

Taken together, this pattern of results suggests that the contextual information can be adapted relatively efficiently to a new target location when both target alternatives are simultaneously present in the display, so that both target locations can be learned initially. This stands in contrast with Experiment 1, where the changed target's location was not predictable (i.e., learnable) and consequently no reliable contextual-cueing effect could develop after the change.

An alternative to this explanation, which assumes that two target locations are learned initially, would be an account according to which the second target was only newly learned after the switch. The overall RT slowing after the switch may be taken to provide support for this possibility. However, at the same time, this account is relatively unlikely as it is not apparent why new learning should not also have occurred in Experiment 1 (or in Manginelli & Pollmann, 2009, for a target-location change to a previously blank location). Given this, the overall RT slowing, rather than reflecting novel learning, may have occurred because of the change of task—with a more pronounced drop in response speed in Experiment 2 relative to Experiment 1 because the initial target was still present in the displays after the switch, which potentially produced a greater amount of response interference.

In summary, the results of Experiment 2 suggest that two target locations may be learned during the initial phase of the experiment, revealing a potential to adapt to predictable target location changes (at minor costs) in contextual cueing. At the same time, the reduction of search RTs after the change of task suggests that the general increase in search time with practice cannot be generalized to situations that require a novel response.

Note, that there were nevertheless some subtle, numerical learning effects in the second half of Experiment 1, with contextual cueing effects of −39 ms in epoch 4 increasing to 13 ms in epoch 6 (i.e., contextual interference abated). By contrast, in Experiment 2, contextual cueing did not drop to zero immediately after the change, and it remained relatively stable across the epochs following the change, with benefits of 66–95 ms in epochs 4–6; nevertheless, the benefits never reached the same level as during the first half of the experiment (181 ms).

Experiment 3

Experiment 2 suggests that learned contextual item arrangements are adaptable to target (location and identity) changes as long as these changes are predictable. By contrast, in Experiment 1, unpredictable target-related changes (of the target's location and identity) disrupted contextual cueing. Consequently, to test whether the change of the target's location or the change in identity had a negative influence on contextual cueing in Experiment 1, in Experiment 3, only the identity of the target changed (whereas the location of the target remained the same). Thus, in Experiment 3, observers were instructed to search for one type of target (e.g., a T oriented upwards or downwards) in the first half, and for the other type of target (a T oriented left or right) in the second half. However, unlike in Experiment 1, the change of the target identity was not accompanied by a change of the target location. Consequently, if target-location information is crucial for obtaining contextual cueing, then a switch of the target identity alone should not affect contextual cueing. Conversely, if the identity of the target determines whether contextual cueing is effective, then a change of the target type should impair contextual cueing in Experiment 3 to a degree comparable to Experiment 1.

Methods

Apparatus, stimuli, design, and procedure were identical to Experiment 1, except that the target identity was changed without concurrent location changes. As in Experiment 1, the task was to search for one target (e.g., pointing either left or right) in the first 15 blocks and for the other target (e.g., pointing upwards or downwards) for the next 15 blocks. The order of the target type (up/down, or left/right) was counterbalanced across observers. Figure 1c presents examples of the search displays. Ten volunteers (mean age: 26.4 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

Error rates were again low overall (2.3%). An ANOVA with the factors context (old vs. new), part (first half vs. second half of the experiment), and epoch (1–3 vs. 4–6) revealed no significant effects.

Individual mean RTs were computed excluding erroneous 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 individual mean RTs were subjected to a three-way ANOVA with main terms of context (old vs. new), part (first half vs. second half of the experiment), and epoch (1–3 vs. 4–6). This analysis revealed significant main effects of context, $F(1, 9) = 49.77$, $P < 0.001$, and epoch, $F(2.18) = 6.88$, $P < 0.007$, but no significant effects involving the factor part (all P's >0.25). The main effect of context showed that search in old displays was 154 ms faster than search in new arrangements. In addition, the main effect of epoch was due to a decrease in search RTs (by 60 ms) from the first to the third epoch.

