Implicit Adaptation to Change in Memory-Guided Visual Search

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General Introduction

The world is an intricately complex place: A single glance at the world contains an abundance of static or moving objects that are rich in features, nested in events and highly interdependent. But instead of being confused and overwhelmed, humans usually process visual information very efficiently and perform appropriate spatial orientation. A crucial mechanism for the filtering and selection of information seems to be the deployment of attention because observers essentially perceive objects that are in the focus of attention. Visuo-spatial attention has been described as a "spotlight that enhances the efficiency of the detection of events within its beam" (Posner, 1980, p. 172). Other researchers refer to attention as a process that selects perceptual objects rather than “illuminating” them (see Chun & Wolfe, 2001, for review).

Attention can be captured exogenously by particularly salient objects, in an automatic fashion, since salient objects virtually “pop-out” in the visual scene (e.g., red object among green objects; Chun & Wolfe, 2001; and Wolfe & Horowitz, 2004, for reviews on bottom-up capture). The guidance of attention is further influenced by endogenous factors such as goals, experience, and memory (see Chun and Nakayama, 2000, for a review on top-down guidance). More specifically, when observers look for a designated target object among other objects in a visual scene, visual search can be facilitated by (implicit) memory for statistical regularities and covariations (Fiser & Aslin, 2002). For example, observers are sensitive to recurring target locations, which means that observers’ attention is guided to highly probable target locations (e.g., some objects mostly appear above horizon). Similarly, visual search for a particular object can be cued by stable associations with a scene (toaster in kitchen) and with related objects (toaster on counter next to kettle; Bar, 2004, for review). If, for example, an observer is looking for the toaster, she/ he will probably start the search in the kitchen and guide attention to the countertop with the kettle. In other words, memory of spatial regularities in the visual world provides cues to the location of desired target objects, which increases search efficiency.

However, behaviourally relevant changes are likely to occur even in rather stable visual scenes; for example, objects can occur in different recurring locations within otherwise stable visual scene-contexts. Are observers capable to represent objects at multiple target locations and perform equally efficient visual search for them? Furthermore, objects' locations can change permanently within their respective contexts. Consequently, acquired memory representations of the spatial context-target relations deviate from the actual context-target layouts. How do inappropriate contextual cues from memory then affect visual search performance? And how are memory representations adapted to changes in previously stable spatial layouts?

The present series of studies was designed to examine observers' capability to adapt implicit memory representations to changes in spatial context-target configurations. More specifically, we investigated whether observers represent more than one location of a familiar target object that is associated with a stable context of nontarget objects. The following chapter will provide a more elaborate summary of influences of memory on visual search. Subsequently, the introduction will focus on the facilitative impact of spatial context on visual search, and the specific paradigm used in the present studies will be discussed comprehensively. Then, evidence and theoretical assumptions about observers' capability to adapt to changes in contextual cues will be presented. Finally, the most relevant findings of the present studies will be summarised.

Memory-Guided Visual Search

Memory representations can influence the deployment of attention, which is particularly useful for the performance of visual search (see Chun and Nakayama, 2000, for a review). If observers have, for example, an internal representation of the object they are looking for, they can select behaviourally relevant information, while discarding irrelevant information, before they even start the search, which then manifests in the voluntary direction of attention. Thus, top-down knowledge about the physical features (e.g., colour, orientation) of a designated object (i.e., feature template) facilitates guidance of attention in a scene (Wolfe & Horowitz, 2004, for review).

Repeated experience with visual events can also affect the guidance of attention in a rather involuntary manner. For example, search performance benefits from repetitions of target features. Specifically, attentional deployment is more efficient, if currently presented items share features with preceding presentations (e.g., priming of pop-out: Maljkovic & Nakayama, 1994; dimension weighting: Krummenacher & Müller, 2012, for review). While priming of pop-out represents a rather short-lived effect of memory on visual search, observers are also capable to use long-term memory for visual search. Long-term memory can be derived from the abundance of statistical regularities that exist in the visual world ─ human brains essentially work as "statistical sponges" (Clark, in press, p. 57). Repeated experience with statistical regularities of the visual world can result in (implicit) biases that guide visual attention on subsequent encounters.

For example, observers prioritise specific locations, if they have experienced that the target occurs in these locations with a high probability. In a study by Jiang, Swallow, Rosenbaum, and Herzig (2012) observers searched for a target item ('T') presented in a random array of nontargets ('Ls'; see Figure 1). Unknown to observers, the target was more likely to appear in one quadrant of the search array than in all remaining quadrants. Search for the target item in its highly probable location was faster compared to appearances in less probable locations due to probability learning. Faster responses at highly probable locations persisted across a week, and even continued when the target appeared in all possible locations with equal probabilities (see also Huestegge & Koch, 2011, for findings on persistence of attentional sets). Hence, observers incidentally acquire the probability distribution of targets' locations, resulting in a robust attentional bias that facilitates visual search (see also Druker & Anderson, 2010; Geng & Behrmann, 2005; but see Walthew & Gilchrist, 2006).

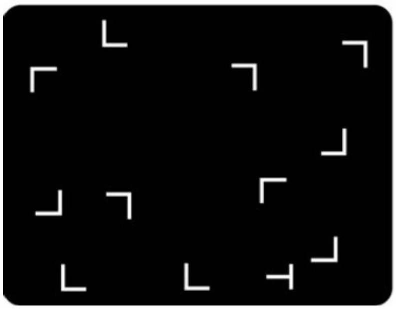

Figure 1: Example search display with a target shaped like the letter 'T' and nontargets shaped like the letter 'L'.

In contrast to some experimental work (e.g., Jiang et al., 2012), real-world objects do not occur in randomly arranged layouts of items that serve to distract attention away from the target. Instead, objects in real-world scenes are usually associated with other objects and with certain environments or scenes, and these statistical regularities additionally contribute to efficient spatial orientation (see Bar, 2004; Chun, 2000; and Oliva & Torralba, 2004, for reviews). More specifically, perceiving one particular object evokes expectations about semantically (e.g., Chun & Jiang, 1999) or temporally (Turk-Browne, Scholl, Johnson, & Chun, 2010) related objects, and it cues the spatial locations of highly related objects (e.g., Fiser & Aslin, 2001; Mack & Eckstein, 2011), which speeds target detection.

A number of studies have shown that scene gist (i.e., global context) primarily supports the identification of objects and likely target locations (e.g., Bar, 2004; Biederman, Mezzanotte, & Rabinowitz, 1982; Castelhano & Henderson, 2007; Neider & Zelinsky, 2006). However, facilitation effects of local object covariations can proceed independently of global context (e.g., Hoffmann & Sebald, 2005). For example, a recent study suggests that object detection is fairly independent of global context, if objects appear in otherwise plausible locations (Castelhano & Heaven, 2011). Observers performed search for a target (mug of paint brushes) that appeared in either a consistent (studio) or inconsistent (bedroom) scene, at either a consistent (on table) or an inconsistent location (on lamp). Scenes were very briefly presented without target objects to instigate scene gist, and afterwards observers were asked to perform search for the target object. If scene gist determined object identification, observers should be faster to find consistent target objects only in consistent scenes compared to all other possibilities. But visual search was fastest for objects in consistent locations, regardless of the consistency of the scene context. Thus, the study showed that expectations of object locations can be exploited independently of scene gist (see also Brooks, Rasmussen, & Hollingworth, 2010; Jiang et al., 2012). Nevertheless, it is quite reasonable to assume an interactive process, in which contextual information facilitates object processing, while objects stimulate scene processing simultaneously (Bar, 2004; Brockmole & Võ, 2010; Wolfe, Võ, Evans, & Greene, 2011).

The investigation of visual search in real-world scenes has revealed that spatial attention can be guided by scene gist (e.g., Castelhano & Henderson, 2007), by consistent spatial positions (e.g., Castelhano & Heaven, 2011), by relations between neighbouring objects (Mack & Eckstein, 2011), and by interactions between global and local context information (Brockmole & Võ, 2010). However, the use of real-world pictures bears substantial limitations (Chun, 2000): On the one hand, experimental control is severely limited as pictures usually contain high levels of variability (e.g., colours, object sizes), and present both semantic and spatial cues to target locations. On the other hand, this line of research does not contribute evidence on the acquisition of spatial contextual relations because already existing knowledge about regularities in the visual world is tested. In order to achieve greater experimental control and to examine the process of learning contextual relations, Chun and Jiang (1998) introduced a paradigm that has been providing valuable insights on the guidance of attention in visual search through spatial contextual cues.

Context-Guided Visual Search

Chun and Jiang (1998) argued that the visual world consists of stable regularities, which cue attention to the locations of relevant objects. Accordingly, they tested whether observers use spatial regularities to deploy attention more efficiently in a visual search task. Observers were presented with search displays that contained a target object (the letter 'T') and eleven nontarget objects (the letter 'L'; see Figure 1). The task was to search for the target object and indicate whether it was oriented to the left or right. Unknown to observers, a set of search displays was repeated throughout the experiment. Each one of these old contexts presented a unique invariant configuration of nontargets paired with a particular target location. Hence, the spatial contexts of nontargets were predictive of target locations. Search times in old contexts were compared to performance in randomly generated configurations of nontargets and target locations (new contexts). To control for learning of location probabilities (e.g., Jiang et al., 2012), a limited number of target locations were repeated in both old and new contexts. Consequently, the only difference between old and new contexts was the predictive nature of the surrounding context of nontargets in old contexts.

General practice effects with the task as well as the repetition of target locations in both old and new contexts resulted in a progressive reduction of search times (i.e., reaction times, RTs; see Figure 2 for a typical pattern of results). More important, the study (Chun & Jiang, 1998) revealed that search for target locations became faster in old contexts in comparison to new contexts across repetitions (see Figure 2). The developing difference between search in old contexts and search in new contexts is the contextual-cueing effect [RT(new) - RT(old)]. Thus, observers learned the spatial relations of old contexts incidentally, which then guided observers' spatial attention more efficiently to target locations as compared to new contexts. The study further showed that contextual cueing was not affected when item identities changed during the experiment (Experiment 2), which means that global spatial configurations were learned rather than perceptual identities of search items. The importance of stable spatial relations between target locations and contexts was further supported by a lack of contextual-cueing effects when target locations randomly varied in old-context displays (Experiment 3; see also Wolfe, Klempen, & Dahlen, 2000). Thus, contextual cueing represents an outcome of associative learning of context-target relations, rather than a general increase in processing efficiency.

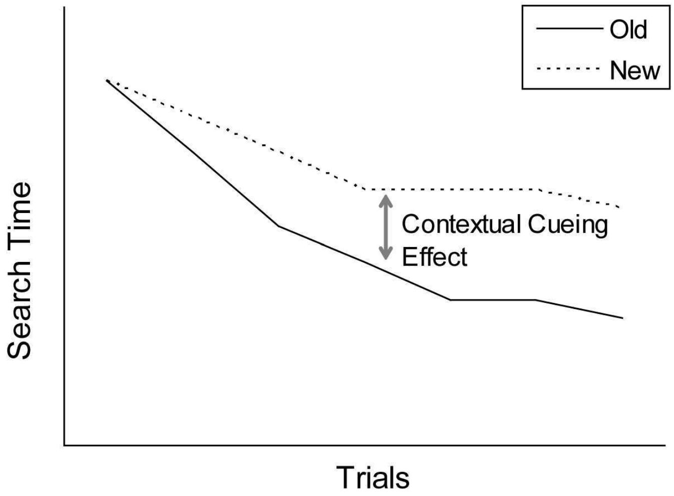

Figure 2: Schematic illustration of a typical pattern of search times for old and new contexts (solid and dashed lines, respectively) across trials in a contextual cueing experiment.

Based on their findings, Chun & Jiang (1998) concluded that contextual cues guide attention in visual search in an instance-based manner. Instance theory (Logan, 1988, 2002) addresses differences between automatic and non-automatic processing and assumes that automatic processing is, essentially, memory retrieval. When novices perform a task for the first time, they rely on an algorithm that is sufficient to perform the task. However, each repeated encounter with a stimulus leads to the accumulation of episodic traces, which are separately stored and recruited at the time of retrieval. A particular characteristic of episodic traces is the exclusive representation of information relevant to perform the task. Because of the accumulation of episodic traces, observers are eventually able to retrieve an episode from memory instead of using the more laborious algorithm. In other words, automation marks a shift from reliance on a general algorithm to retrieval of specific episodic instances.

Applied to contextual cueing this means, that observers use a random, sequential item-by-item search as a general algorithm in the beginning of the task (Chun & Jiang, 1998). Due to repeated visual search in old contexts observers incidentally acquire memory representations of old contexts. Thus, each repeated encounter with old contexts is stored as an episodic trace, a contextual cue, which gradually supersedes the algorithm since it guides attention to the target location more efficiently. Because instances only contain information relevant to the task, contextual cueing continues as long as relative spatial positions of nontargets and targets are preserved (see Chun & Jiang, 1998, Experiment 2).

In summary, contextual-cueing effects seem to originate from an interaction between memory and attention. Memory traces cue attention endogenously to the target location ─ similar to the presentation of an arrow cueing attention exogenously to a subsequently appearing target object (Chun & Wolfe, 2001). Even though contextual cues are supposed to guide spatial attention efficiently to target locations (Chun & Jiang, 1998; see also Chun, 2000; and Chun & Nakayama, 2000, for reviews), visual search proceeds relatively slowly in old contexts in comparison to, for example, guidance by automatic capture. Therefore, the assumed impact of contextual memory on the deployment of attention in visual search is debatable.

Context Guides Attention

Search efficiency as measured by slopes of reaction time and set size functions (i.e., search slopes) is a useful indicator of attentional guidance. When the number of items is increased in search displays, search efficiency is reduced. That means the more items a display contains the more time it takes to inspect each one of them (ms/ item). If search is guided by, for example, salient objects, search becomes more efficient as indicated by a decrease in search slopes, in particular for larger numbers of search items. Chun and Jiang (1998) tested whether search slopes are reduced by the repetition of old contexts, which would point to attentional guidance by contextual memory (i.e., the target becomes more "salient" through memories). To this end, different numbers of nontargets were presented (8, 12, or 16) in search displays (Chun & Jiang, 1998, Experiment 4). Indeed, a reduction in search slopes was observed suggesting that contextual-cueing effects are based on attentional guidance. However, the observed decrease in search slopes was rather small, and later studies reported similarly small effects (Kunar, Flusberg, & Wolfe, 2008) or failed to replicate a reduction in search slopes (e.g., Kunar, Flusberg, Horowitz, & Wolfe, 2007).

Instead, some authors have argued that contextual memory speeds processes of response selection rather than guiding attention. Specifically, contextual cueing is supposed to facilitate responses by lowering the response threshold (Kunar et al., 2007), allowing faster response selection (Schankin & Schubö, 2010), or by speeding response execution processes (Schankin & Schubö, 2009). However, a recent study suggested that an actual response is not even necessary to observe contextual-cueing effects (Makovski & Jiang, 2011). Thus, even if response-related processes benefit from contextual cueing, guidance of visual attention seems to be the crucial effect contextual cueing exerts on visual search (see also Zhao, Liu, Jiao, Zhou, Li, & Sun, 2012).

Ogawa, Takeda, and Kumada (2007), for instance, reported evidence for the guidance of attention to target locations through contextual cueing. After observers had performed visual search in old and new contexts, probe dots were presented either at target or at nontarget locations. Instead of performing visual search for target locations, observers were now required to report the presence or absence of probe dots. When probe dots appeared at target locations in old contexts, detection was faster than when they appeared at target locations in new contexts, or at nontarget locations. Hence, contextual cueing facilitated the allocation of attention to target locations, because target locations' salience is amplified through contextual learning (see also Geyer, Zehetleitner, & Müller, 2010).

Furthermore, the measurement of eye movements revealed that observers employed fewer fixations in old contexts compared to new contexts (e.g., Myers & Gray, 2010; Tseng & Li, 2004; Zhao et al., 2012), and that contextual cues increase the chance for the first fixation to land on the target location (Peterson & Kramer, 2001a). Similarly, Johnson, Woodman, Braun, and Luck (2007) argued that contextual cueing increases the probability for attention to be allocated to the target location, whereas a direct shift to the target location is not guaranteed. The authors measured the electrophysiological activity of the brain while observers were performing a contextual-cueing experiment. The experiment revealed an increase in the amplitude of the N2pc component for old contexts in comparison to new contexts. The N2pc component is supposed to reflect focal-attentional selection of task-relevant target objects amongst nontarget objects in visual space (Eimer, 1996); its amplitude indexes the amount of attentional resource allocation. An amplified N2pc for old contexts suggests that contextual cueing facilitates early allocation of attention to the target location (see also Chaumon, Drouet, & Tallon-Baudry, 2008; Olson, Chun, & Allison, 2001; Schankin & Schubö, 2009).

Overall, a number of findings suggest that contextual cues do not turn a rather sequential visual search into a pop-out phenomenon. Rather, it seems that visual search in old contexts starts fairly inefficiently on a global level, but once more local associations in old contexts are "recognised", search is guided more directly to target locations by contextual memory (e.g., Ogawa & Watanabe, 2010; Peterson & Kramer, 2001a; Tseng & Li, 2004; Zhao et al., 2012). Even though this proposal suggests that the visual system has to somehow recognise old contexts to implement cued guidance of attention, it does not imply that observers consciously remember old contexts and direct attention voluntarily to target locations. Instead, learning and "remembering" in contextual cueing are assumed to proceed implicitly (Chun & Jiang, 1998).

Implicit Learning and Memory

Learning and memory are not necessarily dependent on intent and awareness. An abundance of human behaviour is, in fact, based on automatic learning (Logan, 1988) and the application of rather inaccessible knowledge. Reber (1967) was one of the first authors to suggest that subjects learn underlying structures of complex information in the absence of awareness, which improves performance at a particular task. In his seminal work, observers were presented with strings of arbitrary letters, whose combinations obeyed the rules of an artificial grammar ("artificial grammar learning"). In the first phase of the experiment, observers were asked to just study the strings. Subsequently, observers were able to distinguish novel grammatical from ungrammatical strings, although they could not verbalise the underlying grammatical rules. This result shows that observers automatically learned structures in the absence of knowledge or instructions about them, which means, that learning and the resulting memory representations can be implicit (see Perruchet & Pacton, 2006; Reber, 1989; and Seger, 1994, for reviews). In contrast, observers solve explicit learning tasks in a hypothesis-driven manner, which results in the conscious retrieval and declaration of past facts and events (Cleeremans, Destrebecqz, & Boyer, 1998).

Since Reber's (1967) work, implicit learning has been studied with several other tasks (see Seger, 1994, for review) that usually present stimuli composed by an underlying statistical structure, whilst observers are required to perform an unrelated task (see Perruchet & Pacton, 2006, for a discussion on similarities between statistical and implicit learning paradigms). More specifically, observers are sensitive to lower- and higher-order statistics (Fiser & Aslin, 2002). The first category represents, for example, learning of the probability distribution of target locations (Jiang et al., 2012), whereas the latter refers to the extraction of contextual relations between objects and environments (see Bar, 2004; and Chun, 2000, for reviews). Thus, facilitation effects of recurring locations and covariations in visual search are often based on incidental rather than intentional learning.

Contextual cueing is also considered to occur implicitly (Chun & Nakayama, 2000). In the original study (Chun & Jiang, 1998, Experiments 2 & 5), observers performed a two-alternative forced choice task as a recognition test after the search task, which required a distinction between old and new contexts. This recognition test revealed that observers were not able to discern old from new contexts (performance at chance level), supporting the assumption that the contextual-cueing effect is based on guidance by implicit memory representations of spatial layouts. However, a purely implicit nature of contextual learning and memory has been doubted (Smyth & Shanks, 2008), and studies have occasionally reported that observers were able to recognise old contexts (e.g., Geyer, Shi, & Müller, 2010).

Although recognition of old contexts has been observed, explicit knowledge about display repetitions does not seem to influence performance in contextual cueing (Shanks, 2010; Westerberg, Miller, Reber, Cohen, & Paller, 2011; see also Reber, 1989). For example, Chun and Jiang (2003) instructed one group of observers explicitly about the repetitions of search displays before the experiment started. Another group was only instructed about the search task. The results showed fairly similar contextual-cueing effects for both groups (see also Westerberg et al., 2011) albeit with a trend for smaller contextual-cueing effects in the explicitly instructed group (see also Geyer, Shi et al., 2010). More important, explicit instructions did not result in performance above chance level in a final memory test. Therefore, contextual cueing is considered to derive from implicit learning and mostly implicit memory representations.

Due to its prevalently implicit nature contextual learning might be characterised by both specific advantages and disadvantages in comparison to explicit learning tasks. On the one hand, implicit memory is described as very robust, reliable and long-lasting (Chun, 2000; Chun & Jiang, 2003; Seger, 1994). On the other hand, this robustness might restrain the flexibility of implicit learning severely (Chun & Jiang, 2003; Cleeremans et al., 1998). Consequently, observers might have difficulties to adapt memory representations to deviations from initial experiences in currently presented spatial layouts.

Adaptation to Change in Context-Guided Visual Search

Despite high degrees of stability in the visual world, changes are likely to occur at any time. Are observers still capable to apply memory representations when spatial contexts vary from past exposures? If observers represent contextual cues as instances, they should mostly contain the information that was necessary to perform the task (Logan, 1988, 2002). Specifically, instances in contextual cueing should mainly represent spatial relations between nontarget and target locations (Chun & Jiang, 1998). Hence, successfully matching an incoming context with an existing instance should primarily depend on stable spatial relations. Other variations should barely affect contextual cueing, meaning that contextual cueing should be fairly adaptive and flexible. Chun and Jiang (1998) already reported support for this claim by showing that variations in surface features of search items did not reduce contextual-cueing effects (see also Endo & Takeda, 2004; Olson & Chun, 2002). Similarly, changes in background colour of search displays did not affect contextual cueing (Ehinger & Brockmole, 2008; see also Brooks et al., 2010).

Even spatial variations will not decrease contextual cueing, if they only concern the absolute spatial arrangement of contexts, but not the relative positions in the context-target layout. For example, contextual cueing was observed when search items randomly jittered from one trial to the next within a limited range (Chun & Jiang, 1998, Experiment 6). Similarly, contextual cueing continued when contexts were resized and rescaled (Jiang & Wagner, 2004). More precisely, old contexts were repeatedly presented in a first phase to establish contextual cueing. Then, the same contexts were presented as displaced (relative to the display centre) or rescaled (expanded or contracted). Because relative positions were unaffected by this manipulation, contextual cueing was still observed after the changes.

The same study (Jiang & Wagner, 2004) additionally revealed that episodic instances can even be matched with old contexts, when parts of different old contexts are recombined to form a globally novel context. In the first part of the experiment, pairs of old contexts shared the same target location. In the second part of the experiment, half of one of these old contexts was combined with half of the other paired old context; recombined old contexts were presented with the shared target locations. Even though the global configuration of old contexts had changed, recombined contexts still elicited contextual-cueing effects (see also Jiang & Song, 2005; Ogawa & Kumada, 2008). This result suggests that instances in contextual cueing represent individual nontarget locations and each one's relative position to a target location.

If instances represent individual nontarget locations, rather than the global configuration, partial matches between an incoming display and an instance should also result in contextual cueing. Indeed, contextual cueing was reported for old contexts that only contained the target location and two nontargets (amongst nine new nontargets) from initially presented configurations (Song & Jiang, 2005). Although contextual cueing is supposed to proceed from a global to a local level of context (Chun & Jiang, 1998), this study implied that a continuously invariant global context is not necessary for sustained contextual cueing (once memory traces exist; see also Jiang & Wagner, 2004). A rather small number of consistent spatial relations with nontargets suffice to cue target locations (see above Castelhano & Heaven, 2011; Hoffmann & Sebald, 2005; Peterson & Kramer, 2001b).

Nevertheless, the adaptive properties of contextual cueing are limited. As already mentioned, variations in relative spatial relations should have negative consequences on contextual-cueing effects, as the process of episodic retrieval relies on relative positional stability in old contexts. For example, contextual cueing was reported to depend on the relative position of invariant context in the global layout of the search display (Endo & Takeda, 2005). Invariant contexts were presented in one half of displays together with randomly arranged nontargets (noise) in the other half of the same displays. Contextual cueing was sustained when context and noise remained in their relative position in the overall arrangement of the display. However, contextual cueing ceased when context and noise exchanged positions in the display. A similar reduction of contextual cueing was observed when the presentation of learned contexts deviated from observers' original viewpoint (Chua & Chun, 2003). In this study, contexts were presented with depth information (in 3D) in an initial learning phase. Subsequent search trials were performed in the same contexts, but they were increasingly rotated in relation to observers' original viewpoint (i.e., by 0^o, 15^o, 30^o, & 45^o). As a consequence, contextual cueing was reduced the more a rotated presentation deviated from the original viewpoint. Thus, the distortion of relative spatial information weakens contextual-cueing effects significantly (see also Kawahara, 2003; and Tsuchiai, Matsumiya, Kuriki, & Shioiri, 2012, for similar findings with 3D displays).

Adaptation of Context-Guided Visual Search to Multiple Target Locations

The necessity of maintaining relative spatial positions in invariant contexts should become particularly obvious when changes in target locations occur, since nontargets are specifically represented in relation to respective target locations (Chun & Jiang, 1998; Jiang & Wagner, 2004). Indeed, a change in target locations results in the impairment of contextual cueing (Conci, Sun, & Müller, 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). In the study by Manignelli and Pollmann (2009), contexts were presented with fixed initial target locations in the first phase of the experiment. Then, targets were relocated to new positions within their contexts, where they stayed for all subsequent presentations (see Figure 3). Upon the sudden relocation, search in old contexts became as slow as search in new contexts (see also Chun & Jiang, 1998, last part of Experiment 6). In addition, eye movements showed a bias towards initial target locations, which implies that contextual memory continued to guide attention to initial target locations. However, eye movements started to shift more directly to relocated targets in old contexts by the end of the experiment, but this trend towards relearning of target locations was not reflected by an actual benefit in search times.

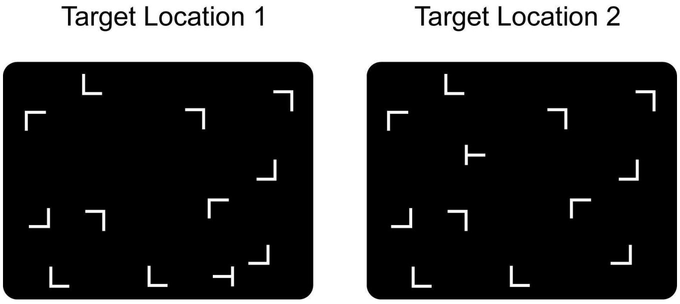

Figure 3: Example display of an old context paired with two different target locations (left and right panel).

Because target objects are always likely to change location in the real-world, observers should be able to update memory representations to include relocated targets. Otherwise search would be continuously (mis-)guided to target locations that are no longer associated with invariant contexts — despite predictive contextual cues search would be inefficient. The present studies investigated whether observers are capable to flexibly adapt existing memory representations of spatial context-target layouts to changes in target locations.

Chun and Jiang (1998, Experiment 6) already reported results in support of adaptation to two target locations. Two different target locations were presented equally often within one context in alternating order across trials (see Figure 3), meaning that each target location appeared in separate trials. In contrast to the design used by Manginelli and Pollmann (2009), who presented target locations sequentially, old contexts were associated with two different target locations throughout the whole experiment. The results revealed reliable contextual cueing for contexts presented with two target locations (*multiple-target learning*), although the overall effect for these contexts seemed diminished in comparison to experiments presenting targets at only one location. But the authors argued that contextual cueing of two target locations should become as strong as for one target location, if the amount of training is increased.

Indeed, several studies suggest that the development of strong contextual-cueing effects mostly depends on the number of repeated encounters with invariant contexts

(Brady & Chun, 2007; Mednick, Makovski, Cai, & Jiang, 2009; Tseng, Hsu, Tzeng, Hung, & Juan, 2011). Based on this view, repeated search for two target locations should result in multiple-target learning. Brady and Chun (2007) supported this claim based on computational modelling of contextual cueing. The proposed model assigns ranked weights to items in spatial configurations. Subsequently, the model "looks" for the target at the position with the highest weight of all positions in the configurations. Once the target location is detected, weights are further adjusted: Due to the repetition of target locations in both old and new contexts, targets are weighted heavier than nontargets. Furthermore, target locations of old contexts receive the strongest weights to represent the highest activations (see also Geyer, Zehetleitner et al., 2010). Nontargets in old contexts receive decreasing weights with increasing distance from the target location. That is, nontargets in proximity of the target location are weighted heavier than peripheral nontargets, which means, that local nontargets (local from the position of the target) exert more influence on the deployment of attention than nontargets in relatively greater distances (see also Ogawa & Watanabe, 2010; Peterson & Kramer, 2001a). In turn, variations in distant nontargets barely affect contextual cueing as long as the local context remains intact (Brady & Chun, 2007).

The authors (Brady & Chun, 2007) also modelled contextual cueing for contexts presented with two different target locations. Because the model intrinsically assumes that repeated search is the most important premise for strong contextual-cueing effects, it produced reliable contextual-cueing effects for contexts paired with two target locations. At the same time, contexts paired with two target locations elicited smaller contextual-cueing effects (on average) than contexts paired with one target location (similar to results of Chun & Jiang, 1998). The reduction of contextual cueing was supposed to result from increased inspection times. More precisely, when observers associate one old context with two different target locations, the old context cues both locations, and both locations can be inspected on any presentation (i.e., two peaks of activation in search display). Consequently, search times in old contexts increase, which decreases the difference to search times in new contexts reducing contextual-cueing effects. Thus, according to Brady and Chun (2007), two target locations are equally associated with one context, but due to competition effects contextual cueing of both target locations is reduced in comparison to contextual cueing of only one target location.

The Present Studies

Repeated visual search in invariant spatial contexts results in the acquisition of memory representations that guide visuo-spatial attention efficiently to target locations on subsequent encounters (Chun & Jiang, 1998). Thus, context-guided visual search develops through repeated experience, and its behavioural effect is based on the guidance of attention by memory representations. Observers acquire episodic instances (Chun & Jiang, 1998) that seem to represent individual item locations of learned contexts, while nontarget locations are necessarily encoded in spatial relation to the associated target locations (Brady & Chun, 2007; Jiang & Wagner, 2004). Therefore, the continuous occurrence of contextual cueing depends, to a large extent, on the stability of spatial context-target relations. However, positional changes are likely to occur even in rather stable visual contexts. Hence, the memory representations underlying contextual cueing should be adapted to changes in context-target relations.

The current line of research examined adaptive properties of memory representations in contextual cueing in particular ─ while the present predictions and findings are also related to implicit statistical learning in general. More precisely, the experiments of the present studies investigated observers' capability to associate an invariant context with more than one target location. As discussed above, a few studies have suggested that observers can associate at least two recurring target locations with one invariant context (Brady & Chun, 2007; Chun & Jiang, 1998). Also, observers might be able to adapt context-target representations to a permanent change in target locations, which requires relearning new target locations in otherwise invariant contexts (Manginelli & Pollmann, 2009). Here, four studies were conducted to expand on these suggestive findings to uncover whether and how adaptation to multiple target locations occurs when observers implicitly learn spatial context-target configurations.

Study I

The first series of experiments (Experiments 1–3) was conducted to test whether contextual cues can guide visual attention efficiently to two different target locations as suggested by Chun and Jiang (1998; see also Brady & Chun, 2007). The authors reported successful contextual cueing for contexts presented with two different target locations on separate trials, and they concluded that observers associate two target locations with one invariant context (*multiple-target learning*). Because the observed cueing effects were reduced in comparison to contexts with one target location, Brady and Chun (2007) later suggested that the inspection of both locations increases search times, which reduces contextual cueing. However, both studies did not actually analyse contextual cueing of each target location separately. Instead, contextual cueing was averaged across both locations to represent the mean contextual-cueing effect of a particular old context. Hence, it can still be hypothesised that contextual cueing only includes one of two target locations (*single-target learning*). If one target location elicits a positive contextual-cueing effect and the other target location shows no or even negative contextual cueing, averaging across these cueing effects would also result in an overall reduced contextual-cueing effect for the respective old context.

To test this alternative explanation, contexts were presented with different numbers of target locations, whose contextual-cueing effects were analysed separately. Experiment 1 and Experiment 2 replicated previous findings (Chun & Jiang, 1998), confirming that the presentation of two different target locations within one old context results in successful contextual cueing that is, however, significantly reduced in comparison to contexts with one target location (Experiment 2). The separate analysis of each target location revealed that one of two target locations elicited contextual cueing (dominant target location), whereas the other target location mostly showed contextual costs (minor target location). That means search for minor target locations was mostly slower than search for target locations in new contexts. Only minor target locations presented in the proximity of dominant target locations showed contextual cueing ─ a halo-effect of contextual cueing of dominant target locations. The same pattern of results was observed when contexts were presented with three alternating target locations in Experiment 3. In sum, the results of the first study suggest that contextual cueing is fairly inflexible because it was restricted to a single target area (Zellin, Conci, von Mühlenen, & Müller, 2011; see Appendix).

Study II

In a further study (Experiments 4–7), we investigated whether contextual cueing would also be restricted to single-target learning when two target locations are presented sequentially (see Manginelli & Pollmann, 2009), instead of alternating presentations (Study I). Specifically, after repeated presentations of initial target locations, targets were relocated within their old contexts and repeatedly presented at new locations, such that old contexts became reliable cues for relocated targets (without potentially interfering presentations of a further target location). Observers were trained with relocated targets under different conditions that are known to facilitate learning processes (Experiment 4A, 4B, & 6). Furthermore, the stability of initially learned associations was tested by a final presentation of initial target locations in two of the experiments (Experiment 4A & 6). Despite improved training conditions, contextual cueing was not observed for relocated targets (Manginelli & Pollmann, 2009); that is, established contextual associations were not adapted to changed requirements. The final presentation of initial target locations revealed that initially learned target locations continued to elicit contextual-cueing effects after prolonged presentations of relocated targets.

Because the lack of contextual cueing of relocated targets could imply that observers have general difficulties to learn new associations successively in contextual cueing, a further series of experiments specifically tested successive new-learning under the same training conditions as used before (Experiments 5A, 5B, & 7). When two different sets of old and new contexts were presented in sequential order, contextual cueing slowly (but successfully) developed for the second set of contexts, while contextual cueing for the first set of contexts was retained across new-learning (Mednick et al., 2009). Hence, observers were not generally restricted in establishing new associations; instead, adaptation to relocated targets was restricted by single-target learning.

Study III

The third study (Experiment 8) expanded on findings from Study II by investigating whether observers would show contextual cueing for relocated targets at new positions after more extensive training (4 days). Additionally, contextual cueing of both initial and relocated targets was tested one week after the last training session of the relocation phase. After target relocation, contextual cueing was impaired, but slowly started to recover on the third day of training and became stable on the following, the last, day of training. Nonetheless, contextual cueing of relocated targets was still significantly smaller than contextual cueing of initial target locations. Only a week later, when both target locations were presented (on separate trials), was similarly effective contextual cueing observed for both target locations (multiple-target learning). The results of this last testing session also indicated, that once two target locations were associated with one context, contextual cueing of both of them proceeded rather competition-free, meaning that contextual cueing was not reduced in comparison to single-target learning (as proposed by Brady & Chun, 2007). Overall, the third study revealed that adaptive processes are successful in implicit contextual learning, but they depend on rather time-consuming training and, possibly, on periods of memory consolidation.

Study IV

In the second and third study, target relocations occurred rather abruptly and introduced completely new and unfamiliar target locations, which could impede adaptation. Therefore, Experiments 9 and 10 were designed to examine whether contextual learning of relocated targets benefits from the use of familiar, predictable target locations (Conci et al., 2011). Instead of relocating targets to new positions within contexts, targets were relocated to positions that were previously associated with another context and familiar through probability learning (Jiang et al., 2012). In other words, target locations were exchanged between contexts after an initial learning phase. Targets were exchanged between either old contexts (Experiment 9), or between old and new contexts (Experiment 10). After several repetitions of exchanged target locations, targets were returned to initial locations within their contexts.

When target locations were exchanged between old contexts, reliable contextual cueing was observed for both initial and exchanged target locations. Hence, multiple-target learning seems possible when relocated targets are already familiar from previous encounters. By contrast, the exchange between old and new contexts resulted in strong contextual costs. Even though target locations of new contexts were familiar from the initial learning phase, they impaired visual search when presented in old contexts. At the same time, visual search in new contexts was facilitated by the presentation of target locations of old contexts. Furthermore, contextual cueing of initial target locations was retained across exchange phases in both experiments.

The results of Study IV suggest that observers represent statistical information that goes beyond location probabilities and spatial relations between contexts and target locations: Observers also encode the contextual past of target locations (cued or uncued), resulting in expectations that modulate subsequent contextual learning.

STUDY I

Context-Guided Visual Search for Multiple Target Locations

Abstract

Visual search for a target object is facilitated when it is repeatedly presented within an invariant context of surrounding nontargets (contextual cueing). The current study investigated whether such invariant contexts can cue more than one target location. In a series of three experiments, we show that contextual cueing is significantly reduced when invariant contexts are paired with two rather than one possible target location, whereas no contextual cueing occurs with three distinct target locations. Closer data inspection revealed that one “dominant” target location always exhibited substantially more contextual cueing than the other “minor” target locations, which caused negative contextual-cueing effects. However, visual search for minor target locations could benefit from invariant contexts when they appeared in proximity to dominant target locations. In sum, our experiments suggest that contextual cueing can guide visual attention to a spatially limited region of the display, only enhancing the detection of targets presented inside that region.