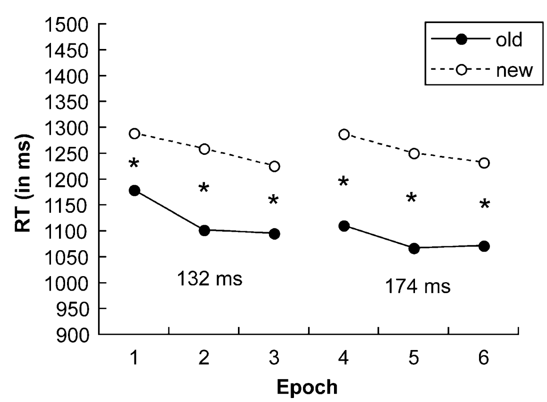


Fig. 5 Mean reaction times (*RTs*) as a function of epoch in Experiment 3. *Filled* and *unfilled symbols* represent old-context and new-context conditions, respectively. *Epochs 1–3* correspond to the initial learning phase, whereas a change of the target identity was introduced in *epochs 4–6*. The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

Finally, to compare how contextual cueing was affected by identity and location changes across all experiments, a mixed ANOVA was performed on the mean RTs with the between-subjects factor experiment (1, 2, 3) and the within-subjects factors context, part, and epoch. This analysis revealed significant within-subject main effects of context, $F(1.27) = 95.6$, $P < 0.001$, epoch, $F(2.54) = 41.8$, $P < 0.0001$, and an interaction of context × part, $F(1.27) = 6.66$, $P < 0.02$, mirroring the results described above for all three experiments. However, importantly, there was also a three-way interaction between context, part, and experiment, $F(2.27) = 4.35$, $P < 0.03$. This interaction showed stable contextual-cueing effects across both halves in Experiments 2 and 3 (181/132 ms vs. 80/174 ms, respectively; all P's >0.17), but a large drop in contextual cueing between both halves in Experiment 1 (184 vs. −13 ms, respectively, $t(9) = 3.1$, $P < 0.02$). This outcome illustrates that unpredictable target (location and identity) changes (Experiment 1) eliminate contextual cueing, whereas predictable target (location and identity) changes (Experiment 2) permit relatively efficient adaption to the novel target-to-context relations. Finally, changes of the target identity alone (Experiment 3) do not affect contextual cueing at all, suggesting that location information is the key determinant of contextual cueing across changes.

Recognition test

Overall mean accuracy in the recognition test was 56%. The hit rate was 60%, but this did not differ from the false alarm rate of 49%, $t(9) = 1.50$, $P = 0.16$. Thus, essentially, there was no explicit awareness for repetitions of old displays.

Discussion

As in Experiments 1 and 2, in Experiment 3 a robust contextual-cueing effect (of 132 ms) was obtained in the first half of the experiment. However, unlike Experiment 1, the change of the target identity in epoch 4 did not affect contextual cueing: contextual cueing remained (at least) equally effective in the second half of the experiment (174 ms). This shows that changes of the target identity alone do not affect contextual learning (see also Chun & Jiang, 1998), whereas changes of the target location (in Experiment 1) lead to a large reduction of contextual cueing (see also Manginelli & Pollmann, 2009; Makovski & Jiang, 2010).

General discussion

The present set of experiments was performed to investigate whether contextual cueing is adaptive to target changes, in terms of location and identity. Our results revealed that the predictability of a change can have a systematic influence on the amount of contextual benefit following the change. In all three experiments, reliable contextual-cueing effects were obtained during the first three epochs, indicating that contextual learning was effective and facilitated search. However, after a target change in epoch 4, contextual cueing largely depended on whether changes were predictable or not. Contextual cueing remained effective after the task switch when the target location remained the same and only the task-relevant identity of the target was changed (Experiment 3). In addition, contextual cueing was also found to be adaptive, with expedited (search) responses to repeated displays (albeit showing some reduction in effect magnitude) when the change in identity was accompanied by a predictable location change (Experiment 2). Only when the change of the location was unpredictable, contextual cueing was non-adaptive and failed to facilitate search immediately after the change (Experiment 1).

Taken together, this pattern of results shows that memory-based contextual associations can adjust, at least to some extent, to a changing environment. However, the degree to which a change can be compensated for depends on relatively specific pre-conditions: changes of the target identity do not affect (spatial) contextual cueing (see also Chun & Jiang, 1998, for a comparable outcome). Moreover, predictable changes of the target location can be compensated for; that is, when the new target location within a repeated arrangement is learnable prior to the change, there can be effective contextual cueing after the instruction to (re-) orient to the new target. By contrast, contextual cueing is not effective when the changed target location is unpredictable in the initial learning phase. In fact, with a changed target location, contextual cueing could not recover within 15 blocks, suggesting that re-learning after an unpredictable change is seriously limited. This latter finding accords with the results of Manginelli and Pollmann (2009, see also Makovski & Jiang, 2010), who showed that when the location change is unpredictable, the learned context biases attention towards the old target location, thus effectively providing a 'misguidance' signal. Thus, an acquired association between a target and a context cannot easily be 'rewired' to represent a novel location, suggesting that contextual remapping suffers from proactive interference (Anderson & Neely, 1996, for review). However, in accordance with previous studies (Manginelli & Pollmann, 2009; Makovski & Jiang, 2010), evidence of misguidance was only observable transiently (in epoch 4 of Experiment 1), with a recovery from this cost but no significant contextual benefit afterwards (in epoch 6 of Experiment 1). Despite of these limitations, contextual cueing can nevertheless flexibly accommodate predictable location changes.