Introduction

Visual scenes typically contain multiple objects of varying complexity that need to be processed selectively in order to achieve behavioural goals. When searching for a specific target object in a given scene, visual selection can be supported by a variety of cues directing attention to relevant, and away from irrelevant, parts of a scene. Thus, for example, search may be guided bottom-up by visual cues that attract attention on the basis of perceptual salience, as well as top-down by a working memory “template” specifying features of the searched-for target (Wolfe & Horowitz, 2004, for review). In addition, visual selection may be supported by learned contingencies within a given environment. Real-world scenes usually consist of a relatively stable collection of co-occurring objects, permitting search for one object to be facilitated via its associations with other objects (Oliva & Torralba, 2007, for review). For example, visual search for a toaster might be quicker when it is presented in a kitchen rather than a garage scene. In general, context information can offer valuable cues to the location of a target object (Bar, 2004, for review; Biederman et al., 1982; Hollingworth, 2006).

The role of such invariant context information on attentional guidance has also been investigated in a number of studies under controlled laboratory conditions (Chun, 2000, for review). Chun and Jiang (1998) reported that implicit memory for spatial context facilitates visual search by guiding attention more efficiently (or directly) towards the target location (contextual cueing). Such a mechanism should also be flexible and adaptive to compensate for variability and possible changes that can occur in the environment. Flexibility could, for instance, mean that one invariant context is associated with multiple target locations. In natural environments, such as a kitchen, visual search might benefit from the stable kitchen layout when it comes to finding a pan located either on the stove or on the table.

Thus far, studies that investigated the adaptivity of contextual cueing to multiple target locations have yielded ambiguous results. Partial support for an adaptive nature of contextual cueing was already provided by Chun and Jiang (1998). In a variant of the contextual cueing paradigm, a given search display was repeatedly presented with two distinct target locations. Thus, on some trials, the invariant context was presented with one target location, whereas on other trials it was presented with a second target location (see left and right panels in Figure 5 for an example.). The results of this experiment showed a somewhat reduced, but nevertheless reliable contextual-cueing effect for contexts with two target locations (see also Conci et al., 2011 for comparable results with simultaneously presented targets). By contrast, invariant contexts paired with three or four repeated target locations were reported not to elicit contextual cueing (Kunar, Michod, & Wolfe, 2005; Wolfe et al., 2000). Other studies revealed that sudden (unpredictable) changes of the target location disrupted contextual cueing (Chun & Jiang, 1998; Conci et al., 2011; Fiske & Sanocki, 2010; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). More specifically, when a target that was learned in an invariant context was suddenly moved to a new, previously empty location, contextual cueing was impaired and did not recover with the repeated presentation of the new target location (Manginelli & Pollmann, 2009). Recently, Makovski and Jiang (2010) further qualified this lack of adaptivity by showing that contextual cueing was transferred to a new target located in close proximity to the original target location. Thus, adaptation of contextual cueing to change seems to occur only within a fairly limited spatial range.

In sum, although some studies reported evidence for adaptation to multiple target locations in contextual cueing (Chun & Jiang, 1998; Conci et al., 2011; Kunar et al., 2005), others clearly failed to provide evidence of flexible compensation for environmental changes (Chun & Jiang, 1998; Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009), or they reported adaptation to occur only within a limited spatial region (Chua & Chun, 2003; Makovski & Jiang, 2010).

The current study was designed to reconcile the contradictory findings on contextual cueing of multiple target locations, and to distinguish between possible alternatives of explaining how contextual cueing is modified by multiple target locations. On the one hand, according to Brady and Chun’s (2007) computational model of contextual cueing, multiple target locations can be (learned to be) associated with one invariant context; that is, contextual learning is adaptive. In this view, the overall reduced magnitude of the contextual-cueing effect (Chun & Jiang, 1998; Kunar et al., 2005) simply results from the number of potential target locations that have to be inspected (multiple-target learning; see right panel in Figure 4). On the other hand, the clear lack of adaptation in other recent studies (Conci et al., 2011; Fiske & Sanocki, 2010; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009) suggests that contextual cueing is restricted to a single target location within an old context and its narrow surround. That is, just one of two (or more) target locations may be reliably cued by an invariant context (single-target learning). If only one target location benefits from contextual cueing, averaging across a cued and an uncued target location (when the invariant context is paired with two target locations) would result in an overall reduced contextual-cueing effect (see left panel in Figure 4). And adding a third (or fourth etc.) repeated target location would further reduce the overall contextual-cueing effect, because averaging would happen across one cued and two (or three, etc.) uncued target locations.

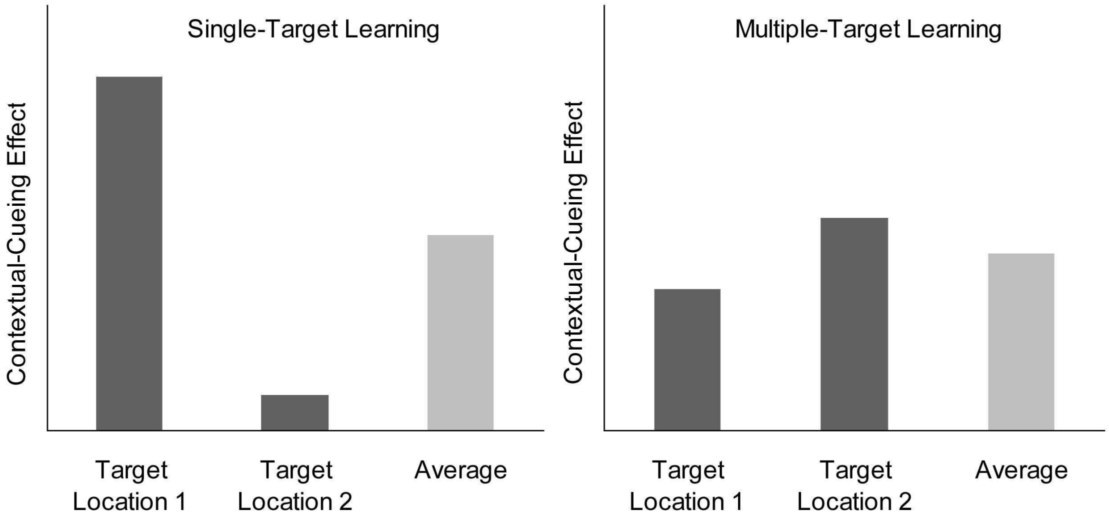

Figure 4: Schematic illustration of expected patterns of results according to the assumption of single-target learning (left panel), and multiple-target learning (right panel).

To determine the degree of adaptivity in contextual learning, three contextual-cueing experiments with multiple target locations were conducted. Contextual-cueing effects were observed with two target locations (Experiments 1 & 2), but the effect was significantly reduced when directly compared to displays with one target location (Experiment 2). Moreover, no contextual-cueing effect was observed for displays that were paired with three possible target locations (Experiment 3). Although this overall pattern of results replicated previous studies (see above), additional post hoc analyses of all three experiments confirmed that one (dominant) target location consistently showed significantly more contextual cueing than the other (minor) locations. Furthermore, proximity between target locations enabled contextual cueing of two or even all three target locations. Taken together, these findings show that contextual cueing does not integrate multiple target locations; successful predictive associations between an invariant context and a target location are, in fact, limited to only one target location and its immediate surround.

Experiment 1

Experiment 1 was designed to replicate the results of Chun and Jiang (1998), who reported that contextual cueing occurred for invariant contexts paired with two possible target locations. Each search display was paired with two distinct target locations (see Figure 5). To ensure that both target locations could be associated equally well with the invariant context, the two target locations were presented in separate, alternating blocks of trials. This variation was used to avoid primacy of one target over the other owing to the order of presentation. If contextual cueing includes two different target locations, a facilitative effect should occur for old contexts with two target locations.

Method

Subjects

Sixteen adults took part in the experiment (10 women; $M_{\text{age}} = 26$ years; age range: 22–49 years). All subjects had normal or corrected-to-normal visual acuity, and all but one was right-handed. They received either payment (8 €) or one course credit.

Apparatus and Stimuli

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

Figure 5. Observers were seated in a dimly lit room with an unrestrained viewing distance of approximately 57 cm from the computer screen.

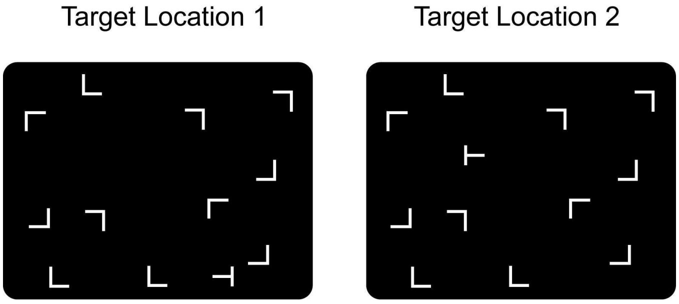

Figure 5: Example search display of an old context paired with two different target locations (left and right panel) in Experiment 1.

Trial Sequence

At the beginning of each trial, a fixation cross was presented for 500 ms at the centre of the screen. Then, a search display appeared and remained visible until observers made a speeded response by pressing one of two mouse buttons (with the left- and right-hand index finger, respectively). Observers were instructed to search for the target ‘T’, and to decide as quickly and accurately as possible whether the stem of the ‘T’ was pointing to the left or the right. In case of a response error, a minus sign appeared on the screen for 1000 ms. An inter-stimulus interval of 1000 ms separated one trial from the next.

Design and Procedure

Experiment 1 implemented a 2 x 8 repeated-measures design, with the (within-subject) factors Context (old, new) and Epoch (1–8). With respect to ‘context’, for old contexts, a set of 12 displays was separately generated for each subject and repeated throughout the experiment (with an invariant arrangement of nontarget items on every presentation). For new contexts, the configuration of nontarget items was generated randomly on each trial. Each display was paired with two target locations. In order to rule out location probability effects, different sets of target locations were selected for old and new contexts, such that, overall, 48 possible target locations were assigned to the displays.

The orientation of the target was random on each trial, whereas the orientations and the jitter levels of the nontargets were held constant for old contexts. Figure 5 depicts an example search display with an invariant configuration of nontargets paired with two different target locations (left and right panels). The second factor ‘Epoch’ divided the experiment into eight equally sized consecutive bins (each bin consisted of 120 trials), which permitted the examination of possible learning effects over the course of the experiment by using aggregated, more robust values.

The experiment started with a practice block of 24 randomly generated displays to familiarise observers with the task. All subsequent experimental blocks (40) consisted of 24 trials, 12 with old- and 12 with new-context displays, presented in random order. The two possible target locations for each (old and new) display were always presented in alternating order (i.e., one of the two possible target locations was presented in all odd blocks, the other target location was presented in all even blocks), such that each target location was presented 20 times. After each block, subjects took a short break and continued with the experiment at their own pace. Overall, observers completed 984 trials.

Recognition Test

After the last search trial, an instruction was presented on the screen informing subjects about the repetition of some of the search displays throughout the experiment. Subjects started the presentation of another 24 trials and decided via mouse button responses whether a particular display had been shown previously (= old) or not (= new). All displays were presented with target locations corresponding only to the odd blocks (i.e., with targets presented in block 1), as the explicit recognition of a given repeated context would not depend on the location of the target, but rather on the arrangement of nontargets. The response was non-speeded and no error feedback was given.

Results

Search Task

Individual mean error rates were calculated for each variable combination. The overall error rate was low (2.9%), and a repeated-measures analysis of variance (ANOVA) with the factors Context (old, new) and Epoch (1–8) revealed no significant effects (*p*s > .1).

Next, individual mean RTs were calculated for old and new contexts, separately for each epoch. Figure 6 shows mean RTs for old and new contexts as a function of epoch. Error trials and RTs exceeding an individual's mean RT by ± 2.5 standard deviations were excluded from the analysis. This outlier criterion led to the removal of 2.3% of the data; the same outlier procedure was applied in all subsequent experiments, resulting in comparable exclusion rates. Greenhouse-Geisser corrected values are reported in case Mauchley's test of sphericity was significant (*p* < .05).

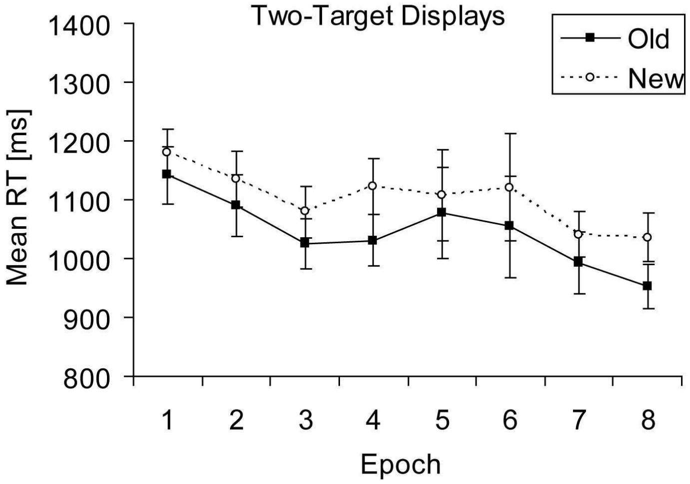

Figure 6: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 1.

A repeated-measures ANOVA with the factors Context (old, new) and Epoch (1–8) yielded a significant main effect of context, *F*(1, 15) = 10.36, *p* < .01, and a marginally significant main effect of epoch, *F*(1.34, 20.13) = 3.27, *p* = .075. RTs were on average 57 ms faster for old than for new contexts, and they decreased by about 166 ms from the first to the last epoch. The interaction between context and epoch was not significant, *F*(7, 105) = 1.31, *p* > .2. When target location (target location in odd blocks, target location in even blocks) was entered as a third factor into the analysis, the Context x Target location interaction did not reach significance, either (*p* > .3; all other effects were as described above); that is, the magnitude of contextual cueing of two target locations was not systematically influenced by the order of presentation (similar results were obtained in Experiment 2). An additional analysis performed on individual blocks (rather than epochs) revealed the first significant difference between old and new contexts to occur in block 5, *t*(15) = -2.86, *p* = .01, which is comparable to findings of fast contextual learning in previous studies (e.g., Conci & von Mühlenen, 2009) and to all subsequent experiments reported here.

Recognition Test

Overall, old and new contexts were classified as old and new in 51% of all trials. Observers correctly identified old contexts in 45.8% of trials (hit rate), and their false-alarm rate of reporting new contexts as old (46.9%) was comparable to the hit rate, *t*(15) = -0.21, *p* = .84. This suggests that observers were unaware of the repeated contexts during the experiment.

Discussion

The results of Experiment 1 replicated previous findings of Chun and Jiang (1998), showing that contextual cueing can occur for old contexts paired with two distinct target locations. Targets in old-context displays were detected 57 ms faster than targets in new-context displays. Moreover, the scores of the recognition test suggested that observers learned associations between invariant contexts and target locations implicitly.

In comparison to Chun and Jiang (1998), who reported only a marginally significant contextual-cueing effect of 35 ms for two target locations, the 57 ms effect observed here was more robust and statistically reliable. This may suggest that both the alternating order of target location presentation ─ which would facilitate associating both target locations equally well with an old context ─ and the larger number of trials contributed to the formation of stronger context-target associations. However, contextual cueing of two-target displays was still substantially reduced as compared to similar experiments with only one target location for each display (e.g., Conci & von Mühlenen, 2009, reported contextual-cueing effects larger than 200 ms). This overall reduction in the magnitude of contextual cueing could be the result of multiple-target learning (as suggested by Brady & Chun, 2007). Alternatively, observers may learn only one of two target locations effectively (single-target learning), in which case contextual cueing would be reduced because positive contextual-cueing effects (for one location) would be averaged with near-zero effects (for the other location).

Experiment 2

In order to examine the effectiveness of contextual cueing for displays with different numbers of target locations, Experiment 2 implemented a within-subject design to enable a direct comparison of contextual cueing between one-target displays (baseline) and two-target displays (see left and right panel in Figure 7). Half of the search displays were paired with one target location and the other half with two target locations. On the basis of Experiment 1 and previous findings (Chun and Jiang, 1998), we expected to find a reduction of contextual cueing when two target locations, rather than one target location, were paired with a given contextual layout.

Method

Apparatus, stimuli, design, and procedure were similar to Experiment 1, except that half of the old and new displays were paired with one target location (baseline) and the other half with two target locations (see Figure 7). Overall, 36 target locations were used in Experiment 2. One-target and two-target displays were randomly intermixed within blocks (40 in total). Again, two-target displays contained one of two possible target locations in alternating order across blocks; that is, each of the two target locations was shown 20 times.

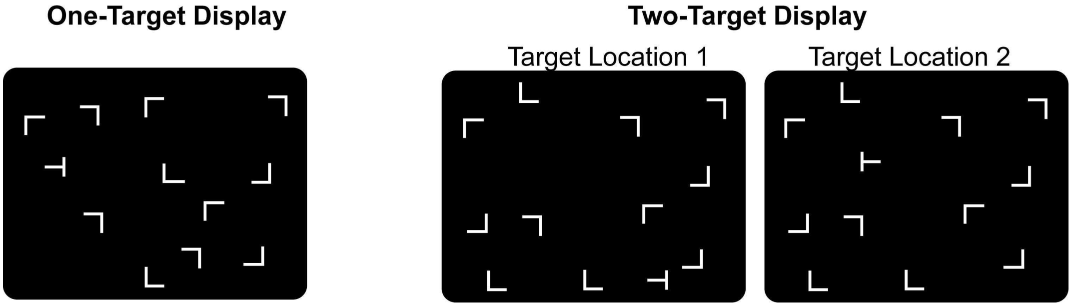

Figure 7: Example search displays of old contexts paired with one target location (left panel), and paired with two different target locations (right panel) in Experiment 2.

Twenty-one adults took part in the experiment (15 women; $M_{\text{age}} = 26.9$ years; age range: 19–50 years). All subjects had normal-or-corrected to normal visual acuity and were right-handed. They received either payment (8 €) or one course credit.

Results

Search Task

The overall error rate was relatively low (2.1%), and a repeated-measures ANOVA with the factors Context (old, new), Targets (one, two), and Epoch (1–8) only revealed a significant interaction between targets and epoch, $F(3.72, 74.39) = 3.42$, $p < .05$. Errors increased slightly from epoch 1 (2.3%) to epoch 8 (2.7%) for one-target displays, as compared to a slight decrease in errors (from 2% to 1.5%) for two-target displays.

Individual mean RTs were calculated for each variable combination excluding error trials and outliers. Figure 8 shows mean RTs for old and new contexts as a function of epoch, separately for displays paired with one (left panel) and two (right panel) target locations. A repeated-measures ANOVA with the factors Context (old, new), Targets (one, two), and Epoch (1–8) revealed significant main effects of context, $F(1, 20) = 14.05$, $p < .01$, and of epoch, $F(3.44, 68,75) = 18.48$, $p < .001$. RTs were on average 67 ms faster for old relative to new contexts, and they decreased by 169 ms from the first to the last epoch. More important, the interaction between context and targets was also significant, $F(1, 20) = 6.19$, $p < .05$, due to larger contextual-cueing effects for one-target displays (101 ms) as compared to two-target displays (33 ms). As illustrated in Figure 8 (right panel), contextual cueing of two-target displays only emerged from epoch 3 onwards, reaching comparable sizes to Experiment 1 in the last two epochs (57 ms and 55 ms), $t(20) = -2.22$, $p = .04$, and $t(20) = -1.93$, $p = .07$, respectively.

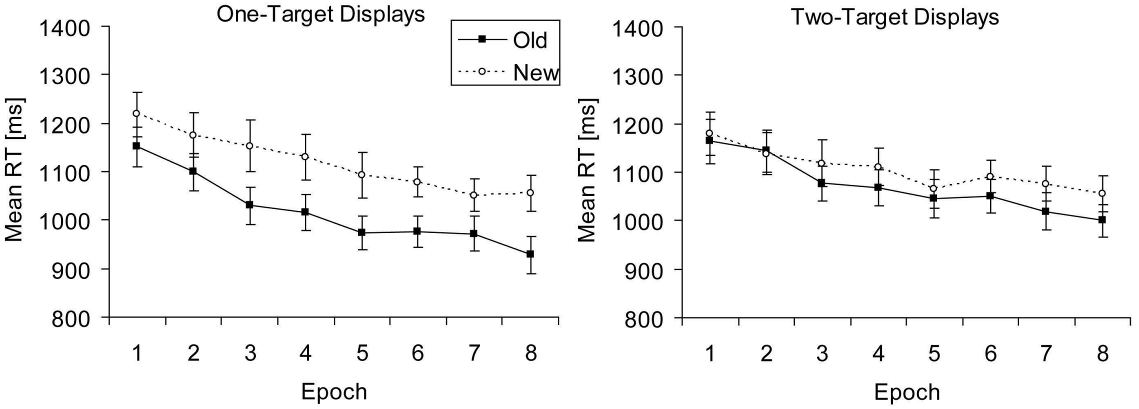

Figure 8: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 2, for displays paired with one (left panel) and displays paired with two target locations (right panel).

Recognition Test

Overall accuracy of recognising old and new contexts was 45.2%. For one-target displays, observers correctly identified old contexts on 56.4% of trials (hit rate), but this did not differ from the false alarm rate of 49.6%, $t(20) = 1.21$, $p = .24$. Similarly, the numbers of hits (57.9%) and false alarms (49.6%) were statistically comparable for two-target displays, $t(20) = 1.84$, $p = .08$, suggesting that observers were mostly unable to explicitly discern between old and new contexts.

Analysis by Separate Target Locations

The results of both Experiments 1 and 2 revealed a contextual-cueing effect for displays with two target locations that was considerably reduced relative to the baseline condition with one target location. To examine whether this reduction was due to learning of only one of two target locations, the data of all two-target displays from Experiments 1 and 2 were collapsed. For each observer, the mean contextual-cueing effect was computed separately for each display and each target location. Subsequently, for each display, the target location with a relatively larger contextual-cueing effect was assigned to a "dominant target" category, while the target location with the smaller contextual-cueing effect was assigned to a "minor target" category. As illustrated in Figure 9, the averaged contextual-cueing effect for dominant target locations (204 ms) was positive and large, whereas it was negative for minor locations (-124 ms), *t*(36) = 18.16, *p* = .00. Contextual cueing of both dominant and minor target locations differed reliably from zero, as revealed by one-sample t-tests, *t*(36) = 11.14, *p* = .00 and *t*(36) = -8.09, *p* = .00, respectively. This pattern of positive and negative cueing effects indicates that only one of two target locations was effectively cued by a repeated context, whereas there were significant costs for the other location.

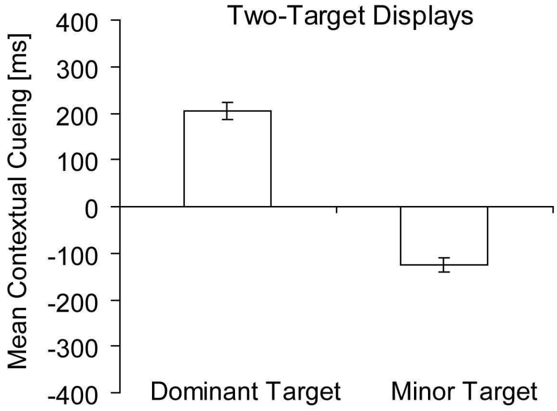

Figure 9: Mean contextual cueing (in ms, and associated standard errors) for dominant and minor target locations of two-target displays (collapsed data for all two-target displays from Experiments 1 and 2).

In order to demonstrate that the difference in contextual cueing between dominant and minor target locations was not simply an artefact of our sorting procedure, one-target displays (baseline) were also examined for equivalent effects (Experiment 2 only). This was done by applying an analogous sorting procedure as with two-target displays: For each observer, pairs of one-target (baseline) displays were randomly selected (which can be considered equivalent to random pairings of target locations for two-target displays), and for each pair, displays that generated a larger and a smaller contextual-cueing effect were assigned to a dominant and a minor category, respectively, identical to the procedure described above. The resulting mean dominant contextual-cueing effect was large and positive (251 ms), and the mean minor effect negative (-49 ms), *t*(20) = 12.56, *p* = .00; note, though, that only the dominant effect differed significantly from zero, *t*(20) = 9.25, *p* = .00; minor effect, *t*(20) = -1.85, *p* = .08. In a subsequent step, dominant and minor contextual cueing in the baseline condition (one-target displays) were compared with contextual cueing of dominant and minor target locations in two-target displays (Experiment 2 only). The results revealed dominant contextual-cueing effects to be comparable between one- and two-target displays (251 ms vs. 205 ms), *t*(20) = 1.30, *p* = .28. By contrast, the cueing effect for minor target locations in two-target displays was significantly smaller compared to minor effects in the baseline (-139 ms vs. -49 ms), *t*(20) = 3.02, *p* = .01 ― indicating considerable costs, of 90 ms, for minor target locations in two-target displays relative to the baseline condition. Thus, while dominant contextual cueing was comparable between both types of displays, there were pronounced contextual costs for minor target locations in two-target displays.

Between-Target Distance Analysis

Additional analyses for all two-target displays were performed on the combined data from Experiments 1 and 2, in order to examine the influence of spatial distance between dominant and minor target locations (range: 2.5°–20.2° of visual angle) on contextual cueing of the latter location. First, a correlation analysis revealed contextual cueing of minor target locations to decrease with increasing distance from dominant target locations, *r* = -.318, *p* = .00. In a further step, we examined whether spatial distance between two locations facilitated positive contextual cueing of one target location or of both target locations. Displays were sorted according to whether there was a positive (i.e., above zero) contextual-cueing effect for both target locations (30.5%), or for only one target location (46.5%; or for none of the locations). Note that three observers had to be excluded from this analysis because they did not show contextual cueing for more than one target location. When both target locations were cued, the mean distance between them was significantly smaller than when only one location was cued, 7.4° and 9.7°, respectively, *t*(33) = 4.27, *p* = .00. This finding implies that smaller distances facilitated contextual cueing of two target locations more reliably than larger distances. Nevertheless, with two cued target locations, the dominant location exhibited more contextual cueing than the minor location, 362 ms and 172 ms, respectively, $t(33) = 10.33$, $p = .00$. It should be noted that the numerically large contextual-cueing effects obtained in this (and subsequent) analysis resulted from the procedure of selecting only relatively extreme cases with large contextual-cueing effects (while excluding smaller or negative values).

Discussion

In agreement with previous studies (e.g., Chun & Jiang, 1998), Experiment 2 demonstrated contextual-cueing effects for both one-target and two-target displays. But at the same time, contextual cueing was significantly reduced for two-target displays relative to one-target displays (33 ms vs. 101 ms), and this reduction resulted from contextual cueing of only one of two target locations.

According to Brady and Chun (2007), a reduction in contextual cueing of two-target displays originates from the increase in inspection times due to multiple-target learning. However, close scrutiny of the collapsed data from Experiments 1 and 2 supports an alternative explanation based on single-target learning. When displays were ranked according to the size of contextual cueing of each target location, only one (the dominant) target location showed strong contextual cueing comparable to learning effects for one-target displays. By contrast, the other (minor) target location was associated with contextual costs, and these costs significantly exceeded negative contextual-cueing effects in baseline displays. This pattern of results suggests that contextual cueing is much less flexible than proposed. Rather, a given invariant context can reliably cue search to only one repeated target location, but (mostly) fails to facilitate search for targets presented at a second repeated location (see also Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). The fact that minor target locations in two-target displays elicited larger contextual costs than any baseline displays indicates that the learned (dominant) target location misdirects spatial-attentional allocation to the dominant location when the target is actually presented at the other (minor) location.

In addition, contextual cueing decreased for minor target locations with increasing distance from the dominant target location, and reliable (i.e., above-zero) contextual-cueing effects for both target locations were only found when these were (relatively) close to each other (see also Brady & Chun, 2007; Makovski & Jiang, 2010). Nevertheless, even when both target locations were cued successfully, one dominant target location could still be identified as exhibiting more contextual cueing than the other (minor) location (362 ms vs. 172 ms). Taken together, this pattern of results demonstrates that contextual cueing is not adapted to multiple target locations, as it effectively facilitates guidance to only one target location (and its immediate surround).

Experiment 3

The results obtained thus far showed that contextual cueing was reduced for two-target relative to one-target displays because only one of two target locations was reliably cued. To examine whether single-target learning applies to multiple repeated target locations in general, in Experiment 3, half of the search displays were paired with three different target locations, and the other half with one (baseline; see right and left panel in Figure 10). We expected to observe contextual cueing of only one out of the three alternating target locations. If reliable contextual cueing occurs for only one out of three target locations, the averaged contextual-cueing benefit for three-target displays should be even more reduced than for two-target displays.

Methods

The methodological details were similar to Experiment 2, except that half of the old and new displays were paired with three distinct target locations and the other half with only one target location (Figure 10).

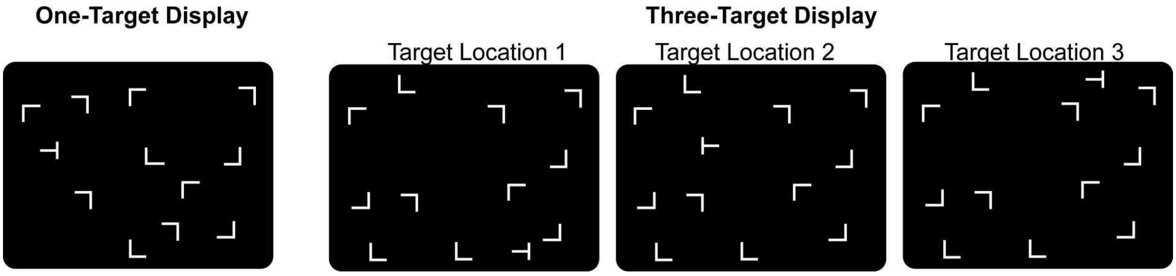

Figure 10: Example search displays of old contexts paired with one target location (left panel), and paired with three different target locations (right panel) in Experiment 3.

Overall, 48 possible target locations were used in Experiment 3. Three-target displays presented all possible target locations in a systematically alternating order across blocks; that is, within a sequence of three blocks the three target locations were presented in random order. Each target of the three-target displays was presented 14 times. In each block, one-target and three-target displays were presented in random order. Altogether, observers completed 42 experimental blocks of trials (1032 trials). Bins of six blocks were aggregated into seven epochs for analysis.

Twenty-two adults took part in the experiment (16 women; $M_{\text{age}} = 26$ years; age range: 18–34 years). All subjects reported normal-or-corrected to normal visual acuity and were right-handed. They received either payment (8 €) or one course credit.

Results

Search Task

The overall error rate was relatively low (2.4%), and a repeated-measures ANOVA with the factors Context (old, new) Targets (one, three) and Epoch (1–7) revealed no significant effects (ps > .3).

Individual mean RTs were calculated for each variable combination after exclusion of error trials and outliers. Figure 11 depicts mean RTs for old and new contexts as a function of epoch, separately for one-target (left panel) and three-target displays (right panel). A repeated-measures ANOVA with the factors Context (old, new), Targets (one, three), and Epoch (1–7) yielded significant main effects of context, $F(1, 21) = 4.57$, $p < .05$, of targets, $F(1, 21) = 16.35$, $p < .01$, and of epoch, $F(2.65, 55.63) = 14.29$, $p < .001$. RTs were faster for old- as compared to new-context displays (by 46 ms), and for one-target as compared to three-target displays (by 71 ms). The main effect of epoch was reflected by a decrease in RTs (160 ms) from the first to the last epoch. Furthermore, the Targets x Context interaction was significant, $F(1, 21) = 7.52$, $p < .05$, due to a strong contextual-cueing effect for one-target displays (95 ms), but not for three-target displays (-3 ms). The factors Context and Epoch also interacted significantly, $F(2.95, 61.93) = 3.64$, $p < .05$, with contextual-cueing effects increasing from -19 ms in epoch 1 to 63 ms in epoch 7. The interaction between targets and epoch was significant, $F(3.91, 82.03) = 3.11$, $p < .05$, with RTs decreasing more across epochs for one-target displays (by 195 ms) than for three-target displays (by 123 ms).

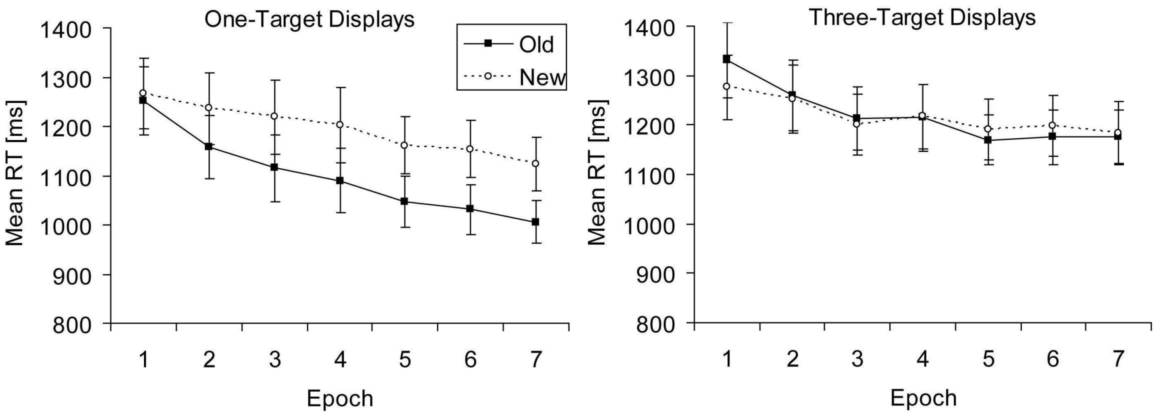

Figure 11: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 3, for displays paired with one target location (left panel) and displays paired with three target locations (right panel).

Recognition Test

Overall, the mean accuracy in the recognition test was 55.1%. For one-target displays, observers correctly identified old contexts on 60.6% of trials (hit rate), and this differed significantly from the false-alarm rate of 46.6%, $t(21) = 2.59$, $p = .02$, suggesting that observers were to some extent aware of the repeated contexts. For three-target displays, the rates of hits (53%) and false alarms (46.6%) were comparable and showed no evidence of explicit recognition, $t(21) = 1.06$, $p = .30$. To further qualify the explicit recognition performance in one-target displays, we examined whether observers' ability to recognise repeated layouts was related to the size of the contextual-cueing effect. Individual sensitivity scores *d'* [z(hits) - z(false alarms)] were computed as a measure of explicit recognition and correlated with the contextual-cueing effect for one-target displays. This analysis produced no evidence of a correlation, $r = -.03$, $p = .89$; that is, recognition performance was not systematically related to the size of contextual cueing for one-target displays (see also Shanks, 2010; Westerberg et al., 2011).

Analysis by Separate Target Locations

In a subsequent step, contextual cueing of all three-target displays was analysed separately for dominant target locations and minor target locations (see Experiment 2 above for details of the analysis procedure). Figure 12 illustrates that the mean contextual-cueing effect for dominant target locations was significantly larger than for minor target locations (271 ms vs. -17 ms vs. -263 ms), *t*(21) = 11.28, *p* = .00, and *t*(21) = 14.64, *p* = .00, respectively. Contextual cueing of minor target locations also differed significantly from each other, *t*(21) = 11.62, *p* = .00. Mean contextual cueing of dominant target locations was significantly larger than zero, *t*(21) = 8.02, *p* = .00, but contextual cueing of minor target locations was equal to or smaller than zero, *t*(21) = -.61, *p* = .55, and *t*(21) = -9.15, *p* = .00, respectively.

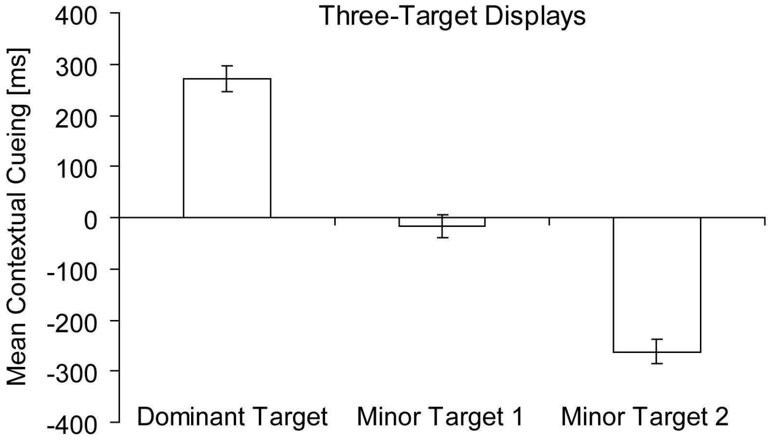

Figure 12: Mean contextual cueing (in ms, and associated standard errors) for dominant and minor target locations of three-target displays in Experiment 3.

In order to compare the contextual-cueing effects for dominant and minor target locations (three-target displays) to corresponding effects in the baseline condition (one-target displays), triplets of one-target displays were randomly selected (for each subject), and then each triplet was sorted by the largest (dominant), the second largest (minor one), and the smallest contextual-cueing effect (minor two, analogous to Experiment 2). Not surprisingly, in the baseline, dominant contextual-cueing effects (331 ms) were greater compared to both minor effects (109 ms and -139 ms, respectively), *t*(21) = 7.73, *p* = .00, and *t*(21) = 9.91, *p* = .00, for the two comparisons; and the latter also differed reliably from each other, *t*(21) = 7.70, *p* = .00. Less trivially, each dominant and minor baseline contextual-cueing effect also differed significantly from zero, *t*(21) = 7.5, *p* = .00, *t*(21) = 3.2, *p* = .00, and *t*(21) = -4.07, *p* = .00, respectively.

Next, dominant and minor contextual cueing in the baseline were compared to contextual cueing of dominant and minor target locations in three-target displays. As in Experiment 2, dominant contextual cueing was comparable between one-target (331 ms) and three-target displays (271 ms), *t*(21) = -1.56, *p* = .13. But contextual cueing of minor target locations (-17 ms vs. -263 ms) was significantly smaller compared to minor contextual-cueing effects in the baseline (109 ms vs. -139 ms), *t*(21) = -2.82, *p* = .01, and *t*(21) = -3.22, *p* = .00, respectively. In sum, dominant contextual-cueing effects in the baseline were similar to those for dominant target locations in three-target displays. By contrast, minor target locations in three-target displays showed no contextual-cueing effects or even contextual costs, whereas minor effects in the baseline still reflected a reliable contextual benefit (at least for the minor-one category). Thus, minor target locations in three-target displays were associated with significant contextual costs beyond the smallest effects observed in the baseline.

Between-Target Distance Analysis

Again, the influence of spatial distance between dominant and minor target locations (range: 2.5°–21.5° of visual angle) on contextual cueing of minor target locations was analysed. Overall, contextual cueing of minor target locations was reduced with greater distance from dominant locations, *r* = -.335, *p* = .00, and *r* = -.331, *p* = .00, respectively (correlations were partially controlled for distance between minor target locations). In a further step, RTs for three-target displays were sorted into three groups, according to whether (above-zero) contextual-cueing effects were obtained for all three target locations (13.6% of the data), for two target locations (30.3%), or for one target location (40.9%; or for none of the target locations). A one-way ANOVA revealed that the mean distance differed significantly between groups, $F(3, 128) = 6.84$, $p < .001$ (with a significant linear trend, $F(1, 128) = 11.10$, $p < .01$). Mean distances were 10.7°, 9°, and 7.6° for contextual cueing of one, two, and three target locations, respectively, suggesting that the integration of multiple target locations into a learned context was only possible with smaller between-target distances. When two target locations were successfully cued, the average effect was 394 ms for dominant target locations and 163 ms for minor target locations (-238 ms for "uncued" locations; all *p*s < .001). When three target locations exhibited contextual cueing, the average cueing effect was 441 ms for dominant target locations, and 319 ms and 155 ms for first and second minor target locations, respectively (all *p*s < .001).

Discussion

In Experiment 3, we compared contextual cueing between one-target displays (baseline) and three-target displays. Overall, only one-target displays, but not three-target displays, generated reliable contextual cueing (95 ms and -3 ms). In addition, search in three-target displays was slowed relative to one-target displays, which might point to extended inspection times due to the resolution of multiple associations between an invariant context and various target locations (see Brady & Chun, 2007). However, further analyses revealed that only a single dominant target location was cued successfully by an invariant context with effects comparable to baseline one-target displays. By contrast, remaining (minor) target locations did not show reliable contextual cueing and were associated with significant contextual costs when compared to the smallest effects in baseline displays. Of course, target locations of three-target displays were presented fewer times than target locations of one-target displays, which could have affected speed of learning, but not the overall contextual-cueing effect of dominant target locations. Therefore, the lack of observable contextual cueing of three-target displays can be attributed to single-target learning.

Moreover, as with to two-target displays (Experiment 2), relative proximity between target locations facilitated contextual cueing of minor target locations and enhanced, to a certain extent, contextual cueing of two or even all three target locations by one-and-the-same, invariant context. However, the size of contextual cueing of one or two proximal target locations never reached the same level as that of dominant target locations. This pattern of results again demonstrates that contextual cueing can index only a single target location (and its immediate surround) reliably, but observers fail to represent multiple target locations within an invariant context.

General Discussion

The repeated presentation of invariant spatial contexts facilitates visual search by guiding attention more directly to learned target locations. In the current study, invariant contexts were paired with multiple target locations (each presented in different trials) to investigate the adaptive properties of contextual cueing. Altogether, our results revealed that contextual cueing integrated only one target location successfully, but failed to reliably facilitate search for a second or third target location.

In line with previous results by Chun and Jiang (1998), contextual-cueing effects were obtained for repeated search displays paired with two target locations (Experiment 1 & 2). However, contextual cueing of two-target displays was significantly reduced in comparison to one-target displays (101 ms and 33 ms, respectively; Experiment 2). Subsequent analyses showed that this reduction was caused by reliable learning of only one of two target locations (i.e., the dominant target location, which was, however, not determined by order of presentation). Search for remaining minor target locations did not benefit from invariant contexts, but rather showed contextual costs that were greater than the costs observed for inefficiently learned baseline displays. Furthermore, when a third target location was paired with a given, invariant context, no contextual cueing was observed overall (-3 ms), while there was reliable contextual cueing, of 95 ms, for one-target displays (Experiment 3). Again, closer inspection of the pattern of results showed that the substantial reduction was caused by reliable cueing of only one of three target locations. By contrast, search for targets appearing at minor locations was again characterised by contextual costs that exceeded the costs observed for inefficiently learned baseline displays. However, additional analyses of all three experiments indicated that, in a subset of the repeated displays, larger distances between dominant and minor target locations were related to reduced contextual-cueing effects (or, in other words, increased contextual costs) for minor target locations. Conversely, proximity between target locations seemed to enable contextual cueing of two or even three locations. Nevertheless, dominant target locations still exhibited more contextual cueing than proximal minor location(s).

In sum, the current study confirmed that contextual cueing could not be adjusted to multiple target locations, but rather indicated that contextual cueing is limited to a single repeated target location – and, possibly, its immediate surround. Accordingly, the overall reduction of contextual cueing by multiple target locations was caused by averaging across cued and uncued target locations. For two-target displays, averaging occurred at a ratio of 1:1, at least halving the overall effect. For three-target displays, this ratio was reduced to 1:2, which explains why contextual cueing of three possible target locations appeared to be ineffective overall. Therefore, our results do not converge with models that proposed a reduction in contextual cueing due to multiple-target learning (see Brady & Chun, 2007).

Previous studies already reported that, following the learning of a first target location, the introduction of a second target location disrupted contextual cueing (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). These findings implied that the learned association between a given target location and a given invariant context hinders adaptation to a second target location. The current pattern of results replicated these findings even for displays that presented possible target locations in alternating order (across blocks of trials), which was expected to provide optimal conditions for learning more than one target location. Consequently, changes in the context-target relation cannot be sufficiently adapted to or compensated for in contextual learning.

Nevertheless, within a relatively narrow spatial range, two-target and three-target displays revealed contextual cueing of multiple target locations, but contextual facilitation dissipated as the spatial distances among target locations increased (see also Makovski & Jiang, 2010, for similar findings). This could mean that contextual cueing establishes multiple memory-based associations between an invariant context and proximal target locations. However, the magnitude of contextual cueing still differed between cued (dominant and minor) target locations, suggesting that contextual cueing of a second or third target location was rather a side-effect of contextual cueing of a dominant target location. Computational models of contextual cueing (Brady & Chun, 2007) assume that observers build up associations between target locations and invariant contexts in repeated visual search. In subsequent search, target locations are cued by a locally activated context, rather than the whole repeated display (see also Geyer, Shi, et al., 2010). Thus, a second or third target located near contextually activated dominant target locations automatically benefits from contextual cueing. Given this, contextual cueing of minor target locations was presumably a side-effect of contextual cueing of a cued target area. Similarly, the prominent contextual costs for distant minor target locations also resulted from (mis-)guidance to the primarily cued target location.

Based on the current results, we assume that observers direct their attention to the learned (dominant) target location, and if the target appears at its expected (i.e., learned) location, robust contextual-cueing effects occur. However, if the dominant target location is absent, observers need to reorient attention to the unlearned (minor) target location, which shows contextual cueing, if it is located near the dominant target location, but this facilitation dissipates, and even turns into considerable costs, with growing distances from the dominant location (see also Manginelli & Pollmann, 2009, who demonstrated comparable results based on eye movement measures).

An interesting finding was that single-target learning was equally effective even when three different target locations were paired with one-and-the-same invariant context. This demonstrates a remarkable degree of selective and noise-resistant (or interference-free) learning. Evidence for the resistance of contextual cueing to interference was already reported by Jiang and Chun (2001), who found contextual learning for a repeated set of nontargets presented among another set of unpredictably changing items (see also Endo & Takeda, 2005; Olson & Chun, 2002). In addition, effective learning of repeated contexts occurred even when these were intermixed with a large number of novel display layouts on five consecutive days (Jiang, Song, & Rigas, 2005). Furthermore, once contextual cueing was established for a set of old-context displays, the subsequent presentation of noise (i.e., the presentation of new-context displays) did no longer affect learned associations (Jungé, Scholl, & Chun, 2007). In general agreement with these findings, contextual memory for dominant target locations was equally strong in the current study, whether they were associated with repeated contexts in 100%, 50%, or in only 33% of all cases. Thus, while contextual learning is rather inflexible in adapting to changing environments (e.g., when the target location changes), learned associations between a repeated context and a target location are remarkably stable.

But what might be the advantage of optimising selectivity at the expense of flexibility? One tentative answer is that contextual learning is, in fact, particularly effective when an invariant context cues only one target region. By contrast, if three (or even more) target locations were learned to be associated with a single invariant context, the context would provide only a vague cue, with a 33% (or smaller) chance of directly guiding attention to the relevant location – thus, substantially compromising the benefit of predictive surrounds (Brady & Chun, 2007). Consequently, preserving the functional role of predictability may be more valuable in repeated visual search than a high degree of flexibility.

In summary, our findings show that contextual cueing lacks the potential of multiple-target learning. However, other adaptive processes appear to be maintained in contextual learning, for example, when a given change preserves the context-target relations (Jiang & Wagner, 2004; Nabeta, Ono, & Kawahara, 2003), or when relational changes are predictable (Conci et al., 2011). Also, natural environments typically contain much richer sources of information than the simple spatial relations in the contextual cueing paradigm, and these, in turn, could facilitate multiple-target learning. For example, contextual learning would not be particularly useful if an environment, such as a kitchen, cued only one location of an object that actually appears at multiple recurring locations (e.g., pan). Hence, factors contributing to multiple-target learning in contextual learning remain a fruitful topic for future studies.

STUDY II

Adaptation of Context-Guided Visual Search to Relocated Targets

Abstract

Visual search for a target object can be facilitated by the repeated presentation of an invariant configuration of nontargets (contextual cueing). Here, we tested adaptation of learned contextual associations after a sudden, but permanent relocation of the target. After an initial learning phase, targets were relocated and repeatedly presented at new locations, before they returned to the initial locations. Relearning was neither observed after numerous presentations of relocated targets, nor after insertion of an overnight break. Further experiments investigated whether relearning of existing contextual associations is comparable to new-learning of further context-target configurations. In contrast to the observed lack of relearning, new-learning developed for further invariant configurations under identical training conditions. Moreover, across all experiments, presenting relocated targets or further contexts did not interfere with contextual cueing of initially learned contextual associations. Overall, relearning of contextual memory was severely constrained and unsuccessful in comparison to new-learning, which suggests that contextual cueing facilitates search for only one repeated target location.

Introduction

Experience greatly influences our perception of the visual world. For example, familiar contingencies between scenes and objects can support target identification (Bar, 2004, for review). Specifically, observers can identify a loaf of bread faster than a similarly shaped post box both presented in the same kitchen scene (Palmer, 1975). Such observations suggest that processing of target objects benefits from a coherent and familiar scene context. Although natural scenes might remain quite stable, observers are often required to detect a target object at changing locations. For example, in an otherwise invariant kitchen scene, a saucepan can sometimes be located on the stove and at other times on the table. If observers are familiar with the kitchen scene, they will find the saucepan relatively quickly irrespective of its variable locations. Other objects, such as a kettle, usually stay in one place in the kitchen, and if they are relocated to a new position, the relocation will be rather permanent. In order to ensure quick search for such permanently relocated targets, context-target associations would have to be adapted to the new situation in the longer term (i.e., relearning already established representations).

In the present study, we investigated whether observers can relearn memory representations of context-target associations when targets are relocated permanently, such that visual search becomes as efficient for relocated targets as for initial target locations. We further distinguished relearning as one kind of adaptation from adapting to entirely new associations (new-learning). For example, new-learning is required when visual search is performed in a further kitchen scene after having successfully learned a different kitchen scene.

To examine relearning of spatial representations as well as new-learning, observers learned spatial contingencies between contexts and target locations within the contextual cueing paradigm (Chun & Jiang, 1998). Furthermore, we examined the adaptation of context-target associations to a second target location after successful learning of a first target location (relearning). Before considering the rationale of our study, we first review previous findings on contextual cueing of two variable target locations (see example above of a saucepan placed at variable locations within a kitchen scene). Next, we summarise studies that investigated relearning of a second, permanently relocated target (see example above of a permanently relocated kettle in a kitchen). Finally, as a comparison, we present studies on sequential new-learning; that is, learning of sequentially presented distinct sets of context-target configurations.

Multiple Target Locations in Contextual Cueing

In agreement with observers' ability to detect targets efficiently at variable locations in natural scenes, Chun and Jiang (1998) reported that old contexts may be associated with at least two target locations. In Experiment 6 of their study, contexts were repeatedly presented with two different target locations (in separate, randomly selected trials), which resulted in reliable contextual cueing (see also Kunar & Wolfe, 2011, for a similar finding). However, the average contextual-cueing effect for old contexts paired with two target locations was reduced in comparison to contexts that were associated with only one target location (in different experiments). Brady and Chun (2007) replicated this observation and explained it in terms of a (computational) model, which assumes that each encounter with an invariant context-target pairing strengthens associations between the target location and its local context of a few neighbouring items. Based on this assumption, the model predicts that repeated visual search for two target locations in the same context results in contextual cueing of both locations (multiple-target learning). The model also predicts that the simultaneous cueing of both learned locations would slow target detection, because both target locations can be inspected. Thus, target locations compete with each other for focal-attentional selection. In this scenario, the location actually containing the target would only be directly selected in some of the trials ─ consequently, the cueing effect of the respective context would be reduced on average compared to contexts with only one target location (see Chun & Jiang, 1998).

This notion has been challenged in Study I, in which we argued that the integration of multiple target locations into one invariant context is rather unlikely. Similar to Chun and Jiang (1998), two (or three) different target locations were presented within a given invariant context in alternating order, such that each target location occurred in separate, consecutive trials. This ensured that the context was equally predictive of each target location. Overall, contextual cueing was reduced for contexts with two target locations in comparison to contexts with one location, consistent with previous findings (Brady & Chun, 2007; Chun & Jiang, 1998; Kunar & Wolfe, 2011). However, more detailed analyses revealed that the overall reduction in contextual cueing was due to an RT-benefit for only one dominant of two (or three) repeated target locations (single-target learning). Thus, reduced contextual cueing for contexts with two target locations as observed in previous studies (Brady & Chun, 2007; Chun & Jiang, 1998; Kunar & Wolfe, 2011) probably resulted from averaging across a cued and an uncued target location. Overall, the results of Study I suggest that the memory representations underlying contextual cueing are rather inflexible regarding the accommodation of multiple repeated target locations.

While multiple-target learning would effectively reduce the average contextual-cueing effect (Brady & Chun, 2007), single-target learning maintains efficient visual search for at least one repeated target location (Study I). Therefore, single-target learning is advantageous, when a target object appears rather unpredictably at different locations (as in the studies discussed above). However, if a target is permanently relocated within its invariant context, the context becomes a reliable cue for this new target location ─ hence, context-target association should be relearned to include the contextually new, highly relevant target location (see also Ogawa & Kumada, 2006).

Relearning in Contextual Cueing

A number of studies on contextual cueing have demonstrated that relearning does not occur when a learned context becomes permanently associated with a new target location (Chun & Jiang, 1998; Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). For example, in Manginelli and Pollmann's (2009) study, after initial target locations had been repeatedly presented within invariant contexts, the targets were suddenly relocated to new, formerly empty locations within the same contexts of nontargets (and then presented repeatedly at novel locations). While contextual cueing was observed for initial target locations, relocated targets did not elicit contextual-cueing effects even after repeated presentations at the new positions (see also Conci et al., 2011; Makovski & Jiang, 2010; see Figure 13, top half, for example displays). Rather, search behaviour, as assessed by RTs and eye movements, was comparable to search in new-context displays ─ suggesting that search was not systematically (mis-)guided to initial target locations, either. Guidance to initial target locations should, in fact, have resulted in noticeably slowed search times (i.e., contextual costs) for relocated targets. In sum, to the best of our knowledge, there are no studies that show successful adaptation of existing contextual representations to permanently relocated targets.

New-Learning in Contextual Cueing

Relearning of new (permanent) target locations in previously learned contexts seems rather improbable in contextual cueing (e.g., Manginelli & Pollmann, 2009). This lack of learning new target locations could imply generic restraints on learning novel contextual information. Rates of new-learning are usually investigated by conducting two contextual cueing experiments sequentially. That is, further invariant contexts are repeatedly presented after an initial learning phase containing different old contexts (see Figure 13, bottom half, for example displays). Using this experimental approach, Mednick et al. (2009) showed that reliable contextual cueing occurred for a second set of old contexts when observers rested or slept between two learning sessions, but not when they were awake. Similarly, successful new-learning was reported for multiple sets of old contexts when they were presented on separate, consecutive days (Jiang et al., 2005). These results imply that new-learning in contextual cueing can develop under specific circumstances, particularly after sleep breaks.

Further studies on other tasks of implicit learning suggest that new-learning (without breaks) may already be facilitated by intense training with the second set of to-be-learned material (statistical learning: Gebhart, Aslin, & Newport, 2009; implicit motor learning: Stephan, Meier, Orosz, Cattapan-Ludewig, & Kaelin-Lang, 2009) ─ though, to our knowledge, this has not been tested for contextual cueing. In sum, a number of studies demonstrate reliable new-learning in implicit learning tasks.

The Present Study

Several studies have shown that contextual adaptation to new target locations is inefficient (Conci et al., 2011; Makovski & Jiang, 2009; Manginelli & Pollmann, 2009). By contrast, learning further old contexts appears to occur reliably under specific training conditions (Jiang et al., 2005; Mednick et al., 2009). The present study was designed to systematically investigate relearning of existing contextual associations and new-learning under identical experimental conditions to uncover similarities and differences between these types of memory adaptation.

In one set of experiments, we examined adaptation to relocated targets within otherwise invariant contexts (relearning). Previous studies only reported fairly immediate consequences of relocated targets on contextual-cueing effects (Chun & Jiang, 1998; Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). Here, we tested adaptation to relocated targets in the longer term. The basic experimental procedure started with a *learning phase*, in which contexts were repeatedly presented with initial target locations. In a subsequent *relocation phase,* targets were presented at formerly empty display positions (see Figure 13, top half, for an example of the experimental phases). Because associations between target locations and surrounding nontarget configurations are consolidated by repeated encounters (Mednick et al., 2009; Tseng et al., 2011; see also Ghilardi, Moisello, Silvestri, Ghez, & Krakauer, 2009; Sanchez & Reber, 2012, for different implicit learning tasks), the learning phase for initial target locations was quite short, which might facilitate relearning due to relatively unconsolidated initial associations (see Luhman, 2011). At the same time, the subsequent relocation phase was much longer than in previous studies (e.g., at least twice as long as in Manginelli & Pollmann, 2009) to provide sufficient training with relocated targets. In addition to learning and relocation phases, a *return phase* was introduced at the end of the experiments, in which targets were presented at initial locations (see Figure 13, top half). The return phase was introduced to test whether the presentation of relocated targets would affect contextual cueing of initial target locations.

To specify memory adaptation in contextual relearning, we also included a second set of experiments that assessed the acquisition of new contextual associations, that is, new-learning. The experimental phases for new-learning were adopted from the relearning experiments (compare top half and bottom half of Figure 13). Thus, identical training conditions were applied to both relearning and new-learning.

New-learning should occur when observers are intensely trained with the second set of displays (see Gebhart et al., 2009), and should be particularly effective after extended breaks including sleep (Jiang et al., 2005). Similarly, contextual cueing should occur for relocated targets under identical training conditions if adaptation to relocated targets involves the acquisition of new contextual information in a similar manner as new-learning. In this view, repeated search for relocated targets should eventually lead to successful relearning, and maybe even to contextual cueing of both initial and relocated targets (multiple-target learning; see Brady & Chun, 2007). On the other hand, adaptation to relocated targets could be rather restricted (single-target learning; Study I), preventing contextual cueing of relocated targets.

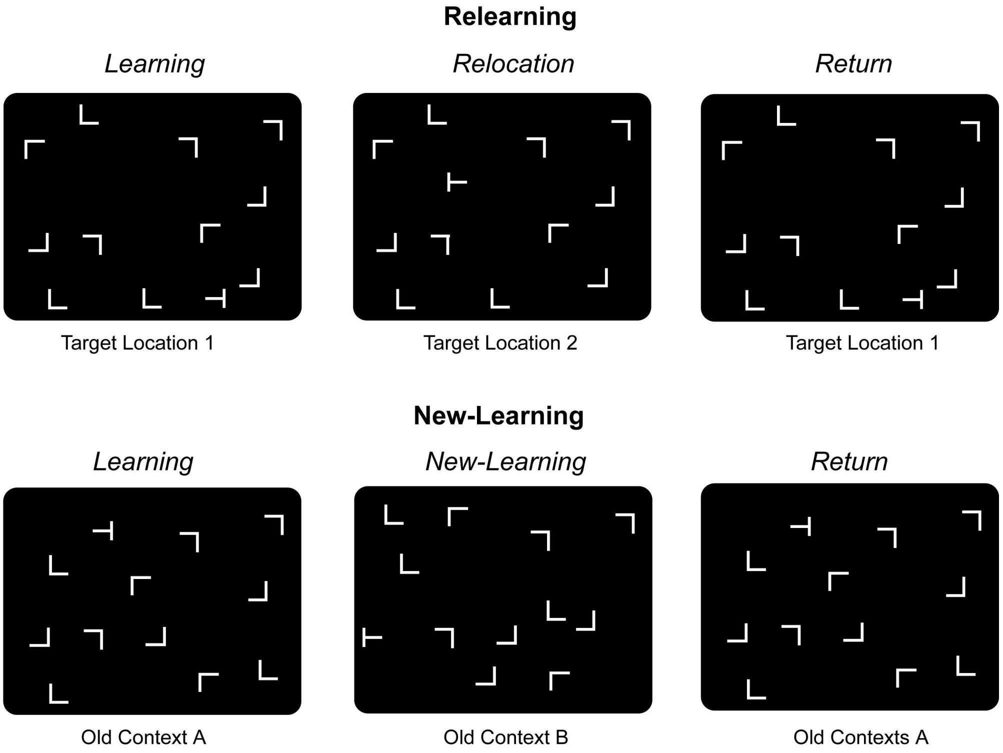

Figure 13: Example search displays and procedure for relearning and new-learning experiments. Relearning (Experiments 4 & 6): (Top Half) Old-context displays were presented with initial target locations in a learning phase (target location 1), followed by a relocation phase, which presented targets repeatedly at novel, previously empty positions (target location 2). In a final return phase, initial target locations (target location 1) were presented again (Experiments 4A & 6 only). New-learning (Experiments 5 & 7): (Bottom Half) Subsequent to an initial learning phase (old context A), a further, completely new set of old-context displays was repeatedly presented during a new-learning phase (old context B). Initial old context displays from the learning phase (old context A) were presented again in a final return phase (Experiments 5A and 7 only).

Experiment 4

Experiment 4 was designed to test whether intensive training promotes relearning of relocated targets. In Experiment 4A, old-context displays were repeatedly paired with initial target locations in a learning phase (3 epochs). Subsequently, targets were relocated to new, formerly empty positions (relocation phase) and repeatedly presented (4 epochs). Following the relocation phase, initial target locations returned for another epoch (return phase; see Figure 13, top half, for an example procedure). Experiment 4B was similar to Experiment 4A, except that the relocation phase was further extended (7 epochs) and there was no return phase.

Method

Subjects

In Experiment 4A, 12 adults (10 women) were tested. Mean age was 23.3 years (age range: 19–31 years). Another 12 adults (9 women) took part in Experiment 4B, with a mean age of 24.4 years (age range: 21–30 years). All subjects reported normal or corrected-to-normal visual acuity and were right-handed. They received either payment (8 or 10 €) or course credits for their participation. As in a previous study (Conci et al., 2011), only subjects who showed positive (i.e., above zero) contextual cueing in the initial learning phase were included in the analysis, because the current study aimed to investigate how changes of target locations affect existing contextual associations. By definition, observers who failed to learn repeated contextual layouts in the first part of the experiment cannot contribute to answering this question. The same procedure was adopted in all other experiments reported below as well as in Study III and in Study IV (see also Albouy, Ruby, Phillips, Luxen, Peigneux, & Maquet, 2006; Conci & Müller, 2012; Kunar & Wolfe, 2011; and Olson et al., 2001, for a comparable procedure).

Apparatus and Stimuli

See Study I.

Trial Sequence

See Study I.

Design and Procedure

Design and Procedure were similar to Study I except for a few differences. Experiment 4 used a repeated-measures design, with the (within-subject) factors Context (old, new) and Epoch [1–8 (1–10), for Experiment 4A (4B), respectively].

An example sequence of the three experimental phases in Experiment 4A is presented in Figure 13 (top half). Displays were presented with initial repeated target locations in the first 15 blocks (aggregated into 3 epochs; learning phase). In 20 subsequent blocks (epochs 4–7) displays were presented with relocated targets (relocation phase), followed by another five blocks (epoch 8) presenting displays again with initial target locations (return phase). Each of two target locations was presented 20 times. Overall, subjects completed 984 trials.

In Experiment 4B, the relocation phase was extended to 35 blocks (epochs 4–10; in total 1224 trials) and the return phase was removed. Note that relocated targets were presented more than twice as often as initial target locations.

Recognition Test

After the search task, observers were asked to perform a final recognition test. Observers completed 24 trials in which they had to decide whether a particular display had been shown previously (old) or not (new) via mouse button responses. All displays were presented with initial target locations, because the explicit recognition of a given old context – if present at all – should be stronger for reliably learned context-target associations (see preconditions above). The response was non-speeded and no error feedback was provided.

Results Experiment 4A

Search Task

Individual mean error rates were calculated for each variable combination. Overall, subjects made relatively few errors (2.1%), and a repeated-measures ANOVA with context (old, new) and epoch (1–8) as within-subject factors did not yield any significant main or interaction effects (all *p*s > .2).

Next, individual mean RTs were calculated for old and new contexts separately for each subject and each epoch. Error trials and RTs exceeding a subject's mean RT by ± 2.5 standard deviations were excluded from the analyses. This outlier criterion led to the removal of 2.5% of all trials; the same procedure was applied in all subsequent experiments resulting in comparable exclusion rates. Greenhouse-Geisser corrected values are reported in case Mauchley's test of sphericity was significant ($p < .05$).

In a first step, individual mean RTs were computed for old and new contexts in each phase (learning, relocation, return). An overall ANOVA with the factors Context (old, new) and Phase (learning, relocation, return) was performed to examine whether contextual cueing changed in the different phases of the experiment. This analysis revealed significant main effects of context, $F(1, 11) = 18.63$, $p < .01$, and of phase, $F(2, 22) = 16.01$, $p < .001$, and a significant interaction between context and phase, $F(2, 22) = 4.55$, $p < .05$. Thus, contextual cueing was affected by the experimental phases (see Figure 14). In order to explore the interaction effect, phases were analysed separately.

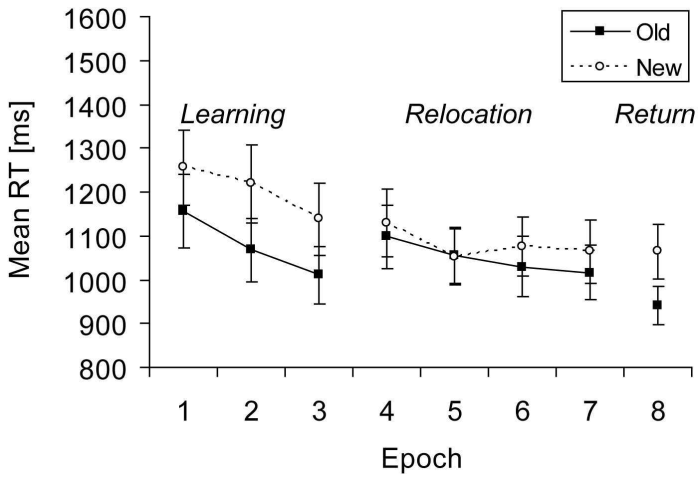

Figure 14: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 4A.

For the learning phase, an ANOVA with the factors Context (old, new) and Epoch (1–3) yielded significant main effects of context, $F(1, 11) = 16.13$, $p < .01$, and of epoch, $F(2, 22) = 25.87$, $p < .001$. RTs were on average 127 ms faster for old contexts as compared to new contexts and decreased by 132 ms across epochs. The interaction did not reach significance ($p > .4$), indicating that observers already showed a robust contextual-cueing effect in epoch 1. This was confirmed by an additional analysis performed on individual blocks (rather than epochs), which revealed the first significant difference between old and new contexts in block 4, $t(11) = -2.5$, $p = .03$, which is comparable to findings of fast contextual learning in previous studies (e.g., Conci & von Mühlenen, 2009), and to all subsequent experiments reported here.

For the relocation phase, an ANOVA with the factors Context (old, new) and Epoch (4–7) revealed only a significant main effect of epoch, $F(3, 33) = 8.29$, $p < .001$, due to faster RTs (by 73 ms) in epoch 7 than in epoch 4. More important, there were no significant effects involving context (*p*s > .2), showing that there was no systematic contextual-cueing effect in the relocation phase.

Finally, in the return phase (epoch 8), the RT-difference between old and new contexts was again significant, *t*(11) = 4.37, *p* = .00, and in terms of magnitude comparable to contextual cueing in the learning phase (124 ms vs. 127 ms, respectively).

In sum, the results of Experiment 4A suggest that contextual associations were not adapted to relocated targets, while contextual cueing of initial target locations was preserved across the presentation of relocated targets.

Recognition Test

Overall, the mean accuracy of recognising old and new contexts was 59%. Observers correctly identified old contexts on 57% of trials (hit rate). The rate of reporting new contexts as old (false alarms) was significantly smaller (38.9%) than the hit rate, *t*(11) = -3.28, *p* = .01. To analyse whether subjects' ability to explicitly recognise old contexts was related to the size of contextual cueing, the individual sensitivity measure *d'* [z(hits) - z(false alarms)] was computed and correlated with the contextual-cueing effects of initial target locations and of relocated targets. Subjects' ability to explicitly recognise old contexts was not significantly correlated with the mean contextual-cueing effects of neither first nor second target locations, *r* = -.17, *p* = .61 and *r* = .06, *p* = .86, respectively. This suggests that the explicit recognition of some of the displays (Smyth & Shanks, 2008) was not related to the occurrence of contextual cueing (see also Shanks, 2010; Westerberg et al., 2011).

Results Experiment 4B

Search Task

Relatively few errors occurred (2.4%) in Experiment 4B. A repeated-measures ANOVA with the factors Context (old, new) and Epoch (1–10) did not yield any significant main or interaction effects (all *p*s > .3).

Error trials and outliers were removed from the data, and individual mean RTs were calculated for old and new contexts, separately for each epoch. Figure 15 shows mean RTs across phases for old and new contexts. First, to analyse RTs, an overall ANOVA with the factors Context (old, new) and Phase (learning, relocation) revealed significant main effects of context, $F(1, 11) = 30.25$, $p < .001$, and of phase, $F(1, 11) = 19.72$ $p < .01$, as well as a significant interaction between context and phase, $F(1, 11) = 6.22$, $p < .01$. Because the experimental phases affected contextual cueing separate analyses follow.

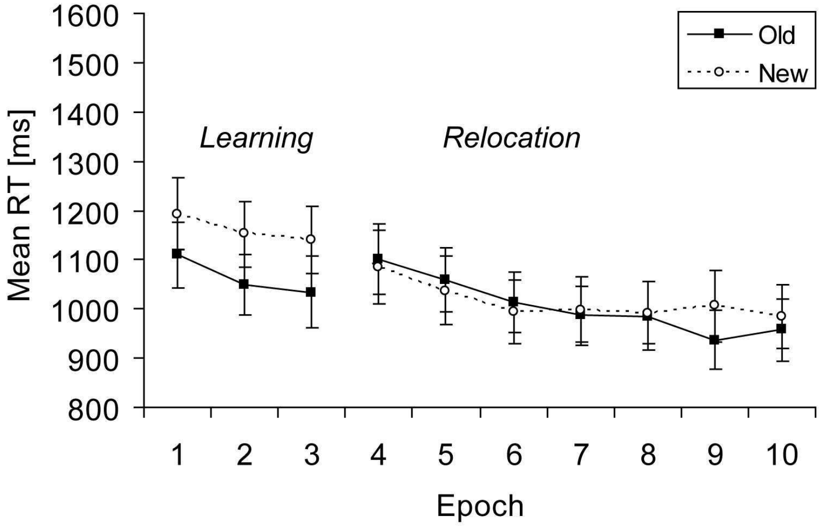

Figure 15: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 4B.

For the learning phase, a context (old, new) by epoch (1–3) ANOVA yielded a significant main effect of context, $F(1, 11) = 17.33$, $p < .01$, and a typical main effect of epoch, $F(2, 22) = 5.67$, $p < .05$. RTs were on average 97 ms faster for old contexts in comparison to new contexts. The interaction between context and epoch was not significant ($p > .7$).

Next, for the relocation phase, an ANOVA with the factors Context (old, new) and Epoch (4–10) revealed a significant main effect of epoch, $F(6, 66) = 17.56$, $p < .001$. In addition, the interaction between context and epoch was significant, $F(6, 66) = 3.09$, $p < .05$. Subsequent paired-sample t-tests between RTs for old and new contexts performed separately for each epoch revealed a significant difference only in epoch 9, $t(11) = 2.73$, *p* = .02, but not in any other epoch of the relocation phase (mean contextual cueing = 8 ms). The significant contextual-cueing effect in epoch 9 (68 ms) appears to be an isolated outlier effect rather than a systematic contextual-cueing effect.

Recognition Test

Overall, the mean accuracy in the recognition test was 48.6%. Observers' hit rate of 57.6% was comparable to the false alarm rate of 60.4%, *t*(11) = -.60, *p* = .56, suggesting that observers were mostly unaware of the repetitions of displays (see Chun & Jiang, 1998).

Discussion

Experiment 4 investigated relearning of contextual associations after target relocations with different presentation times. Observers showed robust contextual cueing in the initial learning phases. However, after target relocation, contextual cueing was greatly reduced and remained insignificant across the shorter and longer relocation phase (see also Conci et al., 2011; Manginelli & Pollmann, 2009). Overall, the results of Experiment 4 suggest that an increased amount of training is not sufficient to enable relearning of relocated targets in contextual cueing.

In the final return phase, initial target locations elicited reliable contextual-cueing effects, which were comparable to cueing-effects in the learning phase. This result suggests that contextual memory for initially learned target locations was stable and unaffected by repeated presentations of the same displays with relocated targets, which is in line with previous findings of durable contextual cueing (Jiang et al., 2005; Jungé et al., 2007; Mednick et al., 2009; see Study I).

Overall, the results of Experiment 4 suggest that an increased amount of training is not sufficient to enable adaptation to relocated targets in contextual cueing. Rather, contextual cueing continued to facilitate search for initial target locations, even when inconsistent context-target pairings were presented in-between.

Experiment 5

Experiment 5 examined contextual new-learning under identical training conditions as used for relearning in Experiment 4. New-learning also involved a critical change after an initial learning phase; a new contextual cueing experiment started presenting an entirely new set of old- and new-context displays (see Figure 13, bottom half). Like Experiment 4A, Experiment 5A had an initial learning phase (3 epochs), followed by a new-learning phase (4 epochs) and a final return phase (1 epoch). Experiment 5B had, like Experiment 4B, an extended new-learning phase of seven epochs and no return phase.

Method

Apparatus, stimuli, design, and procedure were similar to Experiment 4, except that in Experiment 5, observers were presented with one set of 12 old-context displays in the learning phase (epochs 1–3) and a further, distinct set of 12 old-context displays in subsequent epochs of the new-learning phase. Figure 13 (bottom half) illustrates the sequence of experimental phases for Experiment 5A. Subsequent to learning (epochs 1–3), further old-context displays were presented from epoch 4 to epoch 7 (new-learning phase), which was followed by the presentation of old-context displays from the initial learning phase in epoch 8 (return phase). In Experiment 5B, epoch 4 to 10 represented the new-learning phase, which was not followed by a return phase.

In total, 24 old-context displays with 24 different target locations (12 for each set of displays) were generated for each subject. Another 24 different target locations were assigned to new-context displays. In the final recognition test, observers completed 48 trials including the 24 old-context displays and 24 randomly generated displays.

Twelve adults (9 women) took part in Experiment 5A with a mean age of 27.8 years (age range: 22–49 years). Another twelve adults (11 women) were tested in Experiment 5B with a mean age of 26.6 years (age range: 21–32 years). All subjects reported normal or corrected-to-normal visual acuity and were right-handed. They received either payment (8 or 10 €) or course credits for their participation.

Results Experiment 5A

Search Task

Overall, observers made few errors (2.8%). A repeated-measures ANOVA with the factors Context (old, new) and Epoch (1–8) revealed no significant main or interaction effects (all *p*s > .2).

Individual mean RTs were calculated for old and new contexts, separately for each epoch after exclusion of error trials and outliers. For the analysis of RTs, an overall ANOVA with the factors Context (old, new) and Phase (learning, new-learning, return) yielded significant main effects of context, $F(1, 11) = 13.09$, $p < .01$, and of phase, $F(2, 22) = 6.32$, $p < .01$, as well as a significant interaction between context and phase, $F(1.17, 12.85) = 10.48$, $p < .01$. Because the interaction indicates that contextual cueing was affected by the experimental phases (see Figure 16), separate analyses were performed.