One possibility to account for the adaptive nature of contextual cueing would be to assume that all items are prioritized according to their relevance, and associative links are established primarily between the target(s) and the most relevant context. In fact, recent connectionist models of contextual cueing (Brady & Chun, 2007) show that learning may be triggered by a relatively limited set of contextual items. Thus, only two to three associative links between the target and its surrounding nontargets can result in contextual cueing. After a change of the target, the associative links require reorganization to accommodate the novel target location. When the novel target location is not known in advance, the change is likely to disrupt contextual cueing (as in Experiment 1), because there is no learned context that could be associated with the previously unknown target location. However, our results also show that when the novel target location is known beforehand, then the context can accommodate to this item such that contextual guidance immediately adapts following the change (see Experiment 2). This strongly suggests that contextual associations for predictable target location changes might have been learned already in the first phase of the experiment. That is, not only the location of the target response-relevant first, but also that of the target relevant later may have been 'marked' within the learned contexts, perhaps with the target relevant second (i.e., effectively a nontarget item in epochs 1–3) acting as a 'salient' associative cue to the target in the first half of the experiment, and vice versa. On this view, predictable changes permit two locations (response-relevant in separate phases of the experiment) to be integrated within the associative context simultaneously (see also Chun & Jiang, 1998). Moreover, the finding that a learned context can be 'transferred' between target locations bears some similarity to a recent study by Jiang and Leung (2005), who showed that a repeated context can be implicitly learned even in the absence of attention (i.e., for a non-attended subset of search-irrelevant items), whereas the use of the learned context information for explicit recall is dependent on attention (see also Geyer, Shi, & Müller, 2010). In a similar manner, the 'second' target in Experiment 2 could have been learned in the absence of attention already during the first half of the experiment.

While Experiment 2 demonstrated that predictable location changes may be compensated for in contextual cueing, the RT benefit was, nevertheless, numerically smaller after the change (contextual-cueing effects were 181 and 80 ms in the first and second halves of the experiment, respectively). Of course, it would be reasonable to assume that reorienting towards the novel target location incurs some kind of shifting cost. In fact, comparable costs of shifting in contextual cueing have been reported by Chua and Chun (2003), who systematically changed the viewpoint on a given display from initial learning to subsequent testing. On the other hand, combining a probe detection task with contextual cueing, Ogawa, Takeda, and Kumada (2007) recently showed that context-based learning not only facilitates the target location, but also inhibits nontarget locations. Accordingly, reduced contextual cueing after a (predictable) location change might also be explicable (at least to some degree) by inhibition that persists at the previous non-target location after it has become the relevant, target location (see also Makovski & Jiang, 2010).

Apart from facilitatory and inhibitory influences related to target- and nontarget processing, salient (yet irrelevant) items might be processed with priority in contextual cueing while affecting learning of a given display. For instance, task-irrelevant singletons (such as the second, 'irrelevant' target in Experiment 2) can diminish the overall contextual-cueing effect (Conci & von Mühlenen, 2009). This suggests that both the target and the irrelevant singleton share the same context, effectively reducing its influence on search. Moreover, Ogawa and Kumada (2006) showed that attention implicitly prioritizes relevant locations in visual search. Detection of a probe dot was found to be faster when a given display layout was repeated. However, novel stimuli also received priority, suggesting that salience determines whether a given item is integrated within a given context or not. Thus, these studies demonstrate that prioritized items (such as a target or a singleton) are more likely to be integrated within the learned context than other (potentially irrelevant) items. Consequently, adaptation to a change in the environment will only be effective when the new target location is already integrated within the learned context.

In summary, the present results demonstrate that the visual system utilizes the relational properties of the environment to guide search in an adaptive manner. When a predictable change occurs and requires reorienting, contextual cueing can adapt, to a certain extent, to these novel demands. However, unpredictable changes eliminate the advantage from contextual cueing (but do not lead to long-lasting disruption). Consequently, context-based learning is relatively flexible in adjusting to novel, predictable demands, implying that the context can be 'remapped' after a change of the task-requirements (see Pisella & Mattingley, 2004, for a review of spatial remapping studies).

Acknowledgments This work was supported by Deutsche Forschungsgemeinschaft (DFG) Research Group (FOR 480) and CoTeSys Excellence Cluster (142) grants. We would like to thank Bernhard Hommel, Takatsune Kumada, and Stefan Pollmann for valuable comments on an earlier draft of the manuscript.

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