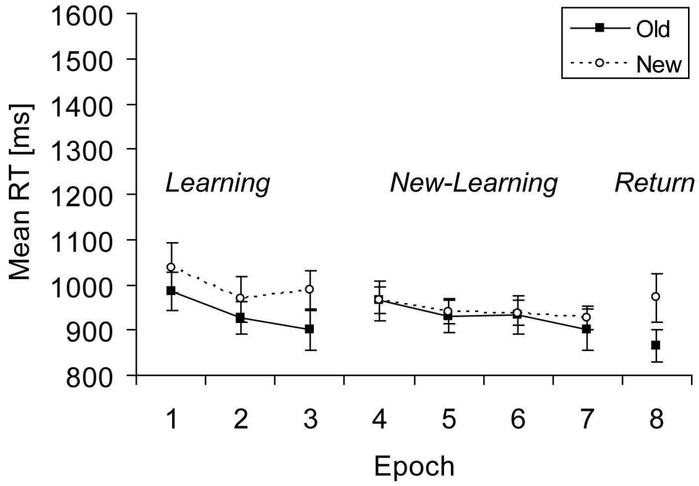

Figure 16: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 5A.

For the learning phase, a context (old, new) by epoch (1–3) ANOVA yielded significant main effects of context, $F(1, 11) = 19.43$, $p < .01$, and of epoch, $F(2, 22) = 8.05$,

$p < .01$. RTs were on average 78 ms faster for old contexts than for new contexts. The interaction between context and epoch was not significant ($p > .7$).

For the new-learning phase, a context (old, new) by epoch (4–7) ANOVA revealed only a main effect of epoch, $F(3, 33) = 4.84$, $p < .01$. The main effect of context and the interaction between context and epoch were not significant (all ps > .1), and mean contextual cueing was -5 ms. Finally, in the return phase (epoch 8), RTs were again faster (by 146 ms) for old contexts than for new contexts, $t(11) = -4.62$, $p = .00$.

In sum, successful new-learning was not observed after four epochs of training in Experiment 5A. At the same time, the presentation of further old-context displays did not affect contextual cueing of initially learned contexts in the return phase.

Recognition Test

Overall, mean accuracy in the recognition test was 47.2%. Observers showed a hit rate of 51.4% and a false alarm rate of 52.1% for the first set of displays, $t(11) = -.16$, $p = 87$. A similar pattern of hits (48.6%) and false alarms (59%) was observed for the second set of displays, $t(11) = -1.7$, $p = .12$, suggesting that neither the first nor the second set of old-context displays was recognised explicitly.

Results Experiment 5B

Search Task

In Experiment 5B, few errors occurred (3.1%). A repeated-measures ANOVA with the factors Context (old, new) and Epoch (1–10) revealed no significant main or interaction effects (all ps > .4).

Error trials and outliers were removed from the data, and individual mean RTs were calculated for old and new contexts, separately for each epoch. An overall ANOVA on the mean RTs with the factors Context (old, new) and Phase (learning, new-learning) yielded significant main effects of context, $F(1, 11) = 9.85$, $p < .01$, and of phase, $F(2, 22) = 6.08$, $p < .05$. The interaction between context and phase was marginally significant, *F*(1, 11) = 4.92, *p* = .05, suggesting that the effect of phase on contextual cueing was now reduced (see Figure 17).

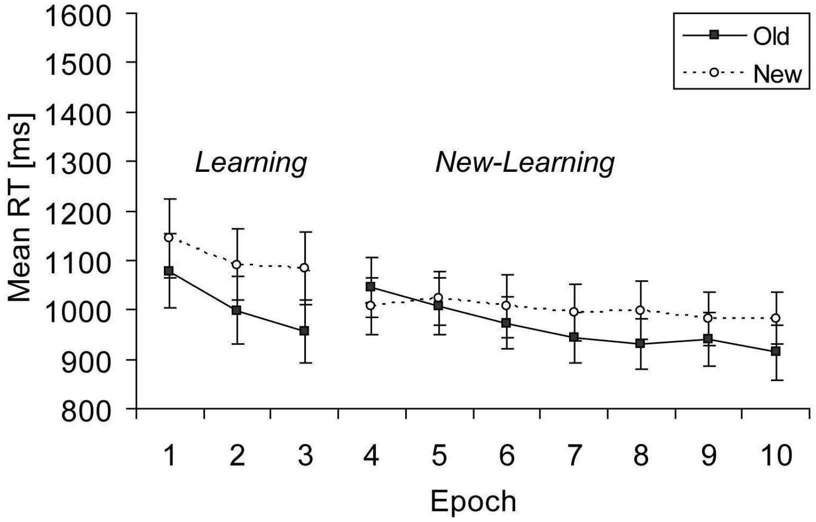

Figure 17: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 5B.

For the learning phase, a context (old, new) by epoch (1–3) ANOVA yielded significant main effects of context, *F*(1, 11) = 16.34, *p* < .01, and of epoch, *F*(2, 22) = 11.85, *p* < .001. RTs were on average 96 ms faster for old contexts than for new contexts. The interaction between context and epoch reached marginal significance, *F*(2, 22) = 3.04, *p* = .07, suggesting that the RT-difference between old and new contexts increased from epoch 1 (67 ms) to epoch 3 (127 ms).

For the new-learning phase, a context (old, new) by epoch (4–10) ANOVA revealed a significant main effect of epoch, *F*(3.03, 33.29) = 6.34, *p* < .01, but no main effect of context (*p* > .2). In addition, the interaction between context and epoch was significant, *F*(6, 66) = 4.72, *p* < .01, reflecting a gradual increase of contextual cueing across epochs. An additional ANOVA with the factors Context (old, new) and Epoch (7–10) revealed a marginally significant main effect of context, *F*(1, 11) = 4.36, *p* = .06, representing a sustained mean cueing-effect of 57 ms across epochs 7 to 10.

Recognition Test

Overall, the mean accuracy in the recognition test was 47.4%. The hit rate for the first set of displays was 45.8%, which was comparable to the false alarm rate of 56.9%, $t(11) = -1.36$, $p = .20$. A similar pattern of hits (55.6%) and false alarms (54.9%) was observed for the second set of displays, $t(11) = .096$, $p = .93$. Overall, this pattern of results suggests that observers were not able to recognise old-context displays.

Discussion

Experiment 5 was designed to investigate successive learning of new contextual information based on intensive training. Contextual cueing was observed for a first set of old-context displays in the initial learning phases, but not for a second set of old-context displays in the shorter version of the new-learning phase. However, more intensive training facilitated the development of contextual new-learning (at least to some extent). As in Experiment 4 of the present study, old-context displays from the initial learning phase elicited large contextual-cueing effects in the return phase.

In sum, the results of Experiment 5 indicate that the acquisition of new associations might develop gradually in contextual cueing. Although the contextual-cueing effect in the longer version of the new-learning phase was relatively small, the results nevertheless indicate that contextual new-learning may gradually increase with training. This finding is in agreement with results presented by Gebhart et al. (2009), who showed that successive learning of two statistical regularities was only observed when the exposure with the second regularity was tripled in time in comparison to the exposure with the first regularity. However, the learning effect was still significantly smaller for the second regularity than for the first regularity ─ mirroring the results in Experiment 5B.

By contrast, a similar trend was not observed for adaptation to relocated targets in Experiment 4B. Two further experiments elaborated differences between relearning and new-learning by introducing an overnight break between subsequent learning phases.

Experiment 6

Experiment 6 tested adaptation to relocated targets after a 24-hour break. The experimental design was similar to Experiment 4A, except that the phases of the experiment were performed on two consecutive days. Observers completed the learning phase (3 epochs) on one day, and the relocation (7 epochs) and return phases (1 epoch) on the next day. The 24-hour break was introduced because successive contextual learning is facilitated by sleep breaks between learning sessions (Jiang et al., 2005; Mednick et al., 2009). Therefore, our manipulation may also enhance adaptation to relocated targets.

Method

Apparatus, stimuli, design, and procedure were similar to Experiment 4A, except that observers completed a total of 1368 trials on two consecutive days. As in Experiment 4A, each old- and new-context display was paired with two different target locations, of which the first target was presented on the first day in three epochs (learning phase). On the next day, the same old-context displays were presented with relocated targets in seven epochs (relocation phase), immediately followed by the presentation of initial target locations in epoch 11 (return phase; Figure 13, top half). The experiment started with a practice block on both days. Subjects completed the recognition test on the second day. Experimental sessions were separated by approximately 24-hours.

Fourteen adults (12 women) took part in the experiment with a mean age of 26.8 years (age range: 19–45 years). All subjects reported normal or corrected-to-normal visual acuity; one subject was left-handed. Subjects received either payment (14€) or course credits.

Results

Search Task

Overall, subjects made few errors (2.1%), and an ANOVA with the factors Context (old, new) and Epoch (1–11) did not result in any significant main or interaction effects (*p*s > .1).

After the exclusion of error trials and outliers, individual mean RTs were calculated for old and new contexts, separately for each epoch. For the analysis of RTs, first, an overall ANOVA with the factors Context (old, new) and Phase (learning, relocation, return) was computed, which revealed significant main effects of context, $F(1, 13) = 13.69$, $p < .01$, of phase, $F(1.20, 15.55) = 5.65$, $p < .05$, and a significant interaction between context and phase, $F(2, 26) = 5.34$, $p < .05$. Since the factor Phase affected contextual cueing (see Figure 18) separate analyses follow.

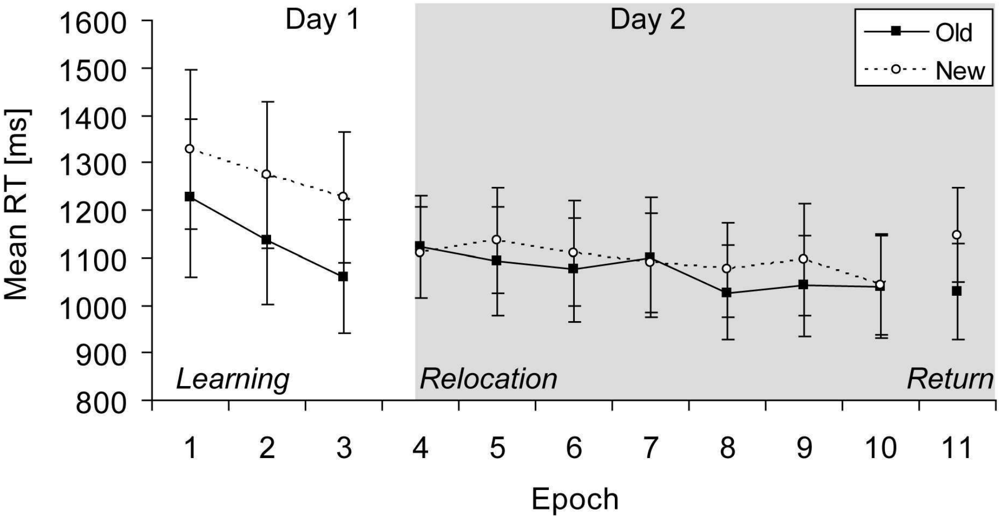

Figure 18: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 6.

For the learning phase, an ANOVA with the factors Context (old, new) and Epoch (1–3) yielded significant main effects of context, $F(1, 13) = 15.45$, $p < .01$, and of epoch, *F*(1.14, 14.84) = 8.99, *p* < .01. RTs were on average 135 ms faster for old in comparison to new contexts. The interaction between context and epoch was marginally significant, *F*(2, 26) = 3.14, *p* = .06, reflecting an increase in contextual-cueing effects from epoch 1 (102 ms) to epoch 3 (166 ms).

For the relocation phase on the next day, an ANOVA with the factors Context (old, new) and Epoch (4–10) revealed a significant main effect of epoch, *F*(2.52, 32.77) = 6.39, *p* < .01. The main effect of context and the interaction between context and epoch were not significant (*p*s > .1). Mean contextual cueing was 23 ms. Finally, in the return phase, when initial target locations returned, RTs for old contexts were 118 ms faster than for new contexts, *t*(13) = 3.01, *p* = .01.

Relearning Across Experiments

A further analysis was computed to examine whether the length of the relocation phases facilitated relearning. To this end, mean contextual cueing was computed for the basic relocation phase in Experiment 4A (epochs 4–7) and compared with the extension of the relocation phase (epochs 8–10) in Experiments 4B and 6 (data collapsed as there was no difference in contextual cueing, *t*(24) = 0.02, *p* = .49, one-tailed). An independent t-test revealed no significant difference between mean contextual cueing of basic and extended training, *t*(36) = -.097, *p* = .46 (one-tailed). This means that basic and extended training resulted in similarly insignificant contextual-cueing effects for relocated targets (32 ms vs. 34 ms, respectively).

Recognition Test

Overall, the mean accuracy in the recognition test was 55.4%. The difference between hits (54.2%) and false alarms (43.5%) was marginally significant, *t*(13) = -2.15, *p* = .05. As in Experiment 4A, the individual sensitivity measure *d'* [z(hits) - z(false alarms)] was computed as a measure of explicit recognition performance and correlated with the contextual-cueing effects for initial target locations and relocated targets. Subjects' ability to explicitly recognise old contexts was not significantly correlated with the mean contextual-cueing effects of neither first nor second target locations, $r = .42$, $p > .10$ and $r = -.16$, $p > .50$, respectively. Thus, the ability to explicitly recognise some of the displays was not related to contextual cueing (see also Shanks, 2010; Westerberg et al., 2011).

Discussion

In Experiment 6, observers completed two learning sessions on two consecutive days in order to investigate relearning of existing contextual associations. Robust contextual cueing was observed for initial target locations in the learning phase on the first day. On the second day, contextual cueing did not occur for relocated targets, although observers were trained with numerous repetitions. Contextual cueing of relocated targets was, in fact, similar to the insignificant effects observed in Experiment 4. Despite the break and considerable amounts of inconsistent information presented during the relocation phase, contextual cueing occurred reliably for initial target locations in the return phase.

The lack of adaptation to relocated targets in Experiment 6 suggests that the conditions known to facilitate contextual new-learning (Jiang et al., 2005; Mednick et al., 2009) do not increase the likelihood of adaptation to relocated targets to occur. Rather, relearning of previously learned contextual associations appears to be fairly restrained.

Experiment 7

Experiment 7 was conducted to investigate whether new-learning occurs after a 24-hour break (see Jiang et al., 2005; Mednick et al., 2009). The experiment was identical to Experiment 6, except that a further distinct set of old-context displays was presented during a new-learning phase on the second day of the experiment.

Method

Apparatus, stimuli, design, and procedure were similar to Experiment 6, except that a further set of distinct old-context displays was presented during a new-learning phase on the second day of the experiment (see Figure 13, bottom half, and Experiment 5A). The final recognition test required observers to complete 48 trials, including the 24 old-context displays and 24 randomly generated novel displays.

Fourteen adults (13 women) took part in the experiment with a mean age of 22.4 years (age range: 18–30 years). All subjects reported normal or corrected-to-normal visual acuity; one subject was left-handed. Subjects received either payment (14€) or course credits.

Results

Search Task

Overall, few errors occurred (1.9%). An ANOVA with the factors Context (old, new) and Epoch (1–11) revealed only a significant main effect of context, $F(1,13) = 8.65$, $p < .05$, reflecting fewer errors for old contexts (1.7%) than for new contexts (2.2%).

Error trials and outliers were removed from the data, and individual mean RTs were calculated for old and new contexts, separately for each epoch. Figure 19 presents RTs for old and new contexts across epochs. An overall ANOVA on the RT data with the factors Context (old, new) and Phase (learning, new-learning, return) yielded significant main effects of context, $F(1, 13) = 14.33$, $p < .01$, and of phase, $F(2, 26) = 20.37$, $p < .001$. The interaction between context and phase was also significant, *F*(2, 26) = 8.15, *p* < .01. Separate analyses follow.

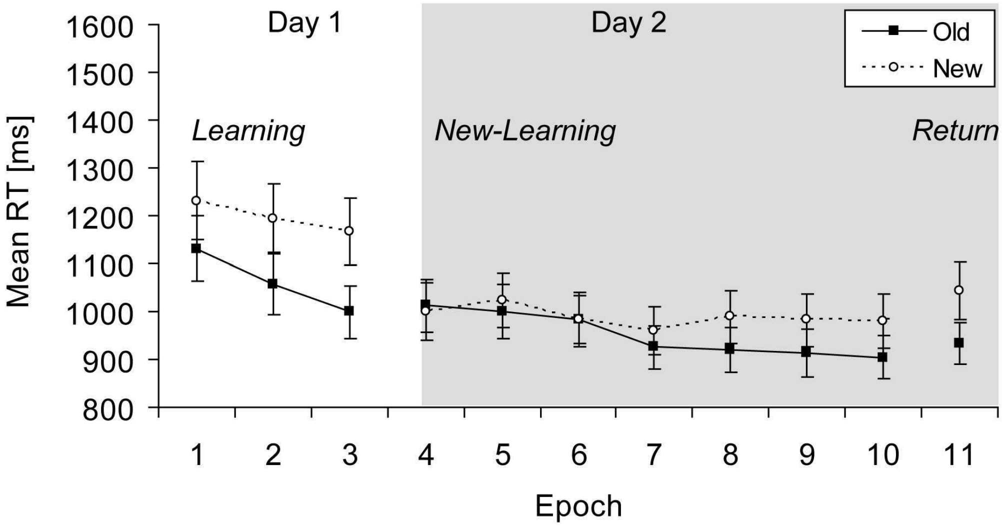

Figure 19: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 7.

For the learning phase, an ANOVA with the factors Context (old, new) and Epoch (1–3) yielded main effects of context, *F*(1, 13) = 18.34, *p* < .01, and of epoch, *F*(2, 26) = 9.57, *p* < .01. RTs were on average 135 ms faster for old relative to new contexts. The interaction between context and epoch was not significant (*p* > .1).

Next, for the new-learning phase on the second day, an ANOVA with the factors Context (old, new) and Epoch (4–10) revealed a significant main effect of epoch, *F*(6, 78) = 10.15, *p* < .001. The main effect of context was not significant (*p* > .1), but the interaction between context and epoch was significant, *F*(6, 78) = 4.44, *p* < .01, reflecting an increase in contextual cueing across epochs. An additional ANOVA with the factors Context (old, new) and Epoch (7–10) revealed a significant effect of context in epochs 7 to 10, *F*(1, 13) = 6.91, *p* < .05, showing a sustained mean contextual benefit of 62 ms.

Finally, in the return phase (on the second day), when initial displays returned, RTs were on average 110 ms faster for old contexts than for new contexts, *t*(13) = 3.56, *p* = .00.

New-Learning Across Experiments

A further analysis was computed to examine whether the extended length of the new-learning phase facilitated new-learning. Mean contextual cueing was computed for the basic new-learning phase in Experiment 5A (epochs 4–7) and compared to the extension of the new-learning phase (epochs 8–10) in Experiments 5B and 7 (data collapsed as there was no significant difference in contextual cueing between Experiments 5B and 7, $t(24) = .31$, $p = .38$, one-tailed). An independent t-test revealed a significant difference in contextual cueing between basic and extended training, $t(36) = 1.94$, $p = .03$ (one-tailed), indicating that contextual cueing was smaller after basic training than after extended training (-5 vs. 65 ms, respectively).

Relearning versus New-Learning

In a final step, we compared contextual-cueing effects between the collapsed data of Experiment 4B and 6 (relearning, $n = 26$) and Experiment 5B and 7 (new-learning, $n = 26$). Contextual-cueing effects were computed for epochs 8 to 10 and entered into a repeated-measure ANOVA with the within-subject factor Epoch (8–10) and the between-subject factor Experiment (relearning, new-learning). The interaction between epoch and experiment was significant, $F(2, 100) = 3.58$, $p < .05$, reflecting a larger contextual-cueing effect for new-learning (65 ms) compared to a smaller and more varying cueing effect for relearning (34 ms) across the last three epochs (main effect of epoch, $F(2,100) = .82$, $p > .4$). This outcome indicates that new-learning was more effective than relearning.

Recognition Test

Overall, the mean accuracy in the recognition test was 47.5%. For the first set of displays, the number of hits (54.2%) was comparable to the rate of false alarms (52.5%), $t(11) = .30$, $p = .77$. A similar pattern of hits (54.8%) and false alarms (46.4%) was found for the second set of displays, $t(11) = 1.16$, $p = .27$. Therefore, observers did not explicitly recognise the old context-displays.

Discussion

The results of Experiment 7 showed contextual learning for two sets of repeated displays when learning was performed on two consecutive days. Observers revealed a robust contextual-cueing effect for a first set of old-context displays in the initial learning phase on the first day. Subsequently, a contextual-cueing effect developed for a second set of old-context displays in the new-learning phase on the next day, which was larger than the effect observed after shorter training in Experiment 5A. Simultaneously, contextual new-learning in Experiment 7 was comparable to the results of Experiment 5B that implemented the same amount of training, but no break between phases. Reliable contextual cueing was also observed for the first set of old-context displays in the return phase.

This pattern of results shows that two sets of old-context displays can be learned on two consecutive days (see also Jiang et al., 2005). However, contextual new-learning did not develop as fast as learning on the first day. Previous studies (Jiang et al., 2005; Mednick et al., 2009; van Asselen & Castelo-Branco, 2009) have already suggested that new-learning may not be as successful as initial learning in contextual cueing. Nevertheless, new-learning was reliable in Experiment 7, which means that our training conditions effectively facilitated new-learning. By contrast, relearning in Experiment 6 was clearly not observed under identical training conditions.

General Discussion

The aim of the present study was to compare and contrast memory adaptation in relearning of existing contextual associations with successive learning of new contextual associations. To this end, we examined contextual relearning and contextual new-learning under identical training conditions. During relearning, target items were relocated to a previously empty display location within their respective invariant contexts. Relearning was observed neither after intensive training (Experiment 4) nor after an extended (24-hour) break including sleep (Experiment 6). Contextual new-learning was examined with the successive presentation of two distinct sets of invariant contexts realised under the same training conditions as used for relearning. The results showed that new-learning did not benefit from relatively short training (Experiment 5A); but when the training phase was further prolonged, a contextual-cueing effect developed for a second set of invariant contexts (Experiment 5B). Similarly effective contextual new-learning was observed after an overnight break (Experiment 7), and it seemed to be somewhat more robust than the cueing-effect observed in Experiment 5B.

An interesting finding was the observation of robust contextual cueing of initially learned contexts in all return phases, irrespective of successful (Experiments 5B & 7) or unsuccessful learning in the meantime (Experiments 4A, 5A, 6). This indicates that established associations of old contextual layouts presented in the initial learning phases were not affected by either relocated targets or further old-context displays.

Most of the previous studies that examined adaptation to relocated targets focused on fairly immediate consequences of target relocations on contextual cueing, and failed to observe cueing effects for relocated targets (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). Even when relocated targets elicited contextual cueing, it occurred at the expense of contextual cueing of initial target locations (Luhman, 2011). In this study, each of two target locations was presented for five repetitions in sequential order, and contextual cueing was only observed for the second target location but not for the first target location. Here, we greatly increased the number of presentations of relocated targets and introduced a break. Nevertheless, adaptation to relocated targets was not reliably obtained. While no contextual cueing occurred after target relocation, there was also no contextual cost, replicating previous studies that reported no or only transient costs directly after target relocation (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). This lack of contextual costs indicates that visual search was probably not continuously guided to initial target locations. At the same time, search was also not cued to relocated targets, which agrees with the proposal that relearning is restrained because contextual cueing is essentially restricted to a single target location (Study I).

Unlike adaptation, new-learning developed after extended training. This suggests that training can facilitate contextual new-learning to some extent, in accordance with findings from other implicit-learning tasks (Gebhart et al., 2009, Stephan et al., 2009). But unlike previous studies on contextual cueing (Jiang et al., 2005; Mednick et al., 2009), successful new-learning was not substantially enhanced after sleep when the same amount of training was applied. In general, sleep should reduce proactive interference; that is, active old memory should interfere less with the acquisition of new memory after sleep (see Anderson & Neely, 1996; and Wixted, 2004, for reviews regarding memory-based interference effects). If proactive interference impaired new-learning in the present study, its effect already subsided over the course of standard training, whereas sleep was not critical for the reduction of proactive interference. In line with other implicit learning-tasks (Gebhart et al., 2009, Sanchez & Reber, 2012; Stephan et al., 2009), our results show that the number of repeated exposures is the most influential contribution to success rates of implicit new-learning.

While learning of further invariant contextual layouts was observed in the present study, existing contextual associations were not relearned to incorporate permanently relocated targets, although the invariant contexts cued relocated targets reliably. Consequently, relearning contextual associations does not appear to be a “simple” case of learning novel contextual information ─ if this were the case, relearning should work once proactive interference is reduced. Rather, in addition to proactive interference, further factors seem to impede adaptation to relocated targets. Specifically, based on the findings of Study I (single-target learning), we propose that predictive contexts can only be associated with a single target location, imposing constraints on any further adaptive processes.

In contrast to our results, research using the incidental Serial Reaction Time (SRT) task suggests that relearning of implicit associations between predictors and targets was achieved with no difficulty (Beesley & Le Pelley, 2010). In this study, observers were trained with a sequence of individually presented cues that predicted the (likely) continuation of that sequence. That is, cues were associated with more or less probable outcomes (similar to the pairing between spatial context and target location in contextual cueing). After training, the cue sequences were paired with new outcomes; and observers were able to successfully associate old cues with new outcomes. Hence, relearning of old associations was observed in an SRT-task, but not for contextual cueing in the present study.

Even though contextual cueing and SRT tasks (as well as other implicit learning tasks) share several similarities, the specifics of the tasks as well as the underlying learning mechanisms might nevertheless differ substantially (e.g., Seger, 1994; and Schwarb & Schumacher, for reviews; see also van den Bos & Poletiek, 2010). In general, observers learn spatio-temporal sequences and rather simple associations between one cue and one highly probable outcome in SRT tasks, whereas contextual cueing involves the acquisition of more complex spatial associations between *multiple* (context-) objects and a definite target location (Chun & Jiang, 2003). These general differences could explain why adaptation occurs readily in SRT learning, but not in contextual (re-)learning. More specifically, in the study by Beesley and Le Pelley (2010), old cues were used as both cues and outcomes to realise new associations in the relearning phase. Hence, new outcomes were familiar objects, which could have facilitated relearning. Indeed, Conci et al. (2011)

have reported contextual cueing for two familiar target locations associated with the same invariant context (see also Conci & Müller, 2012). In Experiment 2 of their study, search displays always contained two targets at two different locations (one was oriented left/ right, one was pointing up-/ downward). Observers searched for one of the targets in one half of the experiment and for the other target in the other half. Reliable contextual cueing was observed for both target locations, due to their simultaneous and, thus, predictable presentation. By contrast, target relocations were unpredictable and introduced completely new target locations in the present study, and this lack of familiarity might have prevented relearning to occur.

When target relocations are unpredictable, observers only learn to associate one target location with a given repeated context. Hence, the current findings are incompatible with the view that the memory representations underlying contextual cueing can integrate up to two target locations (e.g., Brady & Chun, 2007; Chun & Jiang, 1998; Kunar & Wolfe, 2011). If this view would apply unconditionally, repeated search for two target locations in one invariant context should enable learning of both locations. However, this was not observed in the present study, even when observers had more experience with relocated targets than with initial target locations. Although single-target learning renders contextual cueing less flexible than previously proposed (e.g., Brady & Chun, 2007), it nevertheless permits rapid detection of at least one target location (Study I). If two target locations were, in fact, associated with one context, they would compete for focal attention. As a consequence, the benefit deriving from contextual cueing would be reduced compared with learning only one target location (as suggested by Brady & Chun, 2007; Chun & Jiang, 1998). In contrast, single-target learning prevents competition between target locations. Taken together, the results of the present study suggest that, besides repeated exposure, further factors can modulate contextual cueing: While proactive interference seems to impede the successive acquisition of entirely new memory representations with gradually fading impact, single-target learning (Study I) severely constrains the adaptation of established memory representations to environmental change.

Unlike proactive interference, contextual cueing seems to be unaffected by retroactive interference, which was reflected by the overall stability of contextual cueing of learned contextual associations following relocated targets and new-learning in the present experiments. Thus, the current results confirm that the retention of implicit contextual associations is not prone to temporal decay, effects of noise and of additional associations (Chun & Jiang, 2003; Jiang et al., 2005; Jungé et al., 2007; Tunney, 2003; van Asselen & Castelo-Branco, 2009; see also Study I). As proposed by Alberini (2011), consolidated memories typically remain stable when learning has reached an asymptotic level. Although contextual cueing may not have reached asymptotic levels for initial associations in the present study (owing to the short learning phase), memory representations appeared to be robust enough for largely unaffected retention across fairly long periods. Furthermore, successful new-learning combined with contextual cueing in the return phase indicates that implicit (contextual) learning is based upon high, or even unlimited, capacity, at least for distinct memory representations (see also Brady, Konkle, & Alvarez, 2011; Jiang et al., 2005; Sanchez & Reber, 2012).

In conclusion, the present study shows that relearning of existing contextual associations is inflexible in comparison to successive learning of new contextual associations. We propose that the adaptive properties of relearning are restricted because a given context can only be associated with a single target location ─ which is likely to help minimise or avoid competition between multiple target locations (Study I). At the same time, an existing association between a target location and a context is remarkably solid and durable, continuously facilitating efficient visual search across inconsistencies and long periods of time. Unlike relearning, in new-learning, context-target associations are not jeopardised by structural changes in the learned contexts. Hence, new-learning sets in once proactive interference subsides.

STUDY III

Long-Term Adaptation of Context-Guided Visual Search to Relocated Targets

Abstract

The visual world consists of rather stable regularities, which are acquired through experience and can be used for spatial orientation. For example, search for a specific target location becomes progressively faster when it is repeatedly presented with an invariant context of nontargets compared to randomly arranged nontargets (contextual cueing). However, scenes also change, requiring observers to adapt established representations. Here, we investigated whether established context-target representations are adapted to a permanent relocation of targets. Additionally, we tested whether observers represent both initial and relocated targets. On the first day of the study, contexts were presented with initial target locations. Subsequently, observers were trained with the same contexts, but relocated targets on four consecutive days. A week later observers were tested with both target locations. In contrast to fast contextual learning of initial target locations, adaptation to relocated targets only developed slowly after several days of training. However, contextual cueing of relocated targets was reliable in the last training session. Furthermore, the last session of the study revealed that two target locations were eventually cued by invariant contexts. Thus, time-consuming training is necessary to observe adaptation of contextual associations, which results in stable cueing effects for changed context-target relations, but does not interfere with initial contextual associations.

Introduction

In real-world scenes, certain objects co-occur with each other (see Oliva & Torralba, 2007, for review), or are likely to occur at a particular location within a certain environment (Bar, 2004, for review), and these stable regularities can facilitate attentional orienting (Castelhano & Heaven, 2011; Mack & Eckstein, 2011). For example, computer monitors co-occur with keyboards and are likely to be located on a desk in an office. Observers learn such spatial regularities implicitly; that is, just by working in an office, observers incidentally acquire a memory representation of the office's spatial context (see Cleeremans et al., 1998; and Perruchet & Pacton, 2006, for reviews), which then facilitates visual search for particular objects, for instance, search for a filing folder. However, familiar spatial layouts might also undergo changes, such as a permanent relocation of the filing folder to a different shelf in the office. In the present study, we investigated how a sudden, but permanent change in the location of a target object is integrated into an established representation of context-target associations, such that visual search for the new target location becomes as fast as search for the initial target location (relearning).

Previous studies have suggested that observers are rather inflexible to relearn contextual associations, when a target is relocated to a new position within its otherwise invariant context of nontargets (Makovski & Jiang, 2010; Manginelli & Pollmann, 2009; Study II). To test effects of change on contextual cueing, Manginelli and Pollmann (2009), for example, presented each context with a unique target location in a learning phase, after which targets were relocated to new positions within their context. While contextual cueing was observed for initial target locations, no such effect occurred for relocated targets. Furthermore, contextual cueing of relocated targets was not even observed when they were presented more than twice as often as initial target locations (Study II). Hence, recent studies suggest that contextual adaptation to a second target location (subsequently to learning a first target location) is not particularly effective.

The previous lack of adaptation to relocated targets could be related to the assumption that contextual cueing is restricted to a single target location, which could potentially prevent competition between target locations (single-target learning; Study I). If, for example, two target locations were associated with one context, the context would cue both locations (causing competition), and the inspection of both locations would slow visual search, which would reduce the overall contextual-cueing effect of the respective context. By contrast, single-target learning would secure fast visual search for at least one target location. Brady and Chun (2007) also suggested that contextual cueing should be reduced if an invariant context is associated with two different target locations. However, they argued that observers will, in fact, integrate at least two target locations into one invariant context, if they perform repeated visual search for both target locations (see also Chun & Jiang, 1998; Kunar & Wolfe, 2011).

In the present study, we tested whether repeated search for two sequentially presented target locations will result in contextual cueing of both target locations. In particular, we investigated whether a large number of repeated searches (extensive training) would promote the adaptation of contextual associations to relocated targets subsequently to contextual learning of initial target locations. Furthermore, we tested how the (potential) adaptation to relocated targets affects contextual cueing of initial target locations. The study consisted of three phases (see Study II) performed in six separate sessions (similar to Jiang et al., 2005): On the first day of the study, contexts were presented with initial target locations (*learning phase*). Subsequently, targets were relocated to new positions within their respective contexts, and the new context-target pairings were presented on four consecutive days (*relocation phase*) to train observers extensively with relocated targets. About a week after the last session of the relocation phase contextual cueing of both target locations was tested in a final *return phase*.

Training sessions were separated by overnight breaks to facilitate contextual cueing of relocated targets by both reducing proactive interference and by promoting memory consolidation. In general, active old memories tend to impair the acquisition of new memories (proactive interference) in implicit learning tasks (Lustig & Hasher, 2001a, for review), but proactive interference is supposed to subside effectively during sleep (see Jiang et al., 2005; and Mednick et al., 2009, for proactive interference in contextual cueing). Hence, the restraining impact of old context-target associations (from Day 1) on acquiring changed associations (starting on Day 2) should decrease after overnight breaks. Simultaneously, overnight breaks after each relocation session should stimulate memory consolidation (Albouy et al., 2006; Durrant, Taylor, Cairney, & Lewis, 2011; Spencer, Sunm, & Ivry, 2006), which might also increase chances for relearning to occur.

The return phase was implemented to test possible consequences of training in the relocation phase: Both target locations could elicit contextual-cueing effects after prolonged training, but this could result in competition between target locations as reflected by a reduction in contextual-cueing effects (as predicted by Brady & Chun, 2007; see also Lustig & Hasher, 2001b, for competition effects between implicitly cued responses). Alternatively, contextual cueing might only occur for either one of the target locations. On the one hand, adaptation to relocated targets might not occur, while contextual cueing of initial target locations might be retained across the relocation phase (see Study II). On the other hand, adaptation to relocated targets could occur and could result in forgetting of initial target locations. Either result would support the assumption that contextual cueing is restricted to a single target location (as proposed in Study I).

Experiment 8

Method

Subjects

Fourteen adults took part in the experiment (11 women, $M_{\text{age}} = 24.4$ years; age range: 18–29 years). All subjects reported normal or corrected-to-normal visual acuity, and one subject was left-handed. They received either payment (40 €) or six course credits. In order to test adaptation of existing contextual associations to relocated targets, subjects only performed all sessions of the experiment, if they showed above-zero contextual cueing for initial target locations in the learning phase (see Study II).

Apparatus and Stimuli

See Study I.

Trial sequence

See Study I.

Design and Procedure

Design and Procedure were similar to Study I and Study II except for a few differences. We implemented a repeated-measures design, with the (within-subject) factors Context (old, new) and Epoch (1–6) on Day 1 to Day 5. Figure 20 depicts an example search display with an invariant configuration of nontargets paired with two different target locations as well as the experimental procedure.

In each session, the experiment started with a practice block of 24 randomly generated displays to familiarise subjects with the task. Overall, subjects completed 744 trials on each of the first five days.

Day 1 — Learning Phase. Old- and new-context displays were presented with the initial of two possible target locations.

Days 2–5 ─ Relocation Phase. The relocation phase consisted of four separate sessions conducted on four consecutive days. On each day, the experimental design was similar to Day 1, except that relocated targets were presented in old- and new-context displays (Figure 20). Each session was conducted at approximately the same time of day, such that subjects had 24-hour breaks between single sessions.

Day 10 ─ Return Phase. Five days after Day 5 subjects returned to the lab for the last part of the experiment. After an initial practice block, subjects completed ten further blocks (2 epochs) presenting the old-context displays from the first five days and randomly generated new-context displays. Both initial target locations and relocated targets were presented in half of the blocks (5 consecutive blocks each; see Figure 20). The order of target presentation was counterbalanced across subjects: The first target location was presented first for half of the subjects (TL 1 first), the order of presentation was reversed for the other half of the subjects (TL 2 first). The search task was followed by a final recognition test (see Study II).

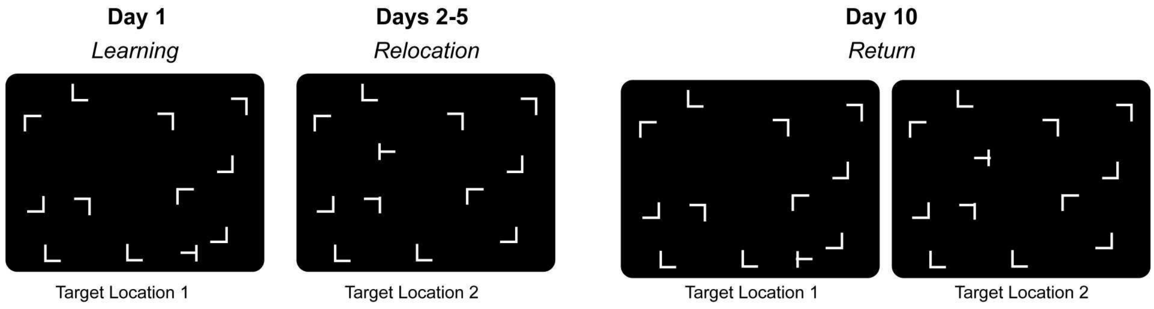

Figure 20: Example old-context display and experimental procedure in Experiment 8. Displays were presented with initial target locations (target location 1) in the learning phase on Day 1. Subsequently, targets were relocated and repeatedly presented at their new location (target location 2) on four consecutive days (relocation phase). On Day 10, displays were presented with both initial (target location 1) and relocated targets (target location 2; return phase).

Results

Search Task

Individual mean error rates were calculated for each variable combination. Across all days, subjects made relatively few errors (range: 1.4% – 2.3%). Repeated-measures ANOVAs with context (old, new) and epoch (1–6) as within-subject factors were computed for the first five days. The only significant effect was a main effect of context on Day 5, $F(1, 13) = 4.99$, $p < .05$, reflecting fewer errors for old contexts (2.1%) compared to new contexts (2.6%). For the sixth day, a separate ANOVA with the within-subject factors Context (old, new) and Target (1, 2) and the between-subject factor Order (TL 1 first, TL 2 first) did not reveal any main or interaction effects (ps > .2).

Next, individual mean RTs were calculated for old and new contexts separately for each day as well as epoch. Error trials and RTs exceeding an individual's mean RT by ± 2.5 standard deviations (outliers) were excluded from RT analyses. The number of outliers was comparable between experimental sessions (range: 2.3% – 2.8%). Greenhouse-Geisser corrected values are reported in case Mauchley's test of sphericity was significant ($p < .05$).

Figure 21 displays the mean RTs for old- and new-context displays across epochs for Days 1 to 5, and Figure 22 shows RTs for old and new contexts separately for each target location on Day 10. As a first step, an overall ANOVA with the within-subject factors Context (old, new) and Day (1–5, 10) yielded main effects of context, $F(1, 13) = 13.50$, $p < .01$, and of day, $F(1.42, 18.51) = 4.99$, $p < .001$. More important, the interaction between context and day was significant, $F(2.14, 27.85) = 8.80$, $p < .01$, indicating that contextual cueing was significantly affected by the changes in target location. To further explore the interaction, separate repeated-measures ANOVAs with the factors Context (old, new) and Epoch (1–6) follow for Days 1 to 5.

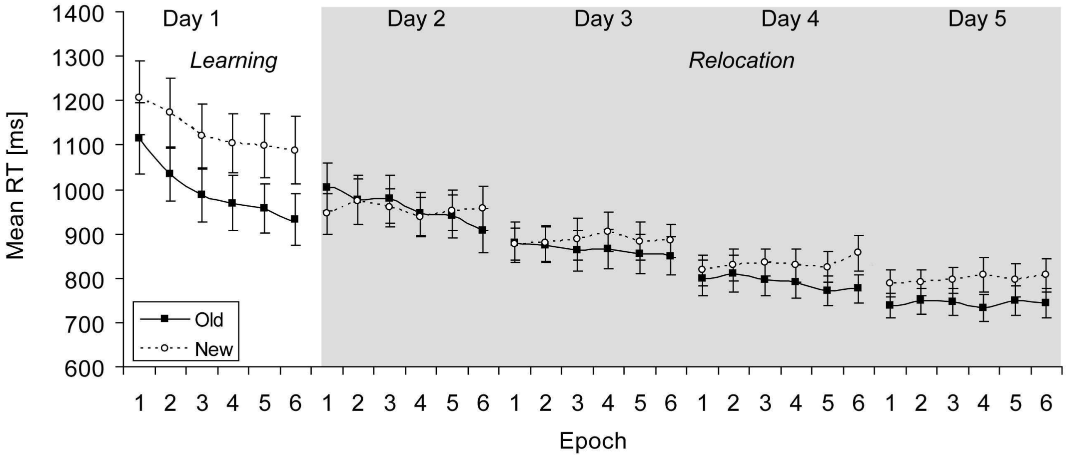

Figure 21: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch on Days 1–5 in Experiment 8.

Day 1 — Learning Phase. For Day 1 (initial target locations), the analysis revealed a significant main effect of context, $F(1, 13) = 24.59$, $p < .001$, and a main effect of epoch, $F(2.18, 28.32) = 14.41$, $p < .001$, but no interaction between context and epoch ($p > .3$). RTs were faster for old contexts in comparison to new contexts (132 ms), and RTs decreased (by 150 ms) across epochs. An additional analysis performed on individual blocks (rather than epochs) revealed the first significant difference between old and new contexts in block 3, $t(13) = -2.46$, $p < .05$, which is comparable to findings of fast contextual learning in previous studies (e.g., Conci & von Mühlenen, 2009).

Days 2–5 — Relocation Phase. For Day 2 (relocated targets), the main effect of epoch was significant, $F(3.30, 42.95) = 3.33$, $p < .05$, and the interaction between context and epoch reached significance, $F(5, 65) = 5.68$, $p < .001$. The RT difference between old and new contexts increased from -60 ms in epoch 1 to 50 ms in epoch 6. To explore this interaction, RTs for old and new contexts in each epoch were compared by computing paired-sample t-tests, which revealed significantly faster RTs for old contexts compared to new contexts only in epoch 6, $t(13) = 2.71$, $p = .02$, but not in any other epoch (ps > .09). The main effect of context was not significant ($p > .8$); mean contextual cueing across all epochs was -5 ms.

Contextual cueing was not observed on Day 3; no main or interaction effects were significant (*p*s > .1). Mean contextual cueing was 21 ms.

For Day 4, the main effect of context became significant, *F*(1, 13) = 5.16, *p* < .05, and a significant interaction between context and epoch, *F*(5, 65) = 3.93, *p* < .01, revealed that contextual cueing developed across epochs from a mean effect of 18 ms in epoch 1 to 80 ms in epoch 6. Mean contextual cueing across all epochs was 41 ms. The main effect of epoch was not significant (*p* > .3).

Contextual cueing became stable on Day 5 as represented by a significant main effect of context, *F*(1, 13) = 11.33, *p* < .01, mean contextual cueing across all epochs was 54 ms. The main effect of epoch and the interaction between context and epoch were not significant (*p*s > .3).

<u>Day 10 — Return Phase.</u> For Day 10 (initial target locations and relocated targets), an ANOVA with the within-subject factors Context (old, new) and Target (TL 1, TL 2) and the between-subject factor Order (TL 1 first, TL 2 first) revealed a significant main effect of context, *F*(1, 12) = 18.78, *p* < .01, reflecting faster RTs for old contexts (by 67 ms) compared to new contexts (see Figure 22). The main effect of target was marginally significant, *F*(1, 12) = 4.68, *p* = .051, representing slower RTs for initial target locations than for relocated targets (by 42 ms). All other main and interaction effects were not significant (*p*s > .1). Contextual cueing was comparable between initial target locations and relocated targets (67 ms and 68 ms, respectively), *t*(13) = -.03, *p* = .97.

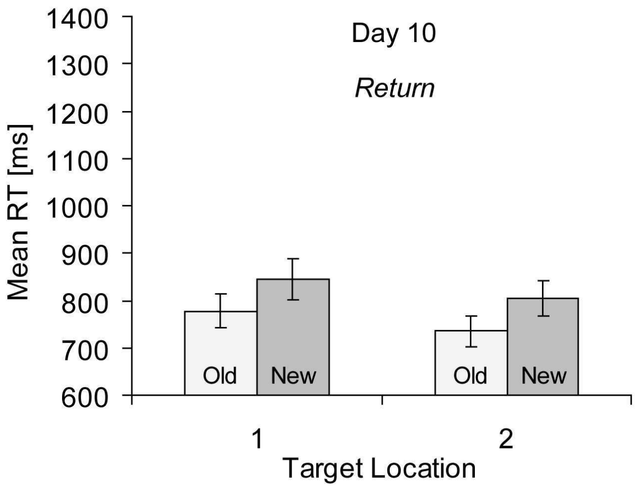

Figure 22: Mean RTs (in ms, and associated standard errors) for old and new contexts, separately for initial target locations (target location 1) and relocated targets (target location 2) on Day 10 in Experiment 8.

Comparison Between Sessions. To compare contextual-cueing effects of the first target location on Day 1 with contextual-cueing effects on all other days, relative contextual-cueing effects were calculated for each day [(RT(new) - RT(old))/RT(new)]. By calculating relative contextual-cueing effects, we take into account that the general acceleration of RTs across days reduces absolute contextual-cueing effects (see Jiang et al., 2005). Simple contrasts were computed between the relative contextual-cueing effect for initial target locations on Day 1 and the relative contextual-cueing effects of all other days (Table 1). Contextual cueing of relocated targets on Days 2 to 5 was significantly smaller than contextual cueing of initial target locations on Day 1. But contextual cueing of both initial target locations and relocated targets on Day 10 was similar to contextual cueing of initial target locations on Day 1. Thus, contextual cueing of relocated targets was only comparable to contextual cueing of initial target locations (baseline) on Day 10; note, though, that contextual cueing of relocated targets did not increase significantly from Day 5 to Day 10, $t(13) = -1.04$, $p = .32$. Furthermore, contextual cueing of initial target locations was as effective on Day 10 as it was on Day 1.

Table 1: Planned contrasts between relative contextual cueing of initial target locations (TL 1) on Day 1 and relative contextual cueing of relocated targets (TL 2) on Days 2–5, as well as relative contextual cueing of both initial target locations (TL 1) and relocated targets (TL 2) on Day 10 in Experiment 8.

	Day 1	*Day 2*	*Day 3*	*Day 4*	*Day 5*	*Day 10*	
	TL 1		*TL 2*			*TL 1*	*TL 2*
M relative contextual cueing (%)	11.20	-.80	2.10	4.50	6.20	7.10	7.80
F(1, 13)		17.88	11.48	7.10	6.01	2.81	1.47
p		.001	.005	.019	.029	.117	.246

Recognition Test

Overall, the mean accuracy of recognising old and new contexts was 52.2%. Subjects identified old contexts on 56.6% of trials correctly (hit rate). The rate of reporting new contexts as old (false alarms) was 53% and did not differ significantly from the hit rate, $t(13) = .73$, $p = .48$, suggesting that subjects were mostly not able to explicitly distinguish between old and new contexts.

Discussion

The present study tested whether established memory representations of spatial context-target layouts can be adapted to changes in target locations. Spatial contexts were presented with initial target locations in a learning phase on Day 1. Subsequently, targets were relocated within their contexts and observers were trained with the new locations on four consecutive days (relocation phase, Days 2–5). Another five days later, observers were tested with both target locations (return phase, Day 10). Overall, we found that observers were rather inflexible to adapt to relocated targets at first, but extensive training in the relocation phase eventually resulted in the successful adaptation of contextual associations to relocated targets. Furthermore, contextual cueing of relocated targets seemed to further consolidate during the break between Day 5 and Day 10, which, however, did not interfere with contextual cueing of initial target locations. In addition, even though the same old contexts were presented on several days, observers were not able to distinguish between old and new contexts (see also Le Dantec, Melton, & Seitz, 2012), which strongly suggests that memory representations in contextual cueing are implicit (Chun & Jiang, 1998, 2003).

The pattern of results of the first three days resembled previous findings: While contextual cueing was observed for initial target locations on the first day, reliable contextual cueing was not observed for relocated targets on the first two days of training in the relocation phase (Manginelli & Pollmann, 2009). However, contextual cueing of relocated targets started to develop on the fourth day, after observers had encountered relocated targets twice as often as initial target locations. Only on Day 5, after three days of training, was contextual cueing of relocated targets reliable across epochs. It therefore seems that single-target learning (Study I) restrained adaptation of contextual associations for a considerable period, but the training conditions in the relocation phase overpowered this restraint.

In Study II, adaptation to relocated targets was not observed, although relocated targets were also presented more than twice as often as initial target locations. In contrast to the present study, the former relocation phase did not consist of multiple sessions performed on consecutive days (besides fewer presentations overall). Thus, it seems that beneficial effects of training with relocated targets are revealed when training sessions are interspersed with overnight breaks. This finding implies that adaptive relearning of contextual associations might have been facilitated by the progressive reduction of proactive interference during sleep (Mednick et al., 2009). In addition, sleep-dependent consolidation processes could have enhanced contextual learning of relocated targets, which generally agrees with previous reports of sleep-dependent consolidation in implicit statistical learning (Durrant et al., 2011; Spencer et al., 2006; but see Arciuli & Simpson, 2012; Mednick et al., 2009). Overall, the findings of the relocation phase showed that contextual associations are slowly adapted to changes in target location, if rather time-consuming training sessions are conducted.

Although contextual cueing of relocated targets developed across consecutive days of training, its magnitude became comparable to contextual cueing of initial target locations only in the final return phase on Day 10 ─ five days after the relocation phase. Hence, memory consolidation for relocated targets might have continued during the 5-day-break between relocation and return phase. This could mean that the newly acquired context-target associations from the relocation phase were further boosted by a rather slow offline consolidation process that occurs independently of sleep-induced effects (McGaugh, 2000). However, contextual cueing of relocated targets was already stable on Day 5, and was not further increased on Day 10. Thus, the current results do not conclusively suggest that adapted context-target associations were consolidated after the end of the relocation phase (see also Arciuli & Simpson, 2012).

Despite successful relearning of new target locations in the relocation phase of the present study, contextual cueing of initial target locations was unaffected, since it was as reliable in the return phase (Day 10) as in the learning phase (Day 1). This finding confirms that initially acquired contextual associations are resistant to retroactive interference (Jiang et al., 2005; Jungé et al., 2007; Study II). In addition, contextual cueing of relocated targets was also retained from the relocation to the return phase. The perseverance of cueing-effects for both target locations supports the assumption that implicitly learned contextual associations are long-lasting and stable (Chun & Jiang, 2003; Jiang et al., 2005; Mednick et al., 2009; van Asselen & Castelo-Branco, 2009; Study II).

In contrast to the results of the present study, observers quickly associate a cue (e.g, FRUIT) with two alternative responses (e.g., BANANA, MANGO) presented in sequential order in explicit learning tasks within a short period of time. However, selectively retrieving the second response upon cueing usually reduces recall performance of the first response. It is assumed that the first association is inhibited to reduce interference between responses at selective retrieval, an effect referred to as retrieval-induced forgetting (see Anderson, 2003, for an overview). Lustig and Hasher (2001a) argued that interference between two possible responses might be even greater in implicit learning, because observers cannot consciously differentiate between responses (Note that these authors were referring to a target and a similar nontarget as possible responses to a cue.). Indeed, in the present study, search times for initial target locations in the return phase were slower than for relocated targets (in both old and new contexts), which might point to slight "inhibition" of initial target locations through the long training with relocated targets. Yet it seems more likely that the larger number of repeated searches for relocated targets relative to initial target locations contributed to the observed advantage for relocated targets through learning of location probabilities (independently of the context; e.g., Chun & Jiang, 1998; Jiang et al., 2012). More important, contextual cueing of initial target locations was not reduced after selectively learning relocated targets for four days, which suggests that retrieval-induced forgetting was not observed in the present study of implicit contextual learning.

Furthermore, the presentation of targets at both locations in the return phase did not seem to result in competition between target locations, which would be reflected by a reduction in contextual cueing compared to cueing of one target location in the learning phase (as suggested by Brady & Chun, 2007). The absence of competition between cued target locations has already been reported for predictable changes in context-target associations (Conci & Müller, 2012; Conci et al., 2011; Study IV). For example, in Experiment 2 of the study by Conci et al. (2011), search displays always contained two targets at two different locations (one was oriented left/ right, one was pointing upward/ downward). Observers searched for one of the targets in one half of the experiment and for the other target in the other half of the experiment, which resulted in comparable contextual cueing for both target locations. Similarly, a reduction of contextual cueing was not observed when relocated targets were familiar to observers from presentations in the learning phase (see Study IV; see Beesley & Le Pelley, 2010, for a similar result with a version of the Serial Reaction Time Task). Even if contextual associations with two target locations cause some kind of response-competition, this does not have an adverse impact on observable contextual-cueing effects.

In sum, the present study showed that implicit contextual representations appeared to be inflexible to adapt to sudden, but permanent relocations of targets at first, but extended training combined with offline consolidation eventually lead to the integration of changed context-target relations. Furthermore, successfully adapting to new target locations did not affect associative memory for initial target locations. Consequently, the current results show that observers are able to associate one context with two (sequentially presented) target locations (as was proposed by Brady & Chun, 2007; and Chun & Jiang, 1998). Finally, associating one contextual cue with two responses did not result in observable response-competition in implicit contextual learning.

STUDY IV

Adaptation of Context-Guided Visual Search to Predictable Target Relocations

Abstract

Observers are capable to extract statistical regularities from the visual world, which can facilitate attentional orienting. For instance, visual search benefits from the repetition of target locations by means of probability learning. Furthermore, repeated contexts of nontargets contribute to fast visual search in comparison to random arrangements of nontargets by cueing target locations (contextual cueing). In the present study we investigated how probability learning modulates the adaptation of contextual cueing to a change in target location. After an initial learning phase, targets were relocated within their respective contexts to positions that were new within a given context, but familiar from previous repeated presentations in old and new contexts. Contextual cueing was observed for relocated targets that originated from old contexts, but turned into costs when relocated targets had previously been presented in new contexts. Thus, probability learning was not sufficient to observe adaptive contextual cueing for relocated targets. Instead, the contextual past of target locations ─ whether they had been cued or not ─ modulated the integration of relocated targets into a learned context. The findings imply that observers extract multiple aspects of available scene statistics interactively, and use them to infer hypotheses about future occurrences of familiar stimuli.

Introduction

In familiar visual scenes, like your own kitchen, statistical regularities contribute to efficient attentional orienting. For example, observers are sensitive to lower-order statistics such as highly probable locations of a target object (e.g., airplane above horizon: Neider & Zelinsky, 2006; see also Druker & Anderson, 2010; Fiser & Aslin, 2002; Geng & Behrmann, 2005; Jiang et al., 2012). Moreover, observers deploy higher-order statistics such as the co-occurrence of objects with each other (e.g., pans and pots; Fiser & Aslin, 2002; see Oliva & Torralba, 2007, for review) and the location of objects in relation to their typical environment (e.g., saucepan on stove in kitchen; Bar, 2004, for review). Thus, observers extract both location probabilities and contextual relations over time, which then facilitate the guidance of attention.

The contextual-cueing effect reported by Chun and Jiang (1998) is an example of statistical learning, which effectively includes both learning of location probabilities and contextual relations. While target locations are mostly fixed for each old context in contextual cueing experiments, real-life objects (such as a pan) are likely to change locations or to appear in several (recurring) positions within their environments. Thus, ideally, statistical learning of contextual relations should be flexibly adapted to changes and should include representations of multiple, recurring target locations. However, several studies have reported that contextual cueing does not occur when targets were relocated within otherwise invariant contexts (Chun & Jiang, 1998; Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). For example, in the study by Manginelli and Pollmann (2009), observers learned to associate old contexts with unique target locations. After this initial learning phase, targets were relocated to new positions within otherwise invariant contexts. Target relocation cancelled the contextual-cueing effect, which did not recover after repeated presentations of the new target locations. Contextual cueing was not even observed, when the relocations were fairly permanent with at least twice as many presentations of relocated targets relative to initial target locations (Study II). This pattern of results suggests that contextual cueing is restricted to single-target learning (Study I), meaning that each old-context display can probably cue only one target location (and its immediate surround; see also Makovski & Jiang, 2010), but no further repeated target locations benefit from invariant contexts.

Yet Conci and colleagues (2011) reported successful contextual learning of two target locations presented in one context. In each trial, search displays contained two targets at two different locations simultaneously (one was oriented left/ right, one was pointing upward/ downward). Both targets were present in each trial, but observers only searched for one of the targets in one half of the experiment and for the other target in the other half of the experiment. Reliable contextual cueing was observed for both target locations, which was probably due to the continuous presence of both targets, making them predictable (multiple-target learning; see also Brady & Chun, 2007; Conci & Müller, 2012; Kunar & Wolfe, 2011). This finding suggests that predictability might be a key factor for successful adaptation to relocated targets in contextual learning. In the present study, we further investigated whether changed target locations are associated with an old context, if changed target locations are predictable instead of being completely new.

As mentioned above, a limited number of target locations are repeated in both old and new-context displays in contextual-cueing experiments. That means, target locations are to some extent predictable independently of the surrounding contexts (in old and new contexts), which enables a progressive reduction in response times through probability learning (Brady & Chun, 2007; Chun & Jiang, 1998; see also Myers & Gray, 2010 for eye movement data). In the present study, we made use of this (lower-order) probability learning to achieve adaptation to relocated targets in (higher-order) contextual learning. Specifically, targets were relocated to previously repeated locations, instead of introducing completely new target locations as in previous studies (e.g., Manginelli & Pollmann, 2009). In an initial learning phase, contexts were presented with fixed target locations (comparable to Manginelli & Pollmann, 2009). Subsequently, target locations were exchanged between old contexts (Experiment 9; see Figure 23). For example, the target location (e.g., the location of a toaster) of old context A (in your kitchen) appeared in old context B (e.g., in your parents' kitchen) and vice versa. In Experiment 10, target locations were exchanged between old- and new-context displays. That means, repeated target locations of random contexts were relocated to old contexts, while repeated target locations of old contexts appeared in randomly arranged (new) contexts (see Figure 25). Similar to the design of Conci et al. (2011), all target locations, including relocated targets, were learnable (familiar) through repeated presentations in the learning phase, and location probabilities were constant throughout the experiments. But contextual relations were varied in the present study, meaning that the actual context-target pairings after target exchange were new (see Manginelli & Pollmann, 2009), requiring observers to adapt learned contextual associations to change. We expected to observe contextual cueing for target locations in the exchange phases, if predictability is a necessary and sufficient premise for adaptation of contextual associations to relocated targets.

After the exchange phases, initial context-target pairings (from the learning phase) were presented again to show that relocated targets do not interfere with initially acquired contextual representations (adopted from Study II and Study III). Furthermore, if contextual cueing occurs in both the exchange and return phases, the study would provide evidence for multiple-target learning (as originally proposed by Brady & Chun, 2007; see also Conci et al., 2011; Kunar & Wolfe, 2011).

Experiment 9

Experiment 9 was designed to investigate whether contextual adaptation to relocated targets would be facilitated, if the relocated targets are already familiar and, therefore, predictable. Each old-context display was paired with a unique target location and repeatedly presented during an initial learning phase. Subsequently, target locations were exchanged between old-context displays (exchange phase; see Figure 23). For example, if one target location was initially paired with context A (and another target location with context B), then, this target location was presented with context B in the exchange phase (and the other target location with context A). In a final phase, target locations were returned to their original contexts (return phase). Unlike previous studies (Manginelli & Pollmann, 2009; Study II), relocated targets were highly familiar from the learning phase in Experiment 9 (see Conci & Müller, 2012; Conci et al., 2011), but completely new within a given old context in the exchange phase (Manginelli & Pollmann, 2009). If predictability facilitates adaptation to relocated targets (Conci & Müller, 2012; Conci et al., 2011), contextual cueing should occur for relocated targets in the exchange phase of Experiment 9.

Methods

Subjects

Thirteen adults took part in the experiment (11 women; $M_{\text{age}} = 24$ years, age range: 19–30 years). All subjects reported normal or corrected-to-normal visual acuity, and one subject was left-handed. They received either payment (8€) or one course credit for their participation. In order to test adaptation of existing contextual associations, we only report results of subjects who showed (above zero) contextual-cueing effects for initial target locations in the learning phase (see Study II and Study III).

Apparatus and Stimuli

See Study I.

Trial Sequence

See Study I.

Design and Procedure

Design and Procedure were similar to the previous studies except for a few differences. Experiment 9 implemented a 2 x 8 repeated-measures design, with the (within-subject) factors Context (old, new) and Epoch (1–8).

Figure 23 depicts example search displays with invariant configurations of nontargets as well as the experimental procedure. After a learning phase of three epochs (blocks 1–15) target locations were exchanged between old-context displays. That is, each old-context display was presented with a target location from another old-context display in epochs 4 to 7 (exchange phase; blocks 16–35). In the last, eighth epoch of the experiment target locations returned to their original old-context display (return phase; blocks 36–40; see Figure 23). Overall, observers completed 984 trials.

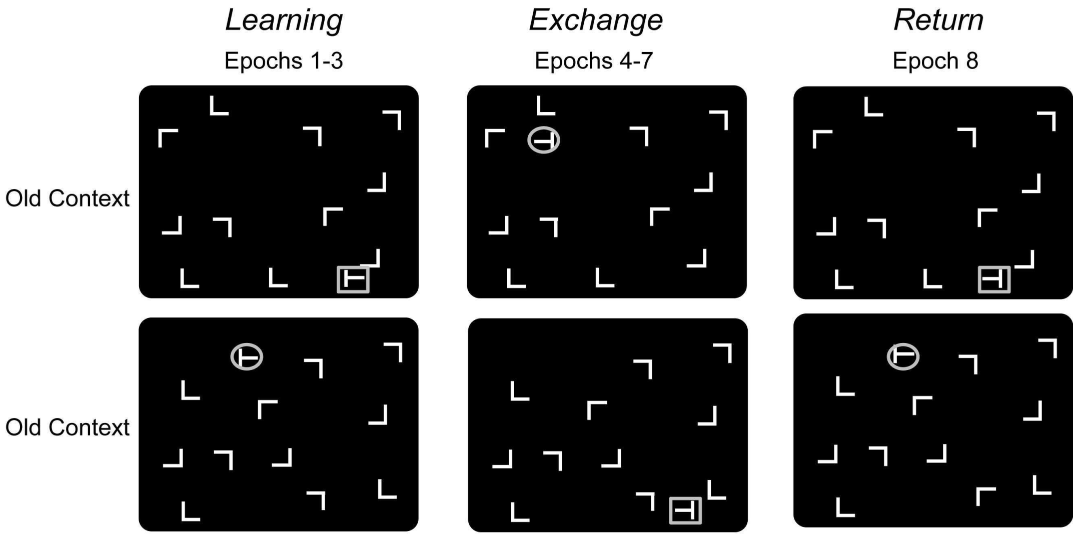

Figure 23: Example old-contexts displays (top and bottom half) and experimental procedure in Experiment 9. Search displays were initially paired with unique target locations in the learning phase (highlighted here by a square and a circle, which were not presented to subjects). Subsequently, target locations were exchanged between old-context displays in the exchange phase. The final return phase presented initial context-target pairings again.

Recognition Test

See Study II and Study III.

Results

Search Task

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

Next, individual mean RTs were calculated for old and new contexts, separately for each epoch. Error trials and RTs exceeding an individual's mean RT by ± 2.5 standard deviations were excluded from analyses. This outlier criterion led to the removal of 2.5% of the data; the same outlier procedure was applied in Experiment 10, resulting in comparable exclusion rates. Greenhouse-Geisser corrected values are reported in case Mauchley's test of sphericity was significant ($p < .05$).

In a first step, individual mean RTs were computed for old and new contexts in each phase (learning, exchange, return). An overall ANOVA with the factors Context (old, new) and Phase (learning, exchange, return) was performed to investigate whether contextual cueing changed in the different phases of the experiment. This analysis yielded significant main effects of context, $F(1, 12) = 15.68$, $p < .01$, and of epoch, $F(1.24, 14.89) = 11.44$, $p < .01$, but the interaction between context and phase was not significant ($p > .2$), which already indicates that the exchange and return of target locations did not affect contextual cueing significantly (see Figure 24). Separate analyses follow for each experimental phase.

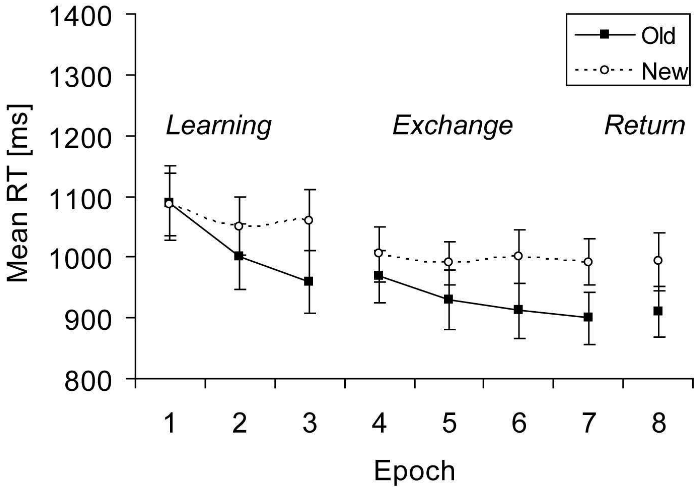

Figure 24: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as a function of epoch in Experiment 9.

For the learning phase (initial target locations), a repeated-measures ANOVA with the factors Context (old, new) and Epoch (1–3) revealed a significant main effect of context, $F(1, 12) = 11.16$, $p < .01$, and a significant main effect of epoch, $F(2, 24) = 10.09$, $p < .01$. RTs were on average 50 ms faster for old contexts than for new contexts and decreased by 78 ms across epochs. The interaction between context and epoch was also significant, $F(2, 24) = 7.25$, $p < .01$, reflecting an increase in the mean contextual-cueing effect during the learning phase (from -2 ms to 102 ms). Further analysis based on blocks rather than epochs revealed the first significant difference in RTs between old and new contexts in block 8, $t(12) = -3.02$, $p = 01$, which is in line with a fast development of contextual cueing in other studies (e.g., Conci & von Mühlenen, 2009) and with Experiment 10 of the present study.

A similar pattern of results was obtained for the exchange phase: A repeated-measures ANOVA with the factors Context (old, new) and Epoch (4–7) yielded significant main effects of context, $F(1, 12) = 10.62$, $p < .01$, and of epoch, $F(3, 36) = 3.28$, $p < .05$. On average, RTs for old contexts were 70 ms faster than for new contexts, and RTs decreased by 41 ms from epoch 4 to epoch 7. The interaction between context and epoch was also significant, $F(3, 36) = 3.08$, $p < .05$, which means that the RT-advantage for old contexts increased across epochs (from 37 ms to 93 ms). The effect of exchanging target locations on contextual cueing was further analysed with an ANOVA with the factors Context (old, new) and Epoch (3–4; i.e., before and after target location exchange). The interaction between context and epoch was significant, $F(1, 12) = 17.52$, $p < .01$ (main effect context, $F(1, 12) = 12.33$, $p < .01$): Upon exchanging target locations, contextual cueing was significantly reduced in epoch 4 (37 ms; difference between old and new contexts was not significant, $t(12) = -1.49$, $p = .16$) in comparison to epoch 3 (102 ms).

In the last epoch of the experiment (return of initial target locations), RTs for old contexts were 82 ms faster than for new contexts, $t(12) = -3.67$, $p = 00$. Returning target locations in epoch 8 did not affect RTs as reflected by an ANOVA with the factors Context (old, new) and Epoch (7–8; i.e., before and after the return of initial target locations), which revealed no interaction between context and epoch ($F < 1$; main effect of context, $F(1, 12) = 17.9$, $p < .01$).

Recognition Test

Overall, the mean accuracy of recognising old and new contexts was 45.8%. Observers recognised old contexts as old contexts on 45.5% of the trials (hit rate), and new contexts as old contexts on 53.9% of the trials (false alarms). The difference between hits and false alarms was not significant, $t(12) = -1.14$, $p = .28$. Because observers did not reliably distinguish between old and new contexts, they were most likely unaware of the repetition of old contexts.

Discussion

The results of Experiment 9 confirmed that one repeated context can cue two different target locations, provided they are predictable (see also Conci & Müller, 2012; Conci et al., 2011). In the learning phase, contextual cueing occurred for old-context displays paired with initial target locations (50 ms). When target locations were exchanged between old-context displays, contextual cueing was transiently reduced, but cueing effects successfully recovered after a few epochs. Contextual-cueing effects for exchanged targets (70 ms) were comparable to contextual-cueing effects for initial target locations towards the end of the exchange phase. Moreover, contextual cueing of initial target locations was preserved throughout the exchange phase, as indicated by robust contextual cueing in the final return phase (82 ms). Thus, initial context-target associations were not affected by repeated presentations of exchanged target locations (see Study II & Study III, for comparable findings).

Experiment 10

In Experiment 10, target locations of old-context displays were exchanged with target locations of new-context displays after an initial learning phase. The exchange phase was again followed by a final return phase, which presented contexts with initial target locations (see Figure 25). Probability learning typically occurs for all repeated target locations in both old- and new-context displays (Chun & Jiang, 1998; Jiang et al., 2012). Hence, target locations of new-context displays should also be more predictable than completely new target locations presented as relocated targets in previous studies (e.g., Conci et al., 2011; Manginelli & Pollmann, 2009; Study II & Study III). Therefore contextual cueing was expected to occur for old-contexts in the exchange phase of Experiment 10.

Methods

The methodological details were similar to Experiment 9, except that target locations were exchanged between old- and new-context displays after the learning phase in Experiment 10 (see Figure 25). Old- and new-context displays were presented with fixed target locations in a learning phase (epochs 1–3). In the subsequent exchange phase (epochs 4–7), target locations from new contexts appeared in old contexts and target locations from old contexts appeared in new contexts. Finally, initial context-target layouts (from the learning phase) were again presented in the return phase (epoch 8).

Twelve adults took part in the experiment (8 women; $M_{\text{age}} = 28.1$ years, age range: 19–38). All subjects reported normal or corrected-to-normal visual acuity, and were right-handed. They received either payment (8€) or one course credit for their participation.

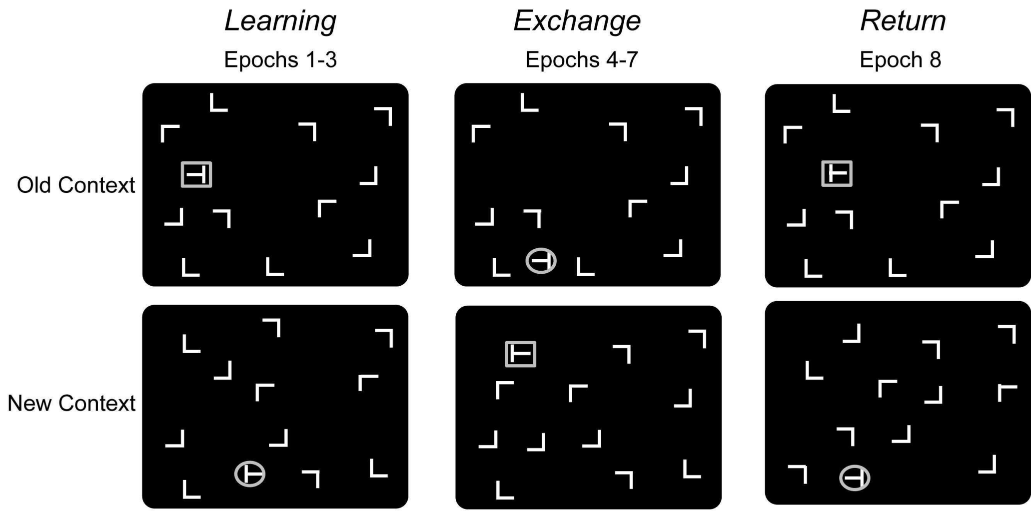

Figure 25: Example old- (top half) and new-context displays (bottom half) and experimental procedure in Experiment 10. Search displays were paired with unique target locations in the learning phase (highlighted here by a square and a circle, which were not presented to subjects). Subsequently, target locations were exchanged between old- and new-context displays in the exchange phase. The final return phase presented initial context-target pairings.

Results

Search Task

Individual mean error rates were calculated for each variable combination. The overall error rate was low (2.2%), and a repeated-measures ANOVA with the factors Context (old, new) and Epoch (1–8) revealed no significant effects (all *p*s > .1).

After the exclusion of error trials and outliers, individual mean RTs were calculated for old and new contexts, separately for each epoch. First, an overall ANOVA with the factors Context (old, new) and Phase (learning, exchange, return) revealed significant main effects of context, $F(1, 11) = 20.79$, $p < .01$, and of phase, $F(1.27, 13.94) = 7.30$, $p < .05$, as well as a significant interaction between context and phase, $F(2, 22) = 18.31$, $p < .001$, which means that the exchange and return of target locations affected contextual cueing (see Figure 26). Separate analyses follow.

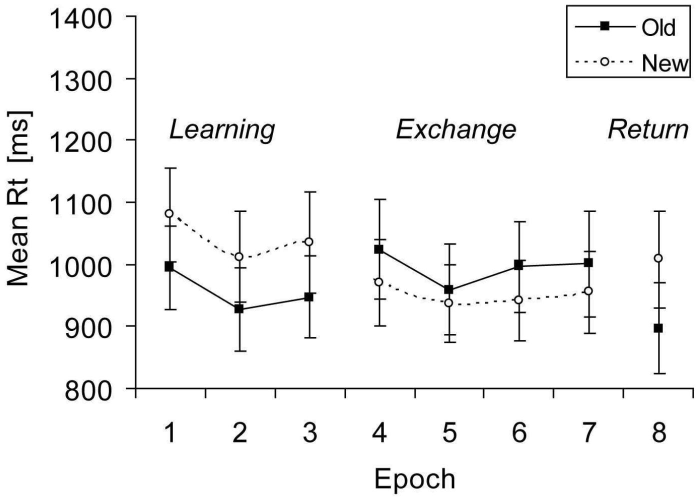

Figure 26: Mean RTs (in ms, and associated standard errors) for old and new contexts (solid and dashed lines, respectively) as function of epoch in Experiment 10.

For the learning phase (initial target locations), a repeated-measures ANOVA with the factors Context (old, new) and Epoch (1–3) revealed significant main effects of context, $F(1, 11) = 36.56$, $p < .01$, and of epoch, $F(2, 22) = 12.52$, $p < .01$. RTs were on average 86 ms faster for old contexts than for new contexts and decreased overall by 46 ms across epochs. The interaction between context and epoch was not significant ($p > .9$).

For the exchange phase, an ANOVA with the factors Context (old, new) and Epoch (4–7) yielded a significant main effect of context, $F(1, 11) = 5.19$, $p < .05$, which, however, reflected faster RTs for new contexts in comparison to old contexts (contextual costs of -44 ms). The main effect of epoch was also significant, $F(3, 33) = 3.85$, $p < .05$, with decreasing RTs (by 20 ms) across epochs. The interaction between context and epoch was not significant ($p > .7$). The effect of exchanging target locations on contextual cueing was further analysed with an ANOVA with the factors Context (old, new) and Epoch (3–4; i.e., before and after target location exchange). The interaction between context and epoch was significant, $F(1, 11) = 8.71$, $p < .05$ (no main effect of context or epoch, ps > .1). Exchanging target locations turned contextual cueing of 89 ms in epoch 3 into contextual costs of -54 ms in epoch 4. Thus, the interaction between context and epoch also reflected an inversion of RTs for old and new contexts from epoch 3 to epoch 4. That is, RTs for new contexts in epoch 4 (with old-context targets) were faster than RTs for new contexts in epoch 3 (by 65 ms), $t(11) = 2.27$, $p = .04$. Conversely, RTs for old contexts in epoch 4 (with new-context targets) were much slower than RTs for old contexts in epoch 3 (by 78 ms), $t(11) = 3.25$, $p = .01$. While visual search in new contexts was accelerated by presenting old-context targets in epoch 4, search in old contexts was impaired by inserting new-context targets.

In the last epoch of the experiment (return of initial target locations), RTs for old contexts were 112 ms faster than for new contexts, $t(11) = 4.70$, $p = 00$. The return of target locations in epoch 8 affected RTs significantly as reflected by an ANOVA with the factors Context (old, new) and Epoch (7–8; i.e., before and after the return of initial target locations), which revealed a significant interaction between context and epoch, $F(1, 11) = 18.06$, $p < .01$, but no main effects of context and epoch (*p*s > .1). Contextual cueing recovered from costs of -46 ms in epoch 7 to a benefit of 112 ms in epoch 8.

Recognition Test

Overall, the mean accuracy of recognising old and new contexts was 55.6%. Observers' hit rate of 56.9% differed significantly from the number of false alarms (45.8%), $t(11) = 2.29$, $p = .04$, which indicates that observers were to some extent aware of the repetition of old contexts. The sensitivity measure *d'* was computed [z(hits) - z(false alarms)] for each subject to relate recognition performance to the magnitude of contextual-cueing effects. Contextual cueing of both initial target locations and exchanged target locations were not significantly correlated with recognition performance, $r = -.21$, $p = .50$, and $r = .45$, $p = .14$, respectively (see also Shanks, 2010; Westerberg et al., 2011).

Discussion

In Experiment 10, no adaptation to relocated targets was observed: Robust contextual cueing occurred for old-context displays paired with initial target locations in the learning phase (86 ms). Moreover, a main effect of epoch implied probability learning for target locations in both old and new-context displays. However, upon target relocation, that is, when target locations were exchanged between old- and new-context displays, visual search was faster in new-context displays than in old-context displays (i.e., contextual costs of -44 ms). While the exchange of target locations in Experiment 9 barely affected contextual cueing, contextual cueing was reversed and did not occur in the entire exchange phase in Experiment 10 (see also Manginelli & Pollmann, 2009; Study II). At the same time, search in new contexts was accelerated when they were paired with old-context targets in the exchange phase (compared to performance in the learning phase). Thus, it appears as if old-context targets maintained their level of facilitation independently of the surrounding context. In the return phase, when old-context displays were presented with initial target locations, contextual cueing was as strong as in the learning phase (112 ms; see also Experiment 9).

General Discussion

In the present study, we investigated whether probability learning would facilitate the adaptation of contextual learning to relocated targets. Old- and new-context displays were paired with unique target locations and presented repeatedly in an initial learning phase. Subsequently, target locations were either exchanged between old-context displays (Experiment 9) or between old- and new-context displays (Experiment 10). Because exchanged target locations (i.e., relocated targets) were familiar from the initial learning phase and, hence, predictable contextual cueing was expected to continue in the exchange phases (Conci et al., 2011). In the final phase of the experiments, target locations returned to their original contexts. Overall, we found that exchanged target locations of old contexts continuously facilitated visual search in both old and new contexts, whereas target locations of new contexts impaired contextual cueing in the exchange phase.

More precisely, successful adaptation to relocated targets was observed when target locations were exchanged between old-contexts displays (Experiment 9). Contextual cueing of relocated targets was, in fact, just as strong as contextual cueing of initial target locations in the learning phase. Conversely, when target locations were exchanged between old- and new-context displays visual search in old-context displays became slower than in new-context displays (Experiment 10). In this case, adaptation to relocated targets was not observed. However, the presentation of old-context targets in new contexts (Experiment 10) facilitated visual search significantly.

In both experiments of our study, the return of initial target locations to invariant contexts elicited reliable contextual cueing comparable to results obtained in the learning phases. Thus, the present study supports previous findings showing that existing contextual associations are retained across inconsistencies and possible sources of retroactive interference (Chun & Jiang, 2003; Jiang et al., 2005; Jungé et al., 2007; Mednick et al., 2009; van Asselen & Castelo-Branco, 2009; see Studies I–III). As for Experiment 9, successful contextual cueing in both the exchange and return phase suggests that repeated contexts cue at least two (predictable) target locations equally efficiently, with no evidence of interference between target locations (see also Conci & Müller, 2012; Conci et al., 2011). Thus, under specific circumstances may multiple target locations be integrated into one invariant context (as originally proposed by Brady & Chun, 2007; and Chun & Jiang, 1998).

Adaptation to relocated targets has usually been tested with the sudden introduction of completely new target locations after a learning phase (Chun & Jiang, 1998; Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). In these cases, adaptation to relocated targets was not observed at all — not even when old contexts were permanently paired with relocated targets (Study II), suggesting that only a single target location can be learned in repeated contexts (Study I). By contrast, we observed contextual cueing of relocated targets when they were familiar from the learning phase, specifically, when they were relocated from one old context to another old context (Experiment 9). Similarly, Conci et al. (2011) demonstrated that contextual cueing of multiple targets in one invariant context can be enabled by using already familiar (i.e., predictable) target locations. However, unlike the present study, these authors presented two target locations simultaneously within one context, and observers searched for one of them at a time (see also Conci & Müller, 2012). Hence, each old context was associated with two target locations from the beginning of the experiment. In the present study, all target locations were also familiar, but contexts were only presented with one target location at a time. Nevertheless, when those familiar target locations were transferred from their initial old contexts to different old contexts they continued to facilitate visual search, although they had not appeared in those old contexts before.

Despite being as predictable from the learning phase as target locations in Experiment 9, relocated targets from new-context displays impaired contextual cueing in Experiment 10. In fact, the observed contextual costs in the exchange phase of Experiment 10 resembled results of impaired visual search when target locations are exchanged with nontargets within their contexts (e.g., Makovski & Jiang, 2010). The impairment of search for targets placed at a nontarget position is supposed to result from the inhibition of nontargets in contextual cueing (see also Ogawa et al., 2007). Consequently, target locations of new-contexts seemed to inhibit visual search in old contexts in the present study.

While all relocated targets were predictable from repeated presentations in the learning phases of the present experiments, only target locations of old-context displays were previously predicted, whereas target locations of new-context displays were not predicted by the surrounding context. This difference in past contextual relations seemed to modulate target locations' transferability to another predictive context. Thus, observers extracted higher-order statistical information beyond our original expectations: Not only did observers learn location probabilities and contextual relations, but they additionally represented the "contextual past" of repeated target locations. The contextual pasts of old- and new-context targets might have resulted in opposing predictions (or hypotheses) about future associations with (in-)variant contexts; and these expectations seemed to be coupled with the respective target locations in the exchange phases of the experiments. In particular, the previous relations of old-context targets allowed learning further associations with another old context, whereas new-context targets caused detrimental effects due to their initial appearance in new contexts.

If previous contextual relations influence subsequent contextual learning, the presentation of old-context targets in new contexts should also result in an impairment of visual search. However, in Experiment 10, search in new contexts benefited from the presentation of old-context targets. A potential explanation for this finding could be that contextual learning in the initial part of the experiment automatically prioritised all old-context target locations over new-context target locations. If, for example, search displays in contextual cueing are represented as activation maps, all search items would receive the same (low) activation at the beginning of an experiment (see Brady & Chun, 2007, for a typical model). Across the experiment, the activation of all repeated target locations (in both old and new contexts) increases through probability learning, reflected as peaks of activation in the map relative to nontargets, which already speeds target detection. In addition, repeated contexts further increase the activation of old-context target locations resulting in an advantage for visual search in relation to new-context targets. Higher activations of old-context target locations might have contributed to fast visual search for old-context targets presented in new contexts in the present study – alongside with potentially reduced activations of new-context targets. Thus, this view suggests that due to their contextual past old-context target locations were represented as high-priority peaks of activation in all displays, which additionally indicates that representations of target locations were somewhat decoupled from the surrounding context (see Jiang & Wagner, 2004, for similar findings on nontarget positions).

In line with our conclusions regarding influences of past contextual learning on future contextual learning, Jungé et al. (2007) already pointed out that observers probably form (implicit) hypotheses about statistical regularities of the presented search displays. In their study, old-context and new-context displays were presented separately in sequential order. When old contexts preceded the presentation of new contexts, reliable contextual cueing was observed. Conversely, when new contexts were presented before old contexts, observers did not show a contextual-cueing effect for old-context displays. In the latter case, observers probably "noticed" the absence of statistical regularities in the first half of the experiment. Afterwards, statistical regularities were not expected and, therefore, contextual cueing did not occur for the actual invariant contexts.

In general, it seems that the statistical past of cues and outcomes seems to greatly influence the success rate of adaptive processes in statistical learning. For example, Beesley and Le Pelley (2010) reported that the predictive past of a cue influenced the subsequent rate of learning of that particular cue. In a variant of the Serial Reaction Time task, observers were trained with good and poor predictors of subsequent outcomes. In a second stage, good and poor predictors were paired with new outcomes; and observers were faster to learn these new associations with previously good predictors relative to poor predictors. In the present study, the statistical past of target locations (target locations might be considered as outcomes) determined whether observers associated them with a further predictive contextual cue or not. When target locations had a “poor” past of associations (i.e., target locations of new contexts), they were not associated with a predictive cue subsequently, but targets with a “good” past continued to facilitate search in further contexts (i.e., target locations of old contexts).

In sum, the present study revealed that one invariant context can cue two target locations successfully. However, unlike our expectation, predictability was not sufficient for adaptive contextual learning. Instead, contextual learning of a second target location depended on its contextual past: Contextual learning occurred for a second target location when it was predictable *and* previously predicted by an old context. Likewise, visual search in new contexts benefited from the presentation of previously predicted target locations. Conversely, contextual costs were observed for target locations when they were predictable, but previously not predicted by a context. Overall, the study suggests that observers extract multiple aspects of statistical information interactively, resulting in implicit predictions of future occurrences of repeated stimuli, which then modulate success rates of subsequent statistical learning.

Summary and Conclusions

Repeated encounters with invariant spatial contexts facilitate the acquisition of implicit memory representations, which guide visual attention to designated target objects efficiently on subsequent encounters (Chun & Jiang, 1998). Because variance is likely to occur even in rather invariant spatial environments, observers should be able to flexibly adapt memory representations of spatial contexts to behaviourally relevant changes. The present line of research was designed to examine observers' capability to represent multiple locations for one target object in an otherwise invariant spatial context.

In all of the reported studies, observers performed visual search for repeated target objects surrounded by either an invariant spatial context of nontarget objects or a randomly arranged spatial context. The first study examined observers' capability to associate spatial contexts with two or three different, repeated target locations. To this end, unique spatial contexts were repeatedly presented with a target object appearing at either two or three equally probable, alternating locations (or at one location). The results revealed that observers showed reliable contextual-cueing effects for only one of two or three target locations. In other words, invariant spatial contexts were exclusively associated with a single target area, although further locations were repeatedly presented. Thus, memory representations in contextual cueing seem to be restricted to a single target location (single-target learning).

In Study II, we investigated whether observers would adapt contextual associations to a permanent change in target locations by relearning already existing memory representations. After a learning phase, targets were relocated to new positions; that is, two target locations were presented in sequential order instead of alternating presentations, and observers were trained intensively with relocated targets. Nevertheless, contextual cueing did not develop for relocated targets. At the same time, contextual cueing of initial target locations was preserved across relocation phases. Because the lack of adaptation could point to generic restraints on learning new associations in contextual cueing (e.g., proactive interference), visual search performance for relocated targets was contrasted with learning a further distinct set of repeated contexts (subsequently to an initial learning phase). Under the same training conditions as used for relearning was contextual cueing observed for a newly introduced set of invariant contexts. Thus, it seems that adaptation to relocated targets was not impaired by generic restraints, but by single-target learning.

The third study tested whether the maladaptive behaviour observed in Study II would be overcome by more optimal training conditions. Specifically, observers were trained with relocated targets on four consecutive days; and, in addition, contextual cueing of both initial and relocated targets was tested a week later. Contextual cueing of relocated targets was only observed after several days of training. But eventually, contextual cueing was as reliable for relocated targets as for initial target locations. Notably, the last testing session revealed that ─ contrary to our previous assumption of single-target learning ─ observers represented both target locations (multiple-target learning).

Finally, in Study IV, we investigated whether adaptation to relocated targets benefits from the use of familiar (predictable) target locations, instead of introducing new target locations as in the studies summarised above. To test this assumption, targets were relocated to positions that were previously associated with another invariant or random context. In other words, target locations were exchanged between contexts. The exchange of target locations between invariant contexts resulted in strong contextual cueing of relocated targets, which did not affect contextual cueing of initial target locations. Hence, invariant contexts can be associated with at least two target locations. By contrast, target locations of random contexts presented in old contexts impaired contextual cueing, while target locations of invariant contexts continued to facilitate visual search when they appeared in new contexts. These results indicate that observers represented the diametrical contextual pasts of target locations, which „travelled“ with the target locations and, thus, modulated visual search and contextual learning differentially.

Taken together, the present studies showed that observers only learn to represent two target locations associated with one invariant context under very specific circumstances. Previous research has already indicated that adaptive resources are restrained in contextual cueing when relative positions of objects in context-target layouts are affected by change (Brady & Chun, 2007; Chua & Chun, 2003; Conci et al., 2011; Endo & Takeda, 2005; Kawahara, 2003; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). Here, we have shown that adaptation is particularly restrained when changes in target locations occur. Hence, our findings agree with the assumption that implicit learning is rather inflexible (Chun & Jiang, 2003; Cleeremans et al., 1998). At the same time, the present results of all studies also confirm that implicit memory representations are particularly robust since we found that existing contextual associations were sustained across long periods of time, noise and possibly interfering associations (see also Jiang et al., 2005; Jungé et al., 2007; Olson & Chun, 2002; Song & Jiang, 2005).

Single-Target Learning

Unlike previous predictions (Brady & Chun, 2007; Chun & Jiang, 1998), the results of Study I revealed that observers did not learn two or three target locations presented in alternating order. By contrast, Conci et al. (2011) reported contextual cueing for two target locations associated with the same invariant context. In this study, target objects of different identities were presented simultaneously at their respective location in each display. That is, both target locations were always predictable as part of the global context and, possibly, as a cue to the other target object/ location. These seemingly small, but fundamental differences to the present studies could have promoted contextual cueing for both target objects, whereas alternating presentations in Study I resulted in contextual cueing of only one of two target locations.

Because learning of two or more target locations could slow visual search, the restriction to a single target location was assumed to secure fast visual search for at least one target location, by avoiding competition between multiple responses (target locations) triggered by a shared cue. However, the results of Study III and Study IV as well as previous research (Conci & Müller, 2012; Conci et al., 2011) showed that contextual cueing is not significantly reduced when two target locations are associated with one invariant context. Hence, the avoidance of competition might not be the basis for the observed lack of adaptation in Study I.

Possibly, deviations from general knowledge about the visual world might have contributed to single-target learning in Study I. Clark (in press) argued that observers are very sensitive to statistical regularities in the sensory world, and that they readily build and adjust prediction models according to sensory input. In addition, the author pointed out that certain “hyperpriors” (p. 13) might constrain the processing of sensory input, such that improbable objects and events are not entirely represented in models about the world. For example, observers might have difficulties to simultaneously perceive two objects presented together, when they have previously learnt that these objects do not exist together in the same place at the same time (e.g., house and face). Similarly, observers might lack experience with objects that constantly alternate between two or more locations within otherwise invariant contexts in the real world (Study I). Indeed, designated objects like a toaster do not typically appear at different, recurring locations each time they are used in a kitchen. Perhaps, observers applied a powerful a priori hypothesis about the visual world that rendered constantly alternating target locations improbable. Consequently, observers only learned one target location in Study I, while performing slower visual search for further repeated target locations than for target locations in new contexts. However, objects' locations might change within a limited area from one encounter to the next; and this variance seems to be represented by prediction models of the visual world since we found contextual cueing for relocated targets occurring near learned target locations (see also Makovski & Jiang, 2010).

Even though the change in target locations became permanent in Study II, contextual cueing was still not observed for more than one, the initial target location. In this scenario, target locations were presented sequentially, which means observers were „taught" that contexts are only associated with one target location in the learning phase. If observers were already applying the hyperprior (Clark, in press) mentioned above, the sequential presentation could have additionally enforced single-target learning. However, because contextual cueing was observed in Study III, it can be assumed that sequential presentations promote rather than impair adaptation. Indeed, a permanent relocation of a familiar object in its typical context (e.g., toaster in kitchen) is more plausible and provides a more reliable signal than alternating object locations.

Nevertheless, the lack of contextual cueing of relocated targets in Study II points to severe restraints on adaptive processes ─ particularly in contrast to studies that reported novel objects to attract attention quite readily (Johnston, Hawley, Plew, Elliott, & DeWitt, 1990). For instance, Ogawa and Kumada (2006) argued that contextually novel objects could signal important information and should therefore attract visual attention. In their study, a novel nontarget (at a new position) was added to old- and new-context displays after an initial learning phase. Observers then had to respond to probe dots presented at target, old nontarget, and novel nontarget locations. Results showed that probe dots at novel nontargets attracted focal attention as reliably as probe dots at old target locations, which was interpreted as a "new object advantage" (p. 547). By contrast, relocated targets were also novel within respective contexts (at first) in Study II, but they did not seem to attract focal attention. Although search for relocated targets should have benefited from a new object advantage, as well as from reliable contextual cues, no facilitation effects on visual search were observed.

The new object advantage could have been "overpowered" by existing representations of initial target locations, which could have diverted visual attention and, thus, interfered with relearning. Initial learning experiences tend to impair subsequent learning of new statistical relations by means of proactive interference (see Anderson & Neely, 1996, for an overview). According to Lustig and Hasher (2001a), proactive interference is particularly effective when response cues are highly similar. In Study II and Study III, contextual cues were identical after target relocation, which certainly provided highly similar response cues. Thus, the continuous presentation of old contexts could have activated initial target locations automatically, which in turn could have guided attention to initial target locations reinforcing initial associations. In addition, automatic activation of initial associations could have reduced attentional resources available for changed associations, which could further impair relearning (Jiang & Chun, 2001; Jiménez & Méndez, 1999; Nokes & Ash, 2010; Peterson & Kramer, 2001b). At least the expression of contextual relearning, but not necessarily relearning itself, could be delayed by a reduction in attentional resources available for relocated targets ("latent learning hypothesis"; see Jiang & Leung, 2005).

Does proactive interference explain the observed lack of adaptation in Study II after all? If the behavioural response had been guided by active old memory throughout the whole relocation phases, more significant contextual costs should have occurred (Manginelli & Pollmann, 2009). Instead, reaction times for old-context displays were comparable to reaction times for new-context displays by the end of the relocation phases. In other words, search behaviour in old contexts was at least adapted to a similar level of efficiency as observed for new contexts. However, contextual costs were also not observed when observers learned further, distinct old contexts in Study II. Hence, effects of proactive interference are not necessarily reflected by contextual costs on the behavioural level. Overall, the results suggest that the usual reduction of proactive interference over time observed in Study II (see also Jiang et al., 2005; Mednick et al., 2009) was delayed for relearning due to maximally similar cues in learning and relocation phases. Thus, single-target learning presumably represents a fairly extreme type of proactive interference that restraints contextual relearning to a considerable extent.

Beside potential hyperpriors and interference-effects, the abrupt introduction of completely new positions as target locations in familiar spatial contexts also seems to contribute to restrained adaptation. While newly introduced relocated targets did not elicit contextual cueing in Study II, contextual cueing continued when relocated targets were transferred from one invariant context to another invariant context in Study IV. Thus, already familiar target locations, which had been cued in the past, facilitated adaptation when they appeared in a different invariant context. Perhaps, expected target locations and expected combinations of contexts and target locations agree with predictions about the visual world (Clark, in press). For example, after repeated search for toaster X in kitchen Y at location Z, observers might “assume” that location Z is an acceptable location for any toaster in any familiar kitchen scene, which could enable swift adaptation to change (see also Conci et al., 2011). In contrast, observers did not show contextual cueing for permanently relocated targets that appeared at unexpected, formerly empty positions (Study II). This finding also relates to a commonly observed phenomenon in attentional research: Unexpected, but obvious items can go unnoticed by observers, if they are focussing attention to another aspect of the display (“inattentional blindness“; see Jensen, Yao, Street, & Simons, 2011, for review). Similarly, contextual (mis-)guidance to initial target locations might have diverted attention away from the actual target locations and, thus, impaired adaptation to change.

Implicit Adaptation

Due to the intensive training in Study III, observers eventually adapted memory representations and showed as reliable contextual cueing for relocated targets as for initial target locations. However, adaptation proceeded remarkably slowly, in particular in comparison to new-learning. Such slow adaptation is rather surprising considering previous findings of Pollmann and Manginelli (2009), who reported that changes in target locations are, in fact, registered by the human brain. Targets were relocated within their contexts after a learning phase, which impaired contextual cueing (see Manginelli & Pollmann, 2009). Based on brain imaging data (fMRI), the authors found that certain areas of the brain showed higher activations after permanent changes in target location (in comparison to activation before relocation). More specifically, target relocations were indexed by brain areas that are associated with the detection of change (frontopolar cortex), the signalling of task-relevant changes to other brain areas (anterior prefrontal cortex), as well as the disengagement of attention to facilitate reorienting (temporo-parietal junction area). Thus, the brain seems to register relocated targets instantaneously, but behavioural consequences ─ adaptive relearning ─ only follow after several days of training (Study III).

Certain characteristics of implicit learning might account for delayed adaptation in contextual relearning. First, implicit memory is particularly robust (Chun, 2000; Chun & Jiang, 2003; Seger, 1994), while being rather inflexible (Chun & Jiang, 2003; Cleeremans et al., 1998). This robustness might restrain flexible adaptation in implicit contextual learning. Second, when changes occur between cues and outcomes in explicit learning tasks, adaptation occurs readily, despite interference from initially learned associations (Anderson, 2003, for an overview). Based on awareness of changes in explicit learning, the resolution of interference can be trained as executive control in working memory (Persson & Reuter-Lorenz, 2008; Wahlheim & Jacoby, 2011). Because active suppression is required for interference resolution (David & Brown, 2003; Healey, Campbell, Hasher, & Ossher, 2010; Pilotti, Chodorow, & Tan, 2004), implicit (re-)learning might be affected by old associations to a larger degree than explicit learning (Lustig & Hasher, 2001a). Thus, the implicit character of contextual cueing sustains effects of proactive interference, which delays adaptive relearning considerably, or in other words "... genuine flexibility necessarily involves phenomenal consciousness . . ." (Cleeremans & Jiménez, 2002, p. 2).

While proactive interference seems to powerfully restrain implicit relearning (see also Jiang et al., 2012), evidence for other types of memory-based interference effects was not revealed in the present studies. More specifically, implicit adaptation to relocated targets did not impair contextual cueing of initial target locations; that is, relearning an existing association did not result in suppression or forgetting of initial associations (Study III & Study IV). Furthermore, representing two different target locations in relation to the same invariant context did not cause observable response competition (Conci & Müller, 2012; Conci et al., 2011). Based on the comprehensive investigations of the present studies it can be concluded that implicit contextual memory is not affected by retroactive interference (see also Chun & Jiang, 2003; Jiang, et al., 2005; Mednick et al., 2009), adding to the notion that implicit memory representations are remarkably robust (Arciuli & Simpson, 2012; Chun, 2000; Jiang et al., 2012; Seger, 1994; Tunney, 2003).

However, a few studies have reported evidence for retroactive interference in implicit learning (e.g., Luhmann, 2011, for contextual cueing). For example, in a study by Eakin and Smith (2012) observers learned pairs of words, of which one word was the cue and the other was the target. Subsequently, cues were paired with new target words in an interpolated study phase. In the recall phase, cues were presented with word stems of target words from the initial learning phase; and, in addition, a hint was presented to not use the specific alternative from the interpolated phase. The hint was supposed to strengthen associations from the interpolated phase and, thus, block the retrieval of initial target words through response competition. In the implicit condition, observers were required to respond with the first appropriate target word that came to mind. The results showed that recall of initially learned target words was retroactively impaired by competing associations. The authors concluded that response competition influences implicit memory – at least when strong manipulations are exerted (see also Lustig & Hasher, 2001b; and Martens & Wolters, 2002, for cued word recall).

Notably, the authors acknowledged that the test of implicit memory could have been affected by traces of explicit memory. This is rather likely, since a relatively small number of familiar, highly distinctive words were presented, which were already represented in a semantic network and, in a sense, overlearned. According to some models of memory, such high-quality strong representations that are integral to relevant meta-representations should be readily available to explicit awareness (see Cleeremans, 2011; and Cleeremans & Jiménez, 2002, for overviews). Therefore, findings on cued word recall are hardly comparable to studies of contextual cueing. In sum, previous research (e.g., Jiang et al., 2005) as well as the present line of evidence suggests that retroactive interference barely affects implicit memory representations.

Memory Representations

Since equal contextual-cueing effects were observed for two target locations in Study III, observers seem to acquire memory representations that do not interfere with each other, such that competition costs do not arise. According to Chun and Jiang (1998), memory representations in contextual cueing can be described as episodic instances of spatial contexts, which are matched with sensory input (Logan, 1988, 2002). Brady and Chun (2007) suggested a model that refined instances in contextual cueing as maps of weighted activations, which represent object locations of spatial context. Through repeated encounters with invariant contexts, target locations receive the highest activation (peak activation), while decreasing activations are assigned to nontargets with increasing distances from target locations.

When a change in target location occurs in invariant contexts (Study II & Study III), which are already represented as weighted activation maps, activations should be re-weighted to accommodate the change in contextual relations (relearning). Indeed, Brady and Chun (2007) proposed that two repeated target locations, presented in alternating order, should result in two peaks of activation within the representation of an invariant context, which enables contextual cueing of both target locations. However, contextual cueing was only observed for one target location in such a scenario in Study I. Hence, two target locations might not be represented as two peaks of activation within one context.

Instead, when two target locations are presented sequentially, the adjustment of weights could proceed as the relocation of peak activation to new target locations. Relocating peak activations would theoretically result in forgetting of initial target locations. Because forgetting was not observed in Study III, the activation of initial target locations was obviously not erased through re-weighting. Consequently, the present results indicate that two learned target locations might, in fact, be represented as two peaks within a single activation map. However, as mentioned above, two peaks of activation would result in a reduction of contextual cueing, caused by response competition (Brady & Chun, 2007), which was not observed in Study III (or IV).

Alternatively, observers could accumulate new instances of old contexts with relocated targets, resulting in separate memory representations of old contexts with new distinct activation maps that peak at relocated targets. If observers represent each of two target locations in separate instances, including distinct activation maps, contextual cues would become more distinguishable for each target location, guiding visual attention reliably to the appropriate target location. Hence, contextual cueing would proceed with very little response competition as observed in Study III and Study IV. Although the present results favour separately weighted instances of two learned target locations, conclusions on memory representations in contextual relearning remain fairly tentative.

The results of Study IV suggest that target locations in contextual cueing are not necessarily represented in relation to spatial context, but they rather seem to be memorised as individual activations in space (Jiang & Wagner, 2004; Song & Jiang, 2005). More precisely, target locations of old contexts facilitated visual search and elicited contextual-cueing effects when they were transferred to another old (or new) context. Thus, even when learned target locations appeared in unrelated spatial contexts, they promoted visual search, which indicates that observers represented them somewhat decoupled from previous contextual relations. Similarly, Castelhano and Heaven (2011) reported that visual search for real-world objects was performed independently of scene-context when objects continued to appear at plausible locations (e.g., mug on table instead of on lamp). In Study IV, relocated targets also occurred at “plausible“ locations, that is, at already familiar and predictable target locations.

However, at first contextual cueing was reduced upon the exchange of old target locations and recovered only subsequently, which implies that old-context targets’ individual activations were not sufficient to maintain strong contextual cueing. Instead, it seems that observers learned to associate old-context targets with further invariant contexts. Hence, high activations of individual target locations do not determine cueing effects autonomously, but they definitely promote statistical relearning in contextual cueing. Furthermore, when repeated target locations of new contexts were transferred to old contexts, contextual cueing was severely impaired; even though these target locations were as predictable (or plausible) as target locations of old contexts. New-context targets should also be represented as peaks of activation ─ albeit with less activation than old-context targets ─ which should facilitate visual search at least to a small extent. But new-context targets impaired visual search in old contexts. Thus, although target locations might be represented individually (Jiang & Wagner, 2004), their representations are also strongly influenced by past contextual relations (cued or uncued). Based on past contextual relations, observers represent target locations' potential for future statistical learning, which may reflect a further kind of hyperprior (Clark, in press).

Overall, the present results are in line with the assumption that object locations of spatial contexts are represented as weighted activations (Brady & Chun, 2007). Because target locations maintained their level of activation when they appeared in unrelated contexts, they might be represented individually (Jiang & Wagner, 2004), instead of as integral pieces of episodic instances (Chun & Jiang, 1998). However, individual representations are modulated by past contextual relations, confirming that local and global levels of scene-context interact with each other in meaningful ways (see also Bar, 2004; Brockmole & Võ, 2010; Wolfe et al., 2011).

Future Directions

The results of Study I showed that observers associate invariant contexts with only one repeated target location, although targets appeared at two or three equally probable locations. However, it is unclear how observers “choose” one of the target locations, and simultaneously “ignore” all further repeated target locations. Possibly, characteristics of search displays could exogenously determine which target locations become to be dominant. In order to test this assumption, groups of observers would be presented with the same old-context displays, and eye movements could be measured in addition to reaction times. Eye movements depict mental processes in visual search online and with high resolution (Rayner, 2009), whereas reaction times represent a conglomerate of a number of neuronal and psychological mechanisms (Tseng & Li, 2004). Thus, eye movements can provide more detailed and precise insights on context-guided visual search.

If a group of observers that is presented with the same set of invariant contexts and target locations would show contextual cueing for the same subset of invariant contexts and target locations, characteristics of search displays that facilitate contextual cueing could be pinpointed. Furthermore, if observers would perform similar eye movements in the learned subset of invariant contexts (see Myers & Gray, 2010), the guidance of attention by particularities of certain spatial configurations could be analysed. If, on the other hand, observers learn completely different invariant contexts and target locations, and differ in eye movement patterns, contextual cueing would be strongly influenced by endogenous influences.

Measuring eye movements would also illuminate the contextual costs for minor target locations in Study I, which indicate that observers were initially guided to dominant target locations and subsequently had to reorient and repeat visual search (see also Manginelli & Pollmann, 2009). However, instead of repeating visual search, observers might avoid minor target locations due to inhibition, or they might perform scan patterns that are comparable to visual search in new contexts. Eye movement data would provide fine-grained evidence to distinguish between these and additional explanations.

Similarly, assumptions about memory representations that guide contextual cueing and that result from adaptation to contextual change could be elaborated with eye movements. Regarding the findings of Study III, eye movements could further support the assumption that two target locations are represented in separate instances, if observers are not guided to currently absent target locations. In other words, if eye movements are guided as efficiently to two target locations as to one target location, separate activation maps are the likely basis for contextual guidance. Furthermore, contextual cueing turned into contextual costs when (previously repeated) new-context targets appeared in old contexts (Study IV). While reaction times only revealed that search slows drastically in this scenario, eye movement data would provide insights on how exactly visual search is impaired. Because observers do not seem to expect new-context targets to occur in old contexts, new-context targets are possibly “ignored” or fixated much longer than old-context targets, both of which would delay behavioural responses. If observers avoid new-context targets, they might, in fact, be represented with very low, or potentially negative, activation due to their contextual past. Alternatively, observers might dwell at new-context targets in invariant contexts, due to difficulties to “accept” combinations of new-context targets and invariant contexts, pointing to influences of predictive processing (Clark, in press).

The results of the present studies showed that implicit memory representations of spatial context are not readily adapted to unexpected, but behaviourally relevant changes. Instead, rather time-consuming training was necessary to observe implicit relearning (Study III). Because the present studies focused on adaptation to change in context-guided visual search, one might assume that the observed resistance to change could be limited to implicit learning of spatial contexts. Chun and Jiang (1999) have reported contextual-cueing effects for novel object shapes that cued specific target objects based on semantic (identity) rather than spatial (position) contextual relations. If the present findings would be replicated in such a scenario, one could generalise that relearning of contextual relations is fairly inflexible. In addition, adaptation might be less restricted if richer contextual information that depicts real-life objects and scenes is available, as already used in previous studies on memory-guided visual search (e.g., Bar, 2004, for review; Castelhano & Heaven, 2011; Mack & Eckstein, 2011).

A critical disadvantage of real-world images is the high likelihood of explicit recognition (e.g., Brockmole & Henderson, 2006; Westerberg et al, 2011; see also Cleeremans & Jiménez, 2002; see Eakin & Smith, 2012, for cued word recall). Hence, when real-world images are used, influences of available information on adaptation might be confounded with explicit awareness. In order to examine characteristics of implicit memory representations independently, performance upon change in learned structures should be investigated with further implicit learning tasks, such as serial reaction time tasks and artificial grammar learning (see Perruchet & Pacton, 2006; and Seger, 1994, for reviews). Furthermore, implicit relearning should be compared to explicit relearning. For example, observers could be trained to explicitly recognise old-context displays in a contextual cueing task before target relocation occurs and adaptation to change is required – of course, in addition to using more conventional explicit learning tasks (see Anderson, 2003, for an overview). Such a systematic approach would reveal whether adaptation to change is generally restrained in implicit statistical learning.

DEUTSCHE ZUSAMMENFASSUNG

Adaptive Prozesse im Impliziten Kontextlernen

Adaptive Prozesse im Impliziten Kontextlernen

Einleitung

Die visuelle Welt enthält eine Vielzahl komplexer Informationen, die gefiltert und selektiert werden müssen, um adäquates Verhalten zu realisieren. Die Lenkung von Aufmerksamkeit trägt dazu bei, dass die Informationsvielfalt gesiebt wird, da wir vor allem das wahrnehmen, was sich im Fokus unserer Aufmerksamkeit befindet. Zur Umschreibung der Funktionsweise von Aufmerksamkeit wird sie mitunter als „Scheinwerferlicht“ bezeichnet („spotlight“, Posner, 1980), das Objekte sozusagen erleuchtet und damit ihre Detektion erleichtert. Andere Forscher sehen die Funktion der Aufmerksamkeit eher in der Selektion von Information (siehe Chun & Wolfe, 2001, für eine Übersicht).

Die Lenkung der Aufmerksamkeit kann durch exogene, sehr auffällige, respektive saliente, Reize erfolgen. Beispielsweise würde ein roter Buchstabe, der zusammen mit anderen grünen Buchstaben präsentiert wird, automatisch Aufmerksamkeit auf sich lenken (siehe Chun & Wolfe, 2001; und Wolfe & Horowitz, 2004, für Übersichten). Neben exogenen Reizen können auch endogene Einflüsse wie Ziele, vorhergehende Erfahrungen und Erinnerungen zur gezielten Lenkung der Aufmerksamkeit beitragen. Wenn zum Beispiel nach einem bestimmten Objekt in einer bekannten visuellen Szene gesucht wird, kann die visuelle Suche nach dem Objekt durch stabile statistische Relationen und Kovariationen erleichtert werden (Fiser & Aslin, 2002). Erscheint ein bekanntes Objekt beispielsweise häufig an einer bestimmten Position im Raum (z. B. über dem Horizont), erfolgt die Suche nach dem Objekt an seiner wahrscheinlichsten Position. Dementsprechend konnte in einer experimentellen Studie gezeigt werden, dass Versuchsteilnehmer lernen, an welcher Position ein Zielobjekt am wahrscheinlichsten auftritt, sodass die Detektion an dieser Position am schnellsten erfolgte (Jiang et al., 2012). In der Studie wurden Suchkonfigurationen mit dem Zielbuchstaben ‚T’ präsentiert, der von Distraktoren in Form eines ‚Ls’ umgeben war. Die Teilnehmer suchten nach dem

Zielbuchstaben, wussten allerdings nicht, dass dieser besonders häufig in einem bestimmten Quadranten der Suchkonfiguration erschien. Da die Suche nach dem Zielobjekt an seiner wahrscheinlichsten Position am schnellsten erfolgte, schlussfolgerten die Autoren, dass die Teilnehmer die Wahrscheinlichkeitsverteilung der Positionen beiläufig gelernt hatten und folglich ihre Aufmerksamkeit danach ausrichteten (siehe auch Druker & Anderson, 2010; Geng & Behrmann, 2005).

Anders als in vielen experimentellen Studien (z. B. Jiang et al., 2012) sind Zielobjekte in der realen Welt selten von sich stets wandelnden Suchkonfigurationen umgeben, deren Distraktoren Aufmerksamkeit vom Zielobjekt ablenken sollen. Vielmehr suchen wir viele Objekte in immer gleichen Umgebungen (z. B. Toaster in Küche) und in Relation zu wiederkehrenden, benachbarten Objekten (z. B. Wasserkocher neben Toaster). Derartig stabile Relationen zwischen Objekten und zwischen Szenen und Objekten werden auch gelernt und erleichtern somit die visuelle Suche nach Zielobjekten erheblich (siehe Bar, 2004; Chun, 2000; und Oliva & Torralba, 2004, für Übersichten).

Werden in experimentellen Studien Bilder von solchen „realen“ Szenen und Objekten verwendet, wird viel Variabilität in Formen, Größen und Farben zugelassen. Gleichzeitig enthalten reale Bilder sowohl semantische als auch räumliche Relationen, die interaktiv auf die Position des Zielobjekts hinweisen können. Zudem lässt sich der Prozess des Lernens stabiler statistischer Relationen nicht abbilden, wenn den Teilnehmern Szenen und Objekte bereits bekannt sind. Um die genannten Konfundierungen auszuschließen und gleichzeitig das Lernen stabiler Relationen zu untersuchen, führten Chun und Jiang (1998) ein Paradigma ein, in dem Teilnehmer räumliche Kontexte implizit lernen, was anschließend die Suche nach Zielobjekten beschleunigt („contextual cueing“).

Implizites Kontextlernen

In der klassischen Studie von Chun und Jiang (1998) wurden Suchkonfigurationen präsentiert, in denen Teilnehmer nach einem ‚T’ unter mehreren ‚Ls’ suchten. Einige der Suchkonfigurationen wurden im Laufe des Experiments regelmäßig wiederholt (alte

Kontexte), und die Suche nach den Zielobjekten in alten Kontexten wurde mit der Suche in zufälligen, jedes Mal neu generierten Konfigurationen verglichen (neue Kontexte). In sowohl alten als auch neuen Kontexten wurde eine bestimmte Anzahl verschiedener Zielpositionen wiederholt (siehe Jiang et al., 2012), sodass die Kontexte sich lediglich darin unterschieden, dass alte Kontexte ihre jeweilige Zielposition vorhersagten. Durch die Wiederholung aller Zielpositionen verkürzten sich die Suchzeiten in alten und neuen Kontexten im Laufe des Experiments. Zusätzlich beschleunigte sich die Suche in alten Kontexten im Vergleich zu neuen Kontexten während des Experiments (Kontexteffekt, „contextual-cueing effect“). Dieser Kontexteffekt reflektiert, dass stabile räumliche Kontexte die Suche nach Zielobjekten erleichtern (siehe Chun, 2000, für einen Überblick).

Anhand der Ergebnisse grundlegender Experimente schlussfolgerten Chun und Jiang (1998), dass alte Kontexte als episodische Exemplare („episodic instances“) repräsentiert werden. Zu Beginn eines Experiments verlassen sich Teilnehmer zunächst auf einen allgemeinen Suchalgorithmus (z. B. serielle Suche), der gleichermaßen in alten und neuen Kontexten angewandt wird. Mit jeder Wiederholung eines alten Kontexts wird ein episodisches Exemplar abgespeichert, das bei der nächsten Begegnung mit demselben Kontext abgerufen werden kann. Durch die Ansammlung episodischer Exemplare wird die Suche in alten Kontexten zunehmend effizienter, was dazu führt, dass der anfängliche Algorithmus nicht mehr benötigt wird. Alte Kontexte können einfach aus dem Gedächtnis abgerufen werden, wodurch die Suche nach der Zielposition relativ automatisch erfolgen kann (siehe Logan, 1988, 2002, für einen Überblick zur „instance theory“).

Kontextlernen lenkt Aufmerksamkeit

Durch die wiederholte Suche in alten Kontexten sammeln sich laut Chun und Jiang (1998) episodische Exemplare im Gedächtnis an, die bei nachfolgender visueller Suche die Aufmerksamkeit effizient zur Zielposition lenken. Obwohl Kontextlernen die Lenkung der Aufmerksamkeit günstig beeinflussen soll, findet die Detektion des Zielobjekts immer noch relativ langsam statt. Daher untersuchten Chun und Jiang (1998) genauer, ob Kontextlernen die Effizienz der Suche tatsächlich durch Lenkung der Aufmerksamkeit beeinflusst. Zu diesem Zweck wurden Suchkonfigurationen verschiedener Größen präsentiert (8, 12 oder 16 Objekte). Normalerweise verlangsamt sich die visuelle Suche je mehr Objekte das Zielobjekt umgeben. Findet jedoch eine Lenkung der Aufmerksamkeit statt, z. B. durch saliente Objekte, wird die Suche auch in großen Konfigurationen auffallend beschleunigt. Tatsächlich berichteten Chun und Jiang (1998), dass die visuelle Suche in größeren Konfigurationen in ähnlicher Weise von der Wiederholung alter Kontexte profitierte.

Da dieses Ergebnis zum Teil nicht repliziert werden konnte (Kunar et al., 2007), vermuteten andere Forscher, dass Kontextlernen Prozesse der (motorischen) Reaktion erleichtert statt Aufmerksamkeit zu lenken (Kunar et al., 2007; Schankin & Schubö, 2009; Schankin & Schubö, 2010). Allerdings hat eine weitere Untersuchung gezeigt, dass eine motorische Reaktion nicht unbedingt notwendig ist, um Kontexteffekte zu beobachten (Makovski & Jiang, 2011). Daher ist anzunehmen, dass Kontextlernen — neben der Förderung der motorischen Reaktion — die Suche nach Zielpositionen vor allem durch Lenkung der Aufmerksamkeit beschleunigt (siehe auch Zhao et al., 2012).

Mithilfe von Augenbewegungen konnte der Effekt von Kontextlernen auf die Lenkung der Aufmerksamkeit ebenfalls bestätigt werden. Es wurde beispielsweise gezeigt, dass weniger Fixationen bei der Suche in alten Kontexten als in neuen Kontexten ausgeführt werden (Myers & Gray, 2010; Tseng & Li, 2004; Zhao et al., 2012). Zudem ist für alte Kontexte die Wahrscheinlichkeit erhöht, dass die erste Fixation direkt bei der Zielposition landet (Peterson & Kramer, 2001a). Zu einem ähnlichen Ergebnis kamen Johnson et al. (2007), die während eines Experiments zum Kontextlernen die elektrische Aktivität des Gehirns aufzeichneten. Insbesondere wurde auf die Komponente N2pc fokussiert, welche die aufmerksamkeitsbezogene Selektion aufgabenrelevanter Objekte reflektiert (Eimer, 1996). Die Autoren (Johnson et al., 2007) berichteten eine erhöhte Amplitude der N2pc für alte Kontexte im Vergleich zu neuen Kontexten, was bedeutet, dass alte Kontexte eine frühe aufmerksamkeitsbezogene Auswahl der Zielposition fördern.

Implizites Lernen

Es wird angenommen, dass alte Kontexte die Aufmerksamkeit bei der visuellen Suche implizit zur Zielposition leiten (Chun & Jiang, 1998). Im Gegensatz zu expliziten Gedächtnisprozessen lernen Teilnehmer in impliziten Aufgaben zugrunde liegende statistische Strukturen ohne Absicht, weshalb die Aufgabenleistung anschließend ohne Bewusstheit gesteigert wird. Reber (1967) stellte eine der ersten wegweisenden Studien zum impliziten Lernen wiederkehrender Strukturen vor. Teilnehmern wurden Buchstabenkombinationen präsentiert, die sie anschauen und sich merken sollten. Die Kombination der Buchstaben folgte einer künstlichen Grammatik, über die die Teilnehmer nicht informiert worden waren („artificial grammar learning“). Nach der Lernphase waren die Teilnehmer in der Lage, neue ungrammatische Kombinationen von grammatischen Kombinationen überzufällig zu unterscheiden, ohne die zugrunde liegenden Regeln verbalisieren zu können. Lernprozesse und Gedächtnisabruf können folglich ohne Bewusstheit der Teilnehmer, also implizit, erfolgen (siehe Perruchet & Pacton, 2006; Reber, 1989; und Seger, 1994, für Überblicke).

Chun und Jiang (1998) zeigten mithilfe eines Gedächtnistests, dass Teilnehmer nach erfolgreichem Kontextlernen nicht in der Lage waren, alte von neuen Kontexten zu unterscheiden. Nach der Suchaufgabe wurde jeweils einer der alten oder ein neuer Kontext präsentiert, und die Teilnehmer sollten entscheiden, ob sie die jeweilige Konfiguration schon einmal gesehen hatten oder nicht. Im Mittel gelang es den Teilnehmern nicht, alte Kontexte zu erkennen, womit Kontextlernen als impliziter Prozess beschrieben werden kann. Mitunter sind Teilnehmer jedoch in der Lage, alte Kontexte sicher von neuen Kontexten zu unterscheiden (z. B. Geyer, Shi et al., 2010), was Zweifel an einer rein impliziten Natur des Kontextlernens geweckt hat (Smyth & Shanks, 2008). Allerdings konnte bisher nicht nachgewiesen werden, dass sich teils explizites Erkennen einiger Konfigurationen in irgendeiner Weise auf Kontexteffekte auswirkt (Shanks, 2010; Westerberg et al., 2011; siehe auch Reber, 1989). Zudem konnten Chun und Jiang (2003) zeigen, dass Kontextlernen selbst dann implizit verläuft, wenn Teilnehmer über die

Wiederholung von Suchkonfigurationen im Voraus informiert worden waren. Daher kann im Allgemeinen angenommen werden, dass Kontextlernen vorrangig durch implizite Lern- und Gedächtnisprozesse geprägt ist.

Adaptive Prozesse im impliziten Kontextlernen

Implizite Lern- und Gedächtnisprozesse zeichnen sich im Vergleich zu explizitem Lernen durch gewisse Vor- und Nachteile aus. Zum einen sollen implizite Erinnerungen sehr robust, zuverlässig und überdauernd sein (Chun, 2000; Chun & Jiang, 2003; Seger, 1994). Zum anderen ergibt sich daraus aber auch eine gewisse Inflexibilität beim Lernen (Chun & Jiang, 2003; Cleeremans et al., 1998). Somit besteht die Möglichkeit, dass Teilnehmer besondere Schwierigkeiten haben, bestehende implizite Gedächtnisinhalte an Änderungen in der äußeren Umwelt anzupassen.

Da angenommen wird, dass Kontexteffekte auf dem Abruf episodischer Exemplare beruhen (Chun & Jiang, 1998), sollten Abweichungen in Suchkonfigurationen den Abruf nicht stören, wenn sie ursprünglich nicht abgespeicherte Details betreffen. Kontexteffekte hängen vornehmlich von den stabilen räumlichen Relationen zwischen der Zielposition und den umgebenden Distraktoren ab (Chun & Jiang, 1998). Folglich findet in alten Kontexten weiterhin schnelle visuelle Suche statt, wenn sich während eines Experiments die Identitäten und Farben der Suchobjekte ändern (Chun & Jiang, 1998; Endo & Takeda, 2004; Olson & Chun, 2002) oder wenn die Hintergrundfarbe variiert wird (Ehinger & Brockmole, 2008; siehe auch Brooks et al., 2010).

Sogar Variationen der räumlichen Konfiguration können kompensiert werden, wenn sie nur die absoluten — aber nicht die relativen — Positionen im räumlichen Kontext betreffen (Chun & Jiang, 1998). Wenn beispielsweise Suchkonfigurationen nach erfolgreichem Lernen ausgedehnt oder verkleinert werden, oder ihre Lage zum Bildschirmmittelpunkt verändern, findet weiterhin effiziente visuelle Suche in alten Kontexten statt (Jiang & Wagner, 2004). In derselben Studie wurde weiterhin gezeigt, dass Teile von alten Kontexten kombiniert werden können (zu einem „neuen“ alten Kontext), ohne Kontexteffekte zu vermindern. Jeweils eine Zielposition wurde mit zwei verschiedenen alten Kontexten gepaart, und anschließend wurde je eine Hälfte des einen Kontexts mit einer Hälfte des anderen Kontexts kombiniert und mit der gemeinsamen Zielposition präsentiert. Obwohl diese kombinierten alten Kontexte vorher unbekannt waren, verlief die Suche nach der Zielposition ähnlich schnell wie in den ursprünglichen alten Kontexten. Daher ist anzunehmen, dass Distraktoren relativ unabhängig voneinander, aber definitiv in Relation zur Zielposition, im Gedächtnis repräsentiert werden (siehe auch Song & Jiang, 2005). Die effiziente visuelle Suche in alten Kontexten kann also durch wenige stabile Relationen aufrechterhalten werden; der globale Kontext muss nicht vollständig erhalten bleiben (siehe auch Castelhano & Heaven, 2011; Hoffmann & Sebald, 2005; Peterson & Kramer, 2001b).

Nichtsdestotrotz finden Anpassungsprozesse im impliziten Kontextlernen nicht unbegrenzt statt. Wie bereits erwähnt, wirken sich Änderungen in den relativen räumlichen Positionen der Suchobjekte negativ auf den Abruf episodischer Exemplare auf. Wenn zum Beispiel alte Kontexte zusammen mit neuen Kontexten (sog. Rauschen) auf dem gleichen Bildschirm präsentiert werden, erfolgt nur dann effiziente visuelle Suche in alten Kontexten, wenn die relative Position des alten Kontexts im Verhältnis zum neuen Kontext gleich bleibt (Endo & Takeda, 2005). Ein ähnlicher Befund ergab sich, wenn alte Kontexte nach erfolgreichem Lernen aus veränderten Winkeln präsentiert wurden (Chua & Chun, 2003). In diesem Experiment wurden Suchkonfigurationen mit Tiefeninformation präsentiert (in 3D). Nach einer Lernphase wurden die alten und neuen Kontexte rotiert, sodass der aktuelle Blickwinkel in immer größeren Stufen vom ursprünglichen Blickwinkel abwich. Mit zunehmender Rotation wurde die Suche in alten Kontexten zunehmend langsamer. Die Verzerrung relativer räumlicher Information führte also dazu, dass Gedächtnisinhalte die Suche in alten Kontexten nicht mehr beschleunigten (siehe auch Kawahara, 2003; Tsuchiai et al., 2012, für ähnliche Ergebnisse in 3D).

Da Distraktoren hauptsächlich in Relation zur Zielposition repräsentiert werden (Chun & Jiang, 1998; Jiang & Wagner, 2004), müssten sich Änderungen in der

Zielposition besonders negativ auf Kontexteffekte auswirken. Tatsächlich führt ein Wechsel der Zielposition zur drastischen Verlangsamung der visuellen Suche in alten Kontexten (Conci, et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). In der Studie von Manginelli und Pollmann (2009) wurden die Zielobjekte alter und neuer Kontexte nach einer Lernphase verschoben und an bisher freien Positionen in den Konfigurationen präsentiert. Nachdem die Suche in alten Kontexten während der anfänglichen Lernphase schneller war als in neuen Kontexten, verschwand dieser Kontexteffekt anschließend mit der Einführung der veränderten Zielpositionen. Obwohl die veränderten Zielpositionen mehrfach wiederholt wurden, blieb die Suche in alten Kontexten ähnlich langsam wie in neuen Kontexten. Bereits bestehende Gedächtnisinhalte wurden somit nicht an die veränderten Anforderungen angepasst; veränderte Zielpositionen scheinen demnach nicht repräsentiert zu werden.

Im Gegensatz dazu berichteten Chun und Jiang (1998), dass alte Kontexte die Suche nach mindestens zwei verschiedenen Zielpositionen beschleunigen können. In Experiment 6 ihrer Studie wurden alte und neue Kontexte mit jeweils zwei verschiedenen Zielpositionen gepaart, die in getrennten Durchgängen (also nicht gleichzeitig) abwechselnd präsentiert wurden. Die Suche nach Zielpositionen in alten Kontexten erfolgte schneller als in neuen Kontexten. Allerdings war der Kontexteffekt alter Kontexte im Mittel geringer als für Kontexte, die nur mit einer Zielposition assoziiert waren (in anderen Experimenten). Die Autoren wiesen aber daraufhin, dass sich dieser Unterschied mit zunehmender Übung verringern sollte, da starke Kontexteffekte vor allem von wiederholter Suche abhängen (siehe auch Brady & Chun, 2007; Mednick et al., 2009; Tseng et al., 2011).

Brady und Chun (2007) leiteten anhand eines Modells zum Kontextlernen ebenfalls ab, dass die Suche nach mindestens zwei Zielpositionen von einem alten Kontext profitiert. In ihrem Modell werden den Suchobjekten in Kontexten gewichtete Aktivierungen zugewiesen; episodische Exemplare (Chun & Jiang, 1998) enthalten sozusagen eine Aktivierungskarte. Durch ihre wiederholte Präsentation erhalten Zielpositionen höhere

Aktivierungen als Distraktoren. Alte Kontexte verstärken zusätzlich die Aktivierung ihrer Zielpositionen, weshalb anschließend schnelle visuelle Suche stattfinden kann. Distraktoren in der Nähe der Zielposition zeichnen sich durch höhere Aktivierungen aus als weiter entfernte Distraktoren. Wenn Kontexte mit zwei Zielpositionen präsentiert werden, entstehen zwei Punkte höchster Aktivierung im Suchfeld. Die aktiven, lokalen Kontexte beider Zielpositionen können sich eventuell überschneiden, wodurch Aufmerksamkeit gleichzeitig auf beide Zielpositionen gelenkt werden könnte. Da nun beide Zielpositionen abgesucht werden können, verlangsamt sich die Suche in alten Kontexten. Dadurch verringert sich der Vorteil im Vergleich zu neuen Kontexten, was wiederum erklärt, warum sich kleinere Kontexteffekte im Vergleich zu Kontexten mit nur einer Zielposition ergeben (siehe oben Chun & Jiang, 1998).

Fragestellung

Während eine Reihe von Studien gezeigt hat, dass eine Änderung der Zielposition in alten Kontexten die visuelle Suche stark verlangsamt (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009), berichteten andere Autoren zuverlässige Kontexteffekte für zwei Zielpositionen innerhalb eines alten Kontexts (Brady & Chun, 2007; Chun & Jiang, 1998). Aufgrund der widersprüchlichen Befundlage gingen die vorliegenden Studien der Frage nach, ob Teilnehmer zwei (oder mehr) Zielpositionen im Zusammenhang mit einem alten Kontext repräsentieren können, sodass die Suche nach zwei gelernten Zielpositionen ähnlich effizient erfolgt wie die Suche nach einer gelernten Zielposition. Die vorliegenden Studien untersuchten also im Speziellen adaptive Prozesse im impliziten Kontextlernen, bieten aber auch wichtige Anknüpfungspunkte zu implizitem Lernen im Allgemeinen.

Studie I

In einigen Studien wurde berichtet, dass Kontexteffekte für mindestens zwei Zielpositionen auftreten, die mit dem gleichen alten Kontext gepaart werden (Brady & Chun, 2007; Chun & Jiang, 1998). Allerdings waren die Effekte für Kontexte mit zwei

Zielpositionen im Mittel geringer als für Kontexte mit einer Zielposition. Brady und Chun (2007) erklärten diesen Unterschied damit, dass sich die visuelle Suche durch zwei gelernte Zielpositionen insgesamt verlangsamt, wodurch sich der entsprechende Kontexteffekt verringert. In beiden genannten Studien wurden mittlere Kontexteffekte für alte Kontexte, aber nicht die separaten Effekte für die jeweiligen Zielpositionen berichtet. Somit könnte dem verringerten mittleren Kontexteffekt alter Kontexte auch eine alternative Erklärung zugrunde liegen: Wenn nur eine Zielposition einen „gewöhnlichen" Kontexteffekt zeigt, die andere Zielposition hingegen keinen Kontexteffekt aufweist, würde im Mittel auch ein verringerter Kontexteffekt für alte Kontexte resultieren.

Um diese Alternativerklärung zu testen, wurden drei Experimente durchgeführt, in denen Kontexte mit einer, zwei oder drei Zielpositionen präsentiert wurden, und für jede Zielposition würde der jeweilige Kontexteffekt berechnet. Zunächst wurden die Beobachtungen von Chun und Jiang (1998) repliziert, indem gezeigt wurde, dass Kontexteffekte für Kontexte mit zwei Zielpositionen erzielt werden können (Experiment 1), aber wesentlich geringer sind als für Kontexte mit einer Zielposition (Experiment 2). Bei der Analyse der Kontexteffekte für jede der zwei Zielpositionen zeigte sich, dass eine Zielposition einen zuverlässigen Kontexteffekt auslöste (dominante Zielposition), während die Suche nach der anderen Zielposition langsamer verlief als in neuen Kontexten (untergeordnete Zielposition). Wenn die Zielpositionen nah nebeneinander lagen, ergab sich für beide ein Kontexteffekt, der aber für untergeordnete Zielpositionen immer noch geringer war als für dominante Zielpositionen. Kontexteffekte sind folglich auf eine Zielregion im alten Kontext beschränkt, weshalb in dieser Region präsentierte Zielobjekte schneller gefunden werden als Zielpositionen in neuen Kontexten. Das gleiche Ergebnismuster wurde auch gefunden, wenn Kontexte mit drei verschiedenen Zielpositionen präsentiert wurden (Experiment 3). Insgesamt lässt sich aus den Ergebnissen der ersten Studie schließen, dass Kontextlernen recht unflexibel ist, da es auf eine Zielregion innerhalb eines alten Kontexts beschränkt ist. Gleichzeitig wird dadurch ein starker Kontexteffekt für eine dominante Zielregion erzielt, der durch weitere wiederholte Zielpositionen nicht eingeschränkt wird (Zellin et al., 2011; siehe Appendix).

Studie II

In der zweiten Studie (Experimente 4–7) wurde untersucht, ob die Beschränkung des Kontexteffekts auf eine Zielregion bestehen bleibt, wenn zwei Zielpositionen sequentiell präsentiert werden, und Teilnehmer bereits bestehende Assoziationen umlernen können (siehe Manginelli & Pollmann, 2009). In einer anfänglichen Lernphase wurden Kontexte mit ihren ersten Zielpositionen präsentiert. Anschließend wurden die Zielobjekte verschoben und an bisher leeren Positionen in den Kontexten präsentiert (Relokationsphase). Um zu testen, ob Übung die Anpassung an veränderte Zielpositionen begünstigen kann (siehe Chun & Jiang, 1998), war die Relokationsphase länger als in früheren Studien, wobei zwei verschiedene Längen angewandt wurden (Experimente 4A, 4B, & 6). Zudem pasuierte eine Gruppe von Teilnehmern eine Nacht vor der Relokationsphase (Experiment 6). Zum Teil wurden die Kontexte nach den Relokationsphasen noch einmal mit ihren ursprünglichen Zielpositionen präsentiert (Rückkehrphase), um zu untersuchen, wie sich mögliche Anpassungsprozesse auf bereits bestehende Repräsentationen auswirken (Experiment 4A & 6). Trotz des umfangreichen Trainings wurden keine Kontexteffekte für veränderte Zielpositionen beobachtet. Bestehende Gedächtnisinhalte (episodische Exemplare) wurden folglich nicht an die veränderten Umstände angepasst. Obwohl veränderte Zielpositionen zum Teil häufiger präsentiert wurden als ursprüngliche Zielpositionen, waren die Kontexteffekte für Letztere in der Rückkehrphase genauso stark wie in der anfänglichen Lernphase.

Das ausbleibende Umlernen könnte daraus resultieren, dass Teilnehmer im Allgemeinen Schwierigkeiten haben, nach einer Lernphase neue Assoziationen zu repräsentieren (Neulernen). Um dies zu untersuchen, wurden in drei weiteren Experimenten (Experiment 5A, 5B, & 7) alte und neue Kontexte in einer anfänglichen Lernphase präsentiert. Direkt im Anschluss an die Lernphase wurden weitere alte Kontexte präsentiert, die vorher nicht gezeigt worden waren und somit neu gelernt werden konnten.

Die Fähigkeit zum Neulernen wurde unter den gleichen Bedingungen wie in den Experimenten zum Umlernen getestet. Im Gegensatz zum Ausbleiben von Kontexteffekten für veränderte Zielpositionen, entwickelten sich Kontexteffekte für weitere Kontexte in den Neulernphasen (Experiment 5B & 7). Teilnehmer waren also in der Lage, weitere Kontexte neu zu lernen (Jiang, et al., 2005; Mednick et al., 2009), während veränderte Zielpositionen nicht mit alten Kontexten assoziiert wurden (Manginelli & Pollmann, 2009). Gleichzeitig blieben die Kontexteffekte für Kontexte aus der Lernphase erhalten (Rückkehrphase).

Insgesamt scheint das Umlernen bestehender Assoziationen wesentlich eingeschränkter zu sein als Neulernen, was möglicherweise auf die Beschränkung von Kontexteffekten auf eine einzige Zielregion zurückzuführen ist (Studie I). Neben den Unterschieden zwischen Umlernen und Neulernen zeigte die Studie aber auch, dass bestehende Repräsentationen äußerst langlebig und widerstandsfähig sind und zuverlässig die visuelle Suche beschleunigen (Jiang, et al., 2005; Mednick et al., 2009).

Studie III

In Experiment 8 wurde untersucht, ob Teilnehmer nach sehr intensivem Training doch in der Lage sind, eine zweite Zielposition innerhalb eines gelernten Kontexts zu repräsentieren. Zu diesem Zwecke fand die Lernphase am ersten Tag der Studie statt, während die Relokationsphase an vier darauf folgenden Tagen durchgeführt wurde. Ungefähr eine Woche nach dem Ende der Relokationsphase wurden die Kontexteffekte beider Zielposition getestet (Rückkehrphase). In der anfänglichen Lernphase wurden zuverlässige Kontexteffekte gefunden. Nach der Einführung der veränderten Zielpositionen am zweiten Tag der Studie verschwanden die Kontexteffekte zunächst. Erst am dritten Tag der Relokationsphase entwickelten sich Kontexteffekte für veränderte Zielpositionen, die sich am letzten Tag des Trainings stabilisierten. Folglich führte das intensive Training dazu, dass bestehende Assoziationen umgelernt wurden, sodass alte Kontexte die Suche nach veränderten Zielpositionen beschleunigten. Unter bestimmten

Umständen ist implizites Kontextlernen also nicht auf eine einzige Zielregion innerhalb eines alten Kontexts beschränkt.

In der Rückkehrphase wurden für beide Zielpositionen ähnliche Kontexteffekte gefunden, die zudem mit den Kontexteffekten der Lernphase vergleichbar waren. Das heißt, erfolgreiches Umlernen wirkte sich nicht nachteilig auf bestehende Assoziationen aus (Jiang, et al., 2005; Mednick et al., 2009). Da die Kontexteffekte in der Rückkehrphase mit denen der Lernphase vergleichbar waren, scheint die Repräsentation beider Zielpositionen ‒ anders als von Brady und Chun (2007) vorhergesagt ‒ die visuelle Suche nicht zu verlangsamen; die Repräsentationen scheinen nicht miteinander zu konkurrieren.

Studie IV

In Studie II und in Studie III erfolgte die Einführung neuer Zielpositionen abrupt, und die Zielpositionen erschienen an bisher leeren, unbekannten Positionen in den räumlichen Kontexten. Da die Unvorhersehbarkeit der neuen Zielpositionen den Prozess des Umlernens erschweren könnte (Conci et al., 2011), wurde in zwei weiteren Experimenten untersucht, ob Anpassungsprozesse durch die Einführung vorhersehbarer Zielpositionen begünstigt werden. Wie oben erwähnt wurde, werden alle Zielpositionen der alten sowie der neuen Kontexte wiederholt, wodurch sie auch ohne Kontextlernen vorhersehbar werden, was die visuelle Suche im Allgemeinen beschleunigt (Chun & Jiang, 1998; siehe auch Jiang et al., 2012). Um nun veränderte Zielpositionen vorhersehbar zu machen, wurden Zielpositionen nach der anfänglichen Lernphase einfach zwischen Kontexten ausgetauscht. Genauer genommen, wurden Zielpositionen nach der anfänglichen Lernphase entweder zwischen alten Kontexten (Experiment 9) oder zwischen alten und neuen Kontexten (Experiment 10) ausgetauscht. Nach der Austauschphase kehrten die Zielpositionen für einige Präsentationen in ihre ursprünglichen Kontexte zurück (Rückkehrphase).

Nach dem Austausch der Zielpositionen zwischen alten Kontexten verringerten sich die Kontexteffekte kurzfristig, aber anschließend wurden zuverlässige Kontexteffekte für ausgetauschte Zielpositionen beobachtet. Vorhersehbare Zielpositionen aus alten Kontexten können also mit einem weiteren alten Kontext assoziiert werden und erleichtern damit Anpassungsprozesse. Im Gegensatz dazu verlangsamte sich die visuelle Suche in alten Kontexten drastisch, wenn der Austausch zwischen alten und neuen Kontexten stattfand. Das heißt, die Präsentation von Zielpositionen aus neuen Kontexten in alten Kontexten verursachte Kosten, obwohl diese Zielpositionen genauso bekannt waren wie Zielpositionen alter Kontexte. Gleichzeitig wurde die Suche in neuen Kontexten durch die Präsentation von Zielpositionen aus alten Kontexten beschleunigt. In beiden Experimenten blieben die Kontexteffekte der ursprünglichen Zielpositionen aus der jeweiligen Lernphase unbeeinflusst vom Austausch der Zielpositionen.

Die Ergebnisse von Studie IV zeigen, dass vorhersehbare Zielpositionen Anpassungsprozesse nur dann begünstigen, wenn sie zusätzlich auch vorhergesagt wurden. Die „kontextuelle Vergangenheit“ einer Zielposition beeinflusst somit die Transferierbarkeit einer Zielposition eines alten Kontexts in einen anderen alten Kontext. Folglich repräsentieren Teilnehmer statistische Informationen, die über das Lernen von wahrscheinlichen Positionsverteilungen (Jiang et al., 2011) und Kontextlernen (Chun & Jiang, 1998) hinausgehen: Teilnehmer enkodieren außerdem die kontextuelle Vergangenheit wiederholter Zielpositionen, was zu Erwartungen über zukünftige Kombinationen von Kontexten und Zielpositionen führt, die wiederum Verhalten modulieren (siehe auch Beesley & Le Pelley, 2010; Jungé et al., 2007).

Zusammenfassung und Schlussfolgerungen

Die visuelle Suche nach Zielpositionen wird durch stabile räumliche Konfigurationen der die Zielposition umgebenden Distraktoren erleichtert (Chun & Jiang, 1998). In den vorliegenden Studien wurde untersucht, ob derartige Kontexteffekte auch für eine zweite (oder dritte) Zielposition innerhalb eines Kontexts beobachtet werden können. Es ging also um die Frage, ob Zielobjekte an mehreren Positionen innerhalb ihres jeweiligen Kontexts repräsentiert werden können.

Die Ergebnisse der ersten Studie ließen den Schluss zu, dass Kontexteffekte lediglich für eine Zielposition innerhalb eines Kontexts auftreten, auch wenn das Zielobjekt in abwechselnder Reihenfolge an zwei oder drei Positionen wiederholt präsentiert wurde. Zudem konnte in Studie II gezeigt werden, dass auch die sequentielle Präsentation von zwei Zielpositionen nicht in Kontexteffekten für die zweite Zielposition resultierte. Obwohl die zweite Zielposition zum Teil häufiger präsentiert wurde als die erste Zielposition, wurden bestehende Assoziationen nicht umgelernt. Das Ausbleiben der Anpassung an die veränderte Situation lag dabei nicht an einer generellen Unfähigkeit, neue Assoziationen zu repräsentieren, nachdem bereits eine Lernphase vollzogen worden war. Die Ergebnisse von Studie II sprachen also auch für eine Begrenzung von Kontexteffekten auf eine einzige Zielposition innerhalb eines Kontexts.

Diese Annahme wurde in Studie III widerlegt, da Teilnehmer aufgrund intensiven Trainings Kontexteffekte für die zweiten Zielpositionen entwickelten. Kontextlernen ist demnach nicht unbedingt auf eine Zielposition beschränkt. In der Studie zeigte sich außerdem, dass letztendlich beide Zielpositionen Kontexteffekte erzeugten, was mit früheren Annahmen anderer Autoren übereinstimmt (Brady & Chun, 2007; Chun & Jiang, 1998). Aber anders als von Brady und Chun (2007) vorhergesagt, konkurrierten zwei gelernte Zielpositionen nicht miteinander um visuelle Aufmerksamkeit. Auch in der vierten Studie wurden Kontexteffekte für die zweiten Zielpositionen beobachtet, allerdings nur wenn sie vorher bereits bekannt waren und schon einmal von einem alten Kontext vorhergesagt wurden (siehe Conci et al., 2011). Die Ergebnisse der letzten Studie deuten somit auch an, dass Repräsentationen von Zielpositionen auch die kontextuelle Vergangenheit beinhalten.

Insgesamt wurde gezeigt, dass die Anpassung an eine zweite Zielposition im Kontextlernen möglich ist, aber nur unter bestimmten Bedingungen gelingt. Die Ergebnisse der vorliegenden Studien legen also nahe, dass adaptive Prozesse im Kontextlernen nur eingeschränkt stattfinden. Dies deckt sich mit früheren Studien, die berichtet haben, dass adaptive Ressourcen für Kontexteffekte beschränkt sind, wenn

Änderungen in den relativen räumlichen Positionen eines Kontexts auftreten (Brady & Chun, 2007; Chua & Chun, 2003; Conci et al., 2011; Endo & Takeda, 2005; Kawahara, 2003; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). Da die Anpassung an eine zweite Zielposition nur sehr langsam verlief, sind implizite Lernprozesse durch eine gewisse Inflexibilität gekennzeichnet (Chun & Jiang, 2003; Cleeremans et al., 1998). Dafür zeichneten sich erlangte Kontexteffekte durch eine erstaunliche Stabilität aus. Obwohl eine erhebliche Menge inkonsistenter Information präsentiert wurde, blieben Kontexteffekte für einmal gelernte Zielpositionen und Kontexte über längere Zeiträume erhalten und wurden durch zusätzlich gelernte Assoziationen nicht verringert (siehe auch Jiang et al., 2005; Jungé et al., 2007; Mednick et al., 2009; Olson & Chun, 2002; Song & Jiang, 2005).

Kontexteffekte für eine Zielposition

In Studie I wurde beobachtet, dass Teilnehmer bei abwechselnder Präsentation nur für eine von zwei (oder drei) Zielpositionen Kontexteffekte aufwiesen. Theoretisch könnte Kontextlernen auf eine Zielposition beschränkt sein, damit mehrere Zielpositionen nicht um Aufmerksamkeit konkurrieren, und damit Kontexteffekte verringern (siehe Brady & Chun, 2007). Allerdings wurde diese Annahme in Studie III und Studie IV widerlegt, da hier zwei Zielpositionen gelernt wurden und die Kontexteffekte dennoch nicht reduziert waren (siehe auch Conci & Müller, 2012; Conci et al., 2011). Daher stellt sich die Frage, durch welchen Mechanismus die Anpassung an mehrere Zielpositionen in Studie I verhindert wurde.

Möglicherweise verstößt die abwechselnde Präsentation von Zielpositionen gegen allgemeine Annahmen über die visuelle Welt. Laut Clark (in press) verarbeitet das menschliche Gehirn bereitwillig jedwede statistische Information der sensorischen Umwelt, anhand derer Modelle über die äußere Welt entstehen, die zur Vorhersage von Ereignissen genutzt werden. Zusätzlich nimmt der Autor an, dass Modelle von bestimmten übergeordneten Annahmen („hyperpriors“, S. 13) beschränkt werden können, sodass zum Beispiel unwahrscheinliche Ereignisse nicht vollständig im Modell repräsentiert werden.

So könnte es Teilnehmern Schwierigkeiten bereiten, zwei zusammen präsentierte Objekte, die sonst nie gleichzeitig existieren, wahrzunehmen. Auf die Ergebnisse von Studie I übertragen, könnte dies bedeuten, dass nur eine Zielposition gelernt wurde, weil es nicht üblich ist, dass ein Objekt von einem Tag auf den anderen abwechselnd an verschiedenen Positionen erscheint.

Obwohl die Änderung der Zielposition in Studie II relativ permanent — und damit zuverlässig — war, stellten sich immer noch keine Kontexteffekte für die zweiten Zielpositionen ein. Da durch die Ergebnisse von Studie III klar ist, dass die sequentielle Präsentation der Zielpositionen eine Anpassung begünstigt, stellt sich die Frage durch welchen Mechanismus die Anpassung in Studie II verzögert wurde. Ähnlich wie in den Experimenten zum Lernen neuer Assoziationen (Studie II) könnte die Anpassung an veränderte Zielpositionen durch die Wirkung proaktiver Interferenz verzögert worden sein (Anderson & Neely, 1996, für einen Überblick). Insbesondere könnten aktive alte Assoziationen aus der anfänglichen Lernphase die Anpassung an veränderte Zielpositionen eingeschränkt haben. Erhebliche Einschränkungen durch proaktive Interferenz treten vor allem dann auf, wenn zwei sehr ähnliche Reize die gleiche Reaktion erfordern (Lustig & Hasher, 2001a). In Studie II wurden identische alte Kontexte in der Lern- und Relokationsphase präsentiert. Dadurch könnte die Aufmerksamkeit in der Relokationsphase weiterhin automatisch zu den ersten Zielpositionen gelenkt worden sein, was mit dem Lernen veränderter Zielpositionen interferieren würde. Wie in Studie II weiterhin berichtet wurde, nehmen Effekte proaktiver Interferenz beim Lernen neuer Assoziationen mit der Zeit ab (siehe auch Jiang et al., 2005; Mednick et al., 2009). Da Teilnehmer für das Umlernen alter Assoziationen aber mehr Training benötigten als für Neulernen, kann angenommen werden, dass beim Umlernen extremere Einwirkungen proaktiver Interferenz beobachtet wurden, die sich aus der maximalen Ähnlichkeit der Kontexte vor und nach der Änderung der Zielposition ergaben.

Neben übergeordneten Annahmen („hyperpriors“; Clark, in press) und Interferenzeffekten scheinen auch abrupte, unerwartete Änderungen der Zielposition

Anpassungsprozesse einzuschränken. Während in Studie II keine Anpassung für neu eingeführte Zielpositionen beobachtet wurde, erzeugten veränderte Zielpositionen, die zwischen alten Kontexten getauscht wurden, stabile Kontexteffekte in Studie IV. Eventuell stimmt die Einführung bereits bekannter, vormals vorhergesagter Zielpositionen eher mit Annahmen über die visuelle Welt überein als völlig neue Zielpositionen („hyperpriors"; Clark, in press). Wenn man zum Beispiel Toaster X wiederholt in Küche Y an Position Z gefunden hat, wird vielleicht angenommen, dass Z eine legitime Position für einen Toaster in jeder anderen (stabilen) Küche ist. Folglich würde die Anpassung an veränderte Zielpositionen unterstützt werden.

Implizite Anpassungsprozesse

Dass die Anpassung an veränderte Zielpositionen in Studie III relativ langsam erfolgte, wirkt angesichts der schnellen Registrierung von Änderungen im Gehirn (Pollmann & Manginelli, 2009) überraschend. In dieser Studie wurden Zielobjekte nach einer Lernphase verschoben und wiederholt an neuen Positionen präsentiert. Während auf Verhaltensebene keine Kontexteffekte für veränderte Zielpositionen beobachtet wurden (siehe Manginelli & Pollmann, 2009), wurde anhand eines bildgebenden Verfahrens (fMRT) festgestellt, dass gewisse Bereiche des Gehirns, die u. a. mit dem Signalisieren von Veränderungen aufgabenrelevanter Informationen in Verbindung stehen, nach der Änderung der Zielpositionen mehr Aktivität zeigten als in der Lernphase. Während die Änderung also vom Gehirn registriert wird, stellen sich Anpassungen auf Verhaltensebene erst nach mehreren Tagen Trainings ein (Studie III).

Im Unterschied zu den Beobachtungen in Studie III finden Anpassungsprozesse auf Verhaltensebene in expliziten Lernaufgaben schnell und effizient statt, obwohl auch hier Effekte proaktiver Interferenz auftreten (Anderson, 2003, für einen Überblick). Aufgrund der Bewusstheit in expliziten Lernaufgaben kann Interferenz durch kognitive Kontrolle im Arbeitsgedächtnis gelöst werden (Persson & Reuter-Lorenz, 2008; Wahlheim & Jacoby, 2011); Interferenz wird sozusagen aktiv unterdrückt (David & Brown, 2003; Healey et al., 2010; Pilotti et al., 2004). Durch die bewusste Auflösung von Interferenz aus älteren

Gedächtnishinhalten wird also weiteres Lernen, insbesondere Umlernen, ermöglicht. Da Kontextlernen im Gegensatz dazu implizit abläuft, können Interferenzen nicht aktiv unterdrückt werden, sodass die Anpassung an Änderungen wesentlich langsamer und unter aufwendigen Bedingungen erfolgt. Die implizite Natur des Kontextlernens scheint demnach zur Verzögerung von Anpassungsprozessen beizutragen (siehe auch Lustig & Hasher, 2001a).

Während in den vorliegenden Studien Effekte proaktiver Interferenz beobachtet wurden, fanden sich keine Hinweise auf andere gedächtnisbasierte Interferenzeffekte. Insbesondere führte die erfolgreiche Anpassung an veränderte Zielpositionen in Studie III und in Studie IV nicht zur Verringerung von Kontexteffekten für ursprüngliche Zielpositionen. Das heißt, erfolgreiche Anpassung führt beim impliziten Lernen ─ anders als zum Beispiel in expliziten Lernaufgaben (Anderson, 2003) ─ nicht zur Unterdrückung oder zum Vergessen ursprünglicher Assoziationen (Jiang et al., 2005; Mednick et al., 2009). Zudem scheinen zwei implizit repräsentierte Zielpositionen eines Kontexts nicht miteinander zu konkurrieren, wenn beide abgerufen werden (Conci & Müller, 2012; Conci et al., 2011). Aufgrund der umfangreichen Ergebnisse der vorliegenden Studien lässt sich schließen, dass implizites Lernen und implizite Gedächtnisinhalte nicht von retroaktiver Interferenz betroffen sind; neu gelernte Assoziationen wirken sich nicht negativ auf ältere Assoziationen aus (siehe auch Chun & Jiang, 2003; Jiang, et al., 2005; Mednick et al., 2009). Die Studien bestätigen damit, dass bestehende implizite Repräsentationen außergewöhnlich robust und widerstandsfähig sind (Arciuli & Simpson, 2012; Chun, 2000; Jiang et al., 2012; Seger, 1994; Tunney, 2003).

Gedächtnisrepräsentationen

Da in Studie III keine Interferenz zwischen zwei gelernten Zielpositionen beobachtet wurde, scheinen sie so repräsentiert zu sein, dass sie nicht miteinander konkurrieren, wenn die visuelle Suche im dazugehörigen alten Kontext erfolgt. Laut Chun und Jiang (1998) werden alte Kontexte als episodische Exemplare gespeichert (ähnlich einer Fotografie), die bei der visuellen Suche abgerufen und mit der sensorischen

Information abgeglichen werden. Zudem wird angenommen, dass Distraktoren und Zielpositionen in Kontexten mit gewichteter Aktivierung repräsentiert werden (Brady & Chun, 2007). Zielpositionen alter Kontexte erhalten die höchste Aktivierung, während die Aktivierung der Distraktoren mit zunehmender Entfernung von der Zielposition abnimmt.

Wenn Zielpositionen verändert werden, bestehen bereits gewichtete Repräsentationen von alten Kontexten, in denen die ursprünglichen Zielpositionen die höchsten Aktivierungen aufweisen. Angesichts veränderter Zielpositionen sollten bestehende Aktivierungen umgewichtet werden, um veränderte Zielpositionen adäquat zu repräsentieren. Eine Umgewichtung der Aktivierungen könnte zum einen die Aktivierung der ursprünglichen Zielposition löschen und somit zu ihrem Vergessen führen, was allerdings nicht in Studie III beobachtet wurde. Zum anderen könnten beide Zielpositionen innerhalb des gleichen Kontexts mit hoher Aktivierung repräsentiert werden. Dies sollte laut Brady und Chun (2007) allerdings zur Verringerung der Kontexteffekte führen. Da eine solche Verringerung nicht beobachtet wurde (Studie III), ist es unwahrscheinlich, dass zwei Zielpositionen innerhalb eines Kontexts mit ähnlicher Aktivierung repräsentiert werden.

Möglicherweise werden nach Änderung der Zielpositionen neue episodische Exemplare gespeichert, die ihre eigenen, an der neuen Zielposition kumulierenden Aktivierungskarten aufweisen. Wenn zwei Zielpositionen in getrennten Exemplaren repräsentiert werden, die keine Aktivierungskarte teilen, sondern distinkte Aktivierungen aufweisen, sollte die Suche nach beiden Zielpositionen ähnlich schnell verlaufen. Da ähnlich große Kontexteffekte für zwei Zielpositionen innerhalb eines Kontexts beobachtet wurden (Studie III), kann also vermutet werden, dass die Zielpositionen aus getrennten Repräsentationen abgerufen wurden.

Die Ergebnisse von Studie IV deuten darauf hin, dass die Aktivierungen von Zielpositionen in gewisser Weise unabhängig von ihrem Kontext repräsentiert werden, was bisher vor allem für Distraktoren angenommen wurde (Jiang & Wagner, 2004). Da dem Austausch von Zielpositionen zwischen alten Kontexten eine schnelle Anpassung an veränderte Zielpositionen folgte, kann angenommen werden, dass Zielpositionen alter Kontexte ihre hohe Aktivierung in einen weiteren Kontext „mitnahmen“, obwohl sie mit diesem vormals nicht assoziiert gewesen waren. Obwohl Zielpositionen neuer Kontexte auch wiederholt gezeigt werden, und somit höhere Aktivierung als sie umgebende Distraktoren aufweisen, verhinderten sie nach dem Austausch Anpassungsprozesse in alten Kontexten. Dies lag vermutlich an der kontextuellen Vergangenheit der Zielpositionen aus neuen Kontexten: Sie waren vor dem Austausch nicht von einem Kontext vorhergesagt worden. Somit scheinen Zielpositionen zwar bedingt unabhängig von ihrem Kontext repräsentiert zu werden, die Repräsentationen selbst werden aber bedeutend von kontextuellen Assoziationen beeinflusst.

Ausblick

Die vorliegenden Studien haben gezeigt, dass implizite Gedächtnisinhalte nur mühsam und unter speziellen Bedingungen an Veränderungen angepasst werden. Während die sequentielle Präsentation von Zielpositionen zur Integration der Änderungen beitrug, fanden sich bei abwechselnder Präsentation keine Hinweise auf erfolgreiche Anpassung; Kontexteffekte wurden lediglich für jeweils eine von mehreren Zielpositionen beobachtet (dominante Zielposition). In Bezug auf diese Ergebnisse bleibt offen, wie die dominanten Zielpositionen „ausgewählt“ werden. Zum einen könnten Eigenschaften der Konfigurationen (exogen) die dominanten Zielpositionen hervorheben, zum anderen könnte die Auswahl auch nach inter-individuellen Kriterien (endogen) verlaufen.

Neben der Auswahl der dominanten Zielpositionen wäre außerdem die Verallgemeinerbarkeit der Ergebnisse auf andere Paradigmen von Interesse. In den vorliegenden Studien wurde ausschließlich räumliches Kontextlernen verwendet. Weitere Studien könnten untersuchen, ob die beobachteten Anpassungsprozesse für andere Kontexteffekte, die nicht auf räumlichen, sondern beispielsweise auf semantischen Relationen basieren (Chun & Jiang, 1999), repliziert werden könnten. Außerdem könnte überprüft werden, ob Anpassungsprozesse eher gelingen, wenn Kontexte mit reichhaltigeren Informationen (z. B. Fotos von realen Szenen) präsentiert werden.

Um weiterhin zu untersuchen, inwieweit der implizite Charakter von Kontextlernen Anpassungsprozesse einschränkt, könnten die vorliegenden Untersuchungen mit anderen impliziten Lernaufgaben wiederholt werden (Perruchet & Pacton, 2006; und Seger, 1994, für Überblicke). Zudem sollte der Vergleich mit Anpassungsprozessen in expliziten Lernaufgaben angestrebt werden (Anderson, 2003, für einen Überblick). Mithilfe dieser systematischen Herangehensweise könnte untersucht werden, ob implizite Gedächtnisinhalte im Vergleich zu expliziten Repräsentationen tatsächlich durch verzögerte Anpassung an Veränderungen ─ und gleichzeitig durch größere Robustheit ─ gekennzeichnet sind.

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Figures

Tables

Curriculum Vitae

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Publications

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APPENDIX

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Two (or three) is one too many: testing the flexibility of contextual cueing with multiple target locations

Martina Zellin · Markus Conci ·
Adrian von Mühlenen · Hermann J. Müller

Abstract Visual search for a target object is facilitated when the object is repeatedly presented within an invariant context of surrounding items ("contextual cueing"; Chun & Jiang, Cognitive Psychology, 36, 28–71, 1998). The present study investigated whether such invariant contexts can cue more than one target location. In a series of three experiments, we showed that contextual cueing is significantly reduced when invariant contexts are paired with two rather than one possible target location, whereas no contextual cueing occurs with three distinct target locations. Closer data inspection revealed that one "dominant" target always exhibited substantially more contextual cueing than did the other, "minor" target(s), which caused negative contextual-cueing effects. However, minor targets could benefit from the invariant context when they were spatially close to the dominant target. In sum, our experiments suggest that contextual cueing can guide visual attention to a spatially limited region of the display, only enhancing the detection of targets presented inside that region.

Keywords Contextual cueing · Visual search · Perceptual implicit memory

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Visual scenes typically contain multiple objects of varying complexity that need to be processed selectively in order to achieve one's behavioural goals. When searching for a specific target object in a given scene, visual selection can be supported by a variety of cues directing attention towards relevant, and away from irrelevant, parts of a scene. Thus, for example, search may be guided bottom-up, by visual cues that attract attention on the basis of perceptual salience, as well as top-down, by a working memory "template" specifying features of the searched-for target (see Wolfe & Horowitz, 2004, for a review). In addition, selection may be aided by learned contingencies within a given environment. Real-world scenes usually consist of a relatively stable collection of co-occurring objects, permitting search for one object to be facilitated via its associations with other objects (see Oliva & Torralba, 2007, for a review). For example, visual search for a toaster might be quicker when it is presented in a kitchen rather than a garage scene. Thus, context information can offer valuable cues to the location of a target object (see Bar, 2004, for a review; Biederman, Mezzanotte, & Rabinowitz, 1982; Hollingworth, 2006).

The role of such invariant context information on attentional guidance has also been investigated in a number of studies under controlled laboratory conditions (see Chun, 2000, for a review; Chun & Jiang, 1998). In a typical experiment, search displays consist of 12 items, one T-shaped target and eleven L-shaped nontargets (for an example, see Fig. 1). The task is to find the "T" and indicate its orientation (left or right). Importantly, and unknown to the observers, a set of displays is repeated throughout the experiment with preserved spatial configurations of the target and nontargets. Search performance for these "old" displays is better than performance for displays that are newly generated on every trial, an effect

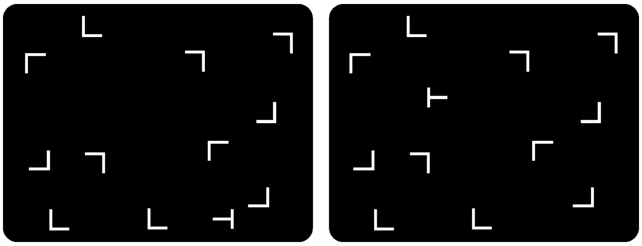

Fig. 1 Example search displays with an old (invariant) context paired with two different target locations

known as *contextual cueing* (Chun & Jiang, 1998). Moreover, a recognition test at the end of the experiment revealed that participants could not reliably discern between old and new configurations, suggesting that participants had no explicit memory of the spatial relations between the target location and its invariant context. Contextual cueing is therefore considered an implicit memory mechanism for spatial context, which facilitates visual search by guiding attention more efficiently (or directly) towards the target location. Guidance by this form of contextual memory may thus provide useful support for attentional orienting in complex environments, as demonstrated in visual search. Such a mechanism should also be flexible and adaptive, to compensate for the variability and possible changes that can occur in the environment. Flexibility could, for instance, mean that one invariant context is associated with multiple target objects. In real environments, such as a kitchen, search might benefit from the stable kitchen layout not only when it comes to finding a toaster, but also when it comes to finding other potentially relevant items, such as a coffee machine.

Thus far, studies investigating the adaptivity of contextual cueing to multiple target locations have yielded ambiguous results. Partial support for an adaptive nature of contextual cueing was already provided by Chun and Jiang (1998). In a variant of the contextual-cueing paradigm, a given search display was repeatedly presented with two distinct target locations. Thus, on some trials, the invariant context was presented with one target location, whereas on other trials it was presented with a second target location (for an example, see the left- and right-hand panels of Fig. 1). The results of this experiment showed a somewhat reduced, but nevertheless reliable, contextual-cueing effect for contexts with two target locations (see also Conci, Sun, & Müller, 2011, for comparable results with simultaneously presented targets). By contrast, invariant contexts paired with three or four repeated targets have been reported as not eliciting contextual cueing (Kunar, Michod, & Wolfe, 2005; Wolfe, Klempen, & Dahlen, 2000). Other studies revealed that sudden (unpredictable) changes of the target location disrupted contextual cueing (Chun & Jiang, 1998; Conci et al., 2011; Fiske & Sanocki, 2010; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). More specifically, when a target that was learned in an invariant context was suddenly moved to a new, previously empty location, contextual cueing was impaired and did not recover with repeated presentation of the new target location (Manginelli & Pollmann, 2009). Recently, Makovski and Jiang further qualified this lack of adaptivity by showing that contextual cueing was transferred to a new target located in close proximity to the original target location. Thus, adaptation of contextual cueing seems to occur only within a fairly limited spatial range.

In sum, while some studies have reported evidence for adaptation to multiple target locations in contextual cueing (Chun & Jiang, 1998; Conci et al., 2011; Kunar et al., 2005), others have clearly failed to provide evidence of flexible compensation for environmental changes (Chun & Jiang, 1998; Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009), or have reported adaptation as occurring only within a limited spatial region (see also Chua & Chun, 2003; Makovski & Jiang, 2010).

The present study was designed to reconcile the contradictory findings on contextual cueing for multiple target locations, and to distinguish between possible alternatives of explaining how contextual cueing is modified by multiple target locations. On the one hand, according to Brady and Chun's (2007) computational model of contextual cueing, multiple target locations can be (learned to be) associated with one invariant context; that is, contextual learning is adaptive. In this view, the overall reduced magnitude found for the contextual-cueing effect (Chun & Jiang, 1998; Kunar et al., 2005) simply results from the number of potential target locations that have to be inspected (*multiple-target learning*). On the other hand, the clear lack of adaptation in other recent studies (Conci et al., 2011; Fiske & Sanocki, 2010; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009) suggests that contextual cueing is restricted to single target locations or their narrow surrounds. That is, only one of two (or more) target locations may be reliably cued by an invariant context (*single-target learning*). If only one target location benefits from contextual cueing, averaging across the cued and uncued target locations (when the invariant context is paired with two target locations) would result in an overall reduced contextual-cueing effect. Adding a third (or fourth, etc.) repeated target location would further reduce the overall effect, because the contextual-cueing effect would be averaged across one cued and two (or three, etc.) uncued target locations.

To determine the degree of adaptivity in contextual learning, three contextual-cueing experiments with multiple target locations were conducted. Contextual-cueing effects were observed with two target locations (Experiments 1 and 2), but the effect was significantly reduced when directly compared to the effect in displays with one target location (Experiment 2). Moreover, no contextual-cueing effect was observed for displays that were paired with three possible target locations (Experiment 3). While, overall, this pattern of results replicated previous studies (see above), additional post-hoc analyses of all three experiments confirmed that one (*dominant*) target location consistently showed significantly more contextual cueing than did the other (*minor*) locations. Furthermore, proximity between targets enabled contextual cueing for two, or even all three, target locations. Taken together, these findings show that contextual cueing does not integrate multiple target locations evenly, but, in fact, the successful predictive association between an invariant context and a target location is limited to only one target location and its immediate surround.

Experiment 1

Experiment 1 was designed to replicate the results of Chun and Jiang (1998), who reported that contextual cueing occurred for invariant contexts paired with two possible target locations. Each search display was paired with two distinct target locations (see Fig. 1 for an example). To ensure that both target locations could be associated equally well with the invariant (old) context, the two targets were always presented in separate, alternating blocks of trials. This variation was used to avoid primacy of one target over the other owing to the order of presentation. If contextual cueing can operate for two different target locations, a facilitatory effect should occur for repeated displays with two target locations.

Method

Participants A group of 16 participants took part in the experiment (10 women, 6 men; mean age = 26 years, age range = 22–49 years). All participants had normal or corrected-to-normal visual acuity, and all but 1 were right-handed. They received either payment (€8) or one course credit.

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

Trial sequence At the beginning of each trial, a fixation cross was presented for 500 ms at the centre of the screen. Then, a search display appeared and remained visible until participants made a speeded response by pressing one of two mouse buttons (with the left- and the right-hand index finger, respectively). Participants were instructed to search for the target "T" and decide as quickly and accurately as possible whether the stem was pointing to the left or the right. In case of a response error, a minus sign appeared on the screen for 1,000 ms. An interstimulus interval of 1,000 ms separated one trial from the next.

Design and procedure In Experiment 1, we implemented a 2 x 8 repeated measures design, with the (within-subjects) factors Context (old, new) and Epoch (1–8). With respect to context, for old contexts, a set of 12 displays was generated for each participant and repeated throughout the experiment (with an invariant arrangement of nontarget items on every presentation). For new contexts, the configuration of nontarget items was generated randomly on each trial. Each display was paired with two target locations. In order to rule out location probability effects, different sets of target locations were selected for old and new contexts, such that, overall, 48 possible target locations were assigned to the displays. The orientation of the target was random on each trial, whereas those of the nontargets were held constant for old contexts. Figure 1 depicts an example search display with an invariant configuration of nontargets paired with two different target locations. The second factor Epoch divided the experiment into eight equally sized consecutive bins (each bin consisted of 120 trials), which permitted the examination of possible learning effects over the course of the experiment by using aggregated, more robust values.

The experiment started with a practice block of 24 randomly generated displays, to familiarise participants with the task. All subsequent (40) experimental blocks consisted of 24 trials, 12 with old and 12 with new context displays, presented in random order. The two possible target locations for each (old and new) display were always presented in alternating order (i.e., one of the two possible target locations was presented in all odd blocks, the other target location was presented in all even blocks), such that each target location was presented 20 times. After each block, participants took a short break and continued with the experiment at their own pace. Overall, participants completed 984 trials.

Recognition test After the last search trial, an instruction was presented on the screen informing participants about the repetition of some of the search displays throughout the experiment. Participants started the presentation of another 24 trials and decided via mouse button responses whether a particular display had been shown previously (= old) or not (= new). All displays were presented with target locations corresponding to the odd blocks only (i.e., with the targets presented in Block 1), since the explicit recognition of a given repeated context would not depend on the location of the target, but rather on the arrangement of the non-targets. The response was nonspeeded, and no error feedback was given.

Results

Search task Individual mean error rates were calculated for each variable combination. The overall error rate was low (2.9%) and a repeated measures ANOVA with the factors Context (old, new) and Epoch (1–8) revealed no significant effects (all $ps > .1$).

Next, individual mean response times (RTs) were calculated for old and new contexts, separately for each epoch. Error trials and RTs exceeding the individual's mean RT by ± 2.5 standard deviations were excluded from the analysis. This outlier criterion led to the removal of 2.3% of the data; the same outlier procedure was applied in all subsequent experiments, with comparable exclusion rates. Further inspection of the RT data revealed normally distributed RTs, as verified by Kolmogorov–Smirnov tests (all $ps > .1$; similar results were obtained in all subsequent experiments). Greenhouse–Geisser corrected values are reported in cases in which Mauchley's test of sphericity was significant ($p < .05$).

Figure 2 shows mean RTs for old and new contexts as a function of epoch. A repeated measures ANOVA with the factors Context (old, new) and Epoch (1–8) yielded a significant main effect of context, $F(1,\ 15) = 10.36$, $p < .01$, and a marginally significant main effect of epoch, $F(1.34,\ 20.13) = 3.27$, $p = .075$. RTs were on average 57 ms faster for old than for new contexts, and they decreased by about 166 ms from the first to the last epoch. The interaction between context and epoch was not significant, $F(7,\ 105) = 1.31$, $p > .2$. When Target Location (location in odd or in even blocks) was entered as a third factor into the analysis, the Context x Target Location interaction did not reach significance ($p > .3$; all other effects were as described above); that is, the magnitude of contextual cueing for the two target locations was not systematically influenced by the order of presentation (similar results were obtained in Experiment 2). An additional analysis performed on individual blocks (rather than epochs) revealed the first significant difference between old and new contexts to occur in Block 5, $t(15) = -2.86$, $p = .01$, which is comparable to findings of fast contextual learning in previous studies (e.g., Conci et al., 2011) and to all subsequent experiments reported here.

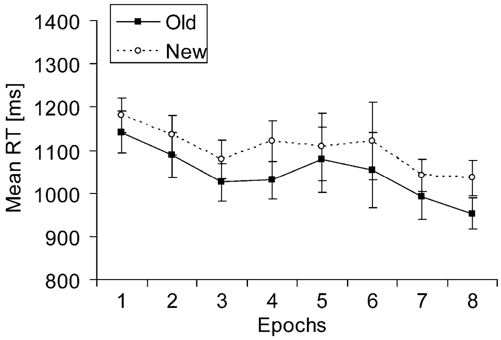

Fig. 2 Mean RTs (in milliseconds, with associated standard error bars) for old and new contexts (filled and unfilled symbols, respectively) as a function of epoch in Experiment 1

Recognition test Overall, old and new contexts were classified as old and new, respectively, in 51% of all trials. Participants correctly identified old contexts in 45.8% of the trials (hit rate), and their false-alarm rate of reporting new contexts as old (46.9%) was comparable to the hit rate, $t(15) = -0.21$, $p = .84$. This suggests that participants were unaware of the repeated contexts during the experiment.

Discussion

The results of Experiment 1 replicated previous findings of Chun and Jiang (1998), showing that contextual cueing can occur for invariant contexts paired with two distinct target locations. Targets in old-context displays were detected 57 ms faster than targets in new-context displays. Moreover, the recognition test scores suggested that participants learned the associations between the invariant context and the target locations implicitly.

In comparison to Chun and Jiang (1998), who reported only a marginally significant contextual-cueing effect of 35 ms for two target locations, the 57-ms effect observed here was more robust and statistically reliable. This may suggest that both the alternating order of target presentations—which would facilitate associating both target locations equally well with the context—and the larger number of trials contributed to the formation of stronger context–target associations. However, contextual cueing for two-target displays was still substantially reduced as compared to similar experiments with only one target location for each display (e.g., Conci & von Mühlenen, 2009, reported contextual-cueing effects greater than 200 ms). This overall reduction in the magnitude of contextual cueing could be the result of multiple-target learning (as suggested by Brady & Chun, 2007). Alternatively, observers may learn only one of two target locations effectively (single-target learning), in which case contextual cueing would be reduced because positive contextual-cueing effects (for one location) would be averaged with near-zero effects (for the other location).

Experiment 2

In order to examine the effectiveness of contextual cueing for displays with different numbers of target locations, in Experiment 2 we implemented a within-subjects design to enable a direct comparison of contextual cueing between one-target displays (baseline) and two-target displays. Half of the search displays were paired with one target location, and the other half with two target locations. On the basis of Experiment 1 and previous findings (e.g., Chun & Jiang, 1998), we expected to find a reduction of contextual cueing when there were two target locations, rather than one target location, paired with a given contextual layout.

Method

The apparatus, stimuli, design, and procedure were similar to those of Experiment 1, except that half of the old and new displays were paired with one target location (baseline) and the other half with two target locations. Overall, 36 target locations were used in Experiment 2. One-target and two-target displays were randomly intermixed within blocks (40 in total). Again, two-target displays contained one of two possible target locations in alternating order across blocks; that is, each of the two target locations was shown 20 times.

A group of 21 participants took part in the experiment (15 women, 6 men; mean age = 26.9 years, age range = 19–50 years). All participants had normal or corrected-to-normal visual acuity and were right-handed. They received either payment (€8) or one course credit.

Results

Search task The overall error rate was relatively low (2.1%), and a repeated measures ANOVA with the factors Context (old, new), Targets (one, two), and Epoch (1–8) only revealed a significant interaction between targets and epoch, $F(3.72, 74.39) = 3.42$, $p < .05$. Errors increased slightly from Epoch 1 (2.3%) to Epoch 8 (2.7%) for one-target displays, as compared to a slight decrease in errors (from 2% to 1.5%) for two-target displays.

Individual mean RTs were calculated for each variable combination, excluding error trials and outliers. Figure 3 shows mean RTs for old and new contexts as a function of epoch, separately for displays paired with one (left panel) and two (right panel) target locations. A repeated measures ANOVA with the factors Context (old, new), Targets (one, two), and Epoch (1–8) revealed significant main effects of context, $F(1, 20) = 14.05$, $p < .01$, and epoch, $F(3.44, 68.75) = 18.48$, $p < .001$. RTs were on average 67 ms faster for old relative to new contexts, and they decreased by about 169 ms from the first to the last epoch. Importantly, the interaction between context and targets was also significant, $F(1, 20) = 6.19$, $p < .05$, due to larger contextual-cueing effects for one-target displays (101 ms) as compared to two-target displays (33 ms). As can be seen in Fig. 3 (right panel), contextual cueing for two-target displays only emerged from Epoch 3 onwards, reaching sizes comparable to those in Experiment 1 only in the last two epochs [57 and 55 ms, $t(20) = -2.22$, $p = .04$, and $t(20) = -1.93$, $p = .07$, respectively].

Recognition test The overall accuracy of recognising old and new contexts was 45.2%. For one-target displays, participants correctly identified old contexts on 56.4% of trials (hit rate), but this did not differ from the false alarm rate of 49.6%, $t(20) = 1.21$, $p = .24$. Similarly, the numbers of hits (57.9%) and false alarms (49.6%) were statistically

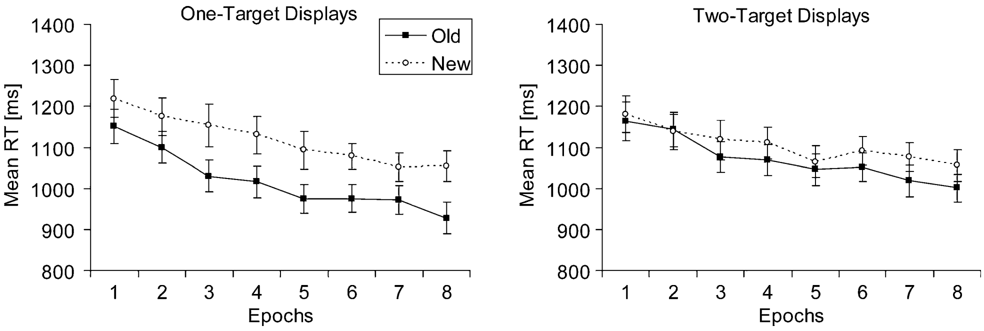

Fig. 3 Mean RTs (in milli seconds, with associated standard error bars) for old and new contexts (filled and unfilled symbols, respectively) as a function of epoch in Experiment 2, for displays paired with one (left panel) and with two (right panel) target locations

comparable for two-target displays, $t(20) = 1.84$, $p = .08$, suggesting that participants were mostly unable to explicitly discern between old and new contexts.

Analysis by separate target locations The results of both Experiments 1 and 2 revealed a contextual-cueing effect for displays with two target locations, but the effect was considerably reduced relative to the baseline condition with one target location. To examine whether this reduction was due to learning of only one of the two target locations, the data of all two-target displays from Experiments 1 and 2 were collapsed. For each participant, the mean contextual-cueing effect was computed separately for each display and target location. Subsequently, for each display, the target location with a relatively larger contextual-cueing effect was assigned to a "dominant target" category, while the target location with the smaller contextual-cueing effect was assigned to a "minor target" category. As can be seen from Fig. 4, the averaged contextual-cueing effect was positive and large only for the dominant target location (204 ms), while being negative for the minor target (−124 ms) [comparison of dominant vs. minor targets: $t(36) = 18.16$, $p = .00$]. Contextual cueing for both the dominant and minor target locations differed reliably from zero, as revealed by one-sample *t* tests, $t(36) = 11.14$, $p = .00$, and $t(36) = -8.09$, $p = .00$, respectively. This pattern of positive and negative cueing effects indicates that only one of two target locations was effectively cued by a repeated context, whereas there were significant costs for the other location.

In order to demonstrate that the difference in contextual cueing between the dominant and minor target locations was not simply an artefact of our sorting procedure, one-target displays (baseline) were also examined for equivalent effects (Experiment 2 only). This was done by applying a sorting procedure analogous to the one with two-target displays: For each participant, pairs of one-target (baseline) displays were randomly selected (which can be considered equivalent to a random pairing of target locations for two-target displays), and for each pair, displays that generated a larger and a smaller contextual-cueing effect were assigned to a "dominant" and a "minor" category, respectively, exactly as in the procedure described above. The resulting mean dominant contextual-cueing effect was large and positive (251 ms), and the mean minor effect negative (−49 ms) [comparison of dominant vs. minor cueing effects: $t(20) = 12.56$, $p = .00$]; note, though, that only the dominant effect differed significantly from zero, $t(20) = 9.25$, $p = .00$ [minor, $t(20) = -1.85$, $p = .08$]. In a subsequent step, dominant and minor contextual cueing effects in the baseline condition (one-target displays) were compared with contextual cueing of dominant and minor target locations in two-target displays (Experiment 2 only). The results revealed the dominant contextual-cueing effects to be comparable between the one- and two-target displays (251 vs. 205 ms), $t(20) = 1.30$, $p = .28$. By contrast, the effect for the minor target location in two-target displays was significantly smaller (i.e., in a more negative direction) compared to the minor effect in the baseline [−139 vs. –49 ms; $t(20) = 3.02$, $p = .01$]—indicating considerable costs, of 90 ms, for the minor target location in two-target displays relative to the baseline condition. Thus, while dominant contextual cueing was comparable between both types of displays, there were pronounced contextual costs for minor target locations in two-target displays.

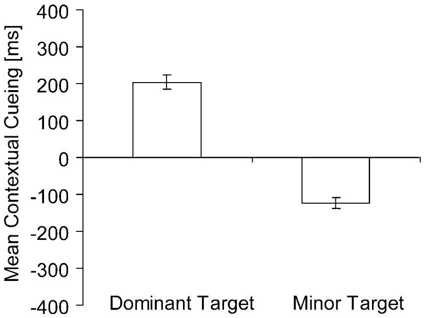

Fig. 4 Mean contextual cueing (in milliseconds, with associated standard error bars) for dominant and minor target locations (collapsed data for all two-target displays from Experiments 1 and 2)

Between-target distance analysis Additional analyses for all two-target displays were performed on the combined data from Experiments 1 and 2 in order to examine the influence of spatial distance between the dominant and minor target locations (range = 2.5º–20.2º of visual angle) on contextual cueing for the latter location. First, a correlation analysis revealed contextual cueing for the minor target location to decrease with increasing distance from the dominant target location, $r = -.318$, $p = .00$. In a further step, we examined whether spatial distance between the two locations facilitated positive contextual cueing for one target location or for both target locations. Displays were sorted according to whether there was a positive (i.e., above zero) contextual-cueing effect for both target locations (30.5%), or for only one target location (46.5%; or for none of the locations). Note that 3 observers had to be excluded from this analysis because they did not show contextual cueing for more than one target location. When both target locations were cued, the mean distance between them was significantly smaller than when only one location was cued, 7.4º versus 9.7º, respectively [$t(33) = 4.27$, $p = .00$]. This finding implies that smaller distances facilitated contextual cueing of two target locations more reliably than did larger distances. Still, with two cued target locations, the dominant location exhibited more contextual cueing than did the minor location, 362 versus 172 ms, respectively [$t(33) = 10.33$, $p = .00$]. It should be noted that the numerically large contextual-cueing effects obtained in these (and subsequent) analyses resulted from the procedure of selecting only relatively extreme cases with large contextual-cueing effects (while excluding smaller or negative values).

Discussion

In agreement with previous studies (e.g., Chun & Jiang, 1998), Experiment 2 demonstrated a contextual-cueing effect for both one-target and two-target displays. But, at the same time, contextual cueing was significantly reduced for two-target displays relative to one-target displays (33 vs. 101 ms).

According to Brady and Chun (2007), a reduction in contextual cueing for two-target displays originates from the increase in inspection times due to multiple-target learning. However, close scrutiny of the collapsed data from Experiments 1 and 2 supports an alternative explanation based on single-target learning. When displays were ranked according to the size of contextual cueing for each target location, only one (the dominant) target location showed strong contextual cueing comparable to learning with one-target displays. By contrast, the other (minor) target location was associated with contextual costs, and these costs significantly exceeded negative contextual-cueing effects in baseline displays. This pattern of results suggests that contextual cueing is much less flexible than proposed. Rather, a given invariant context can reliably cue search to only one repeated target location, but (mostly) fails to facilitate search for a target presented at a second repeated location (for comparable results, see also Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). The fact that minor target locations in two-target displays elicited larger contextual costs than those in any baseline displays indicates that the learned (dominant) target location misdirects spatial–attentional allocation to the dominant location when the target is actually presented at the other (minor) location.

In addition, contextual cueing decreased for minor target locations with increasing distance from the dominant target location, and reliable (i.e., above-zero) contextual-cueing effects for both target locations were only found when these were (relatively) close to each other (see also Brady & Chun, 2007; Makovski & Jiang, 2010). Nevertheless, even if both targets were cued successfully, one dominant target location could still be identified as exhibiting more contextual cueing than the other (minor) location (362 vs. 172 ms). Taken together, this pattern of results demonstrates that contextual cueing is not well adaptive to multiple target locations, because it effectively facilitates guidance to one target location (and its immediate surround) only.

Experiment 3

The results obtained thus far showed that contextual cueing was reduced for two-target relative to one-target displays, and this reduction occurred because only one of two targets was reliably cued. To examine whether single-target learning transfers to multiple repeated target locations in general, in Experiment 3, half of the search displays were paired with three different target locations, and the other half with one (baseline). We expected to observe contextual cueing for only one of the three alternative target locations. If reliable contextual cueing only occurred for one out of three target locations, the averaged contextual-cueing benefit for three-target displays should be even more reduced than that for two-target displays.

Methods

The methodological details were similar to those of Experiment 2, except that now half of the old and new displays were paired with three distinct target locations, and the other half again with only one target location (baseline). Overall, 48 possible target locations were used in Experiment 3. Three-target displays presented all possible target locations in a systematically alternating order across blocks; that is, within a sequence of three blocks, the three target locations were presented in random order. In each block, one-target and three-target displays were presented in random order. Each target of the three-target displays was presented 14 times. Altogether, participants completed 42 experimental blocks of trials (1,032 trials). Bins of 6 blocks were aggregated into seven epochs for analysis purposes.

A group of 22 participants took part in the experiment (16 women, 6 men; mean age = 26 years; age range = 18–34 years). All participants had normal or corrected-to-normal visual acuity and were right-handed. They received either payment (€8) or one course credit.

Results

Search task The overall error rate was relatively low (2.4%), and a repeated measures ANOVA with the factors Context (old, new), Targets (one, three), and Epoch (1–7) revealed no significant effects ($ps > .3$).

Individual mean RTs were calculated for each variable combination after exclusion of error trials and outliers. Figure 5 depicts the mean RTs for old and new contexts as a function of epoch, separately for one-target (left panel) and three-target (right panel) displays. A repeated measures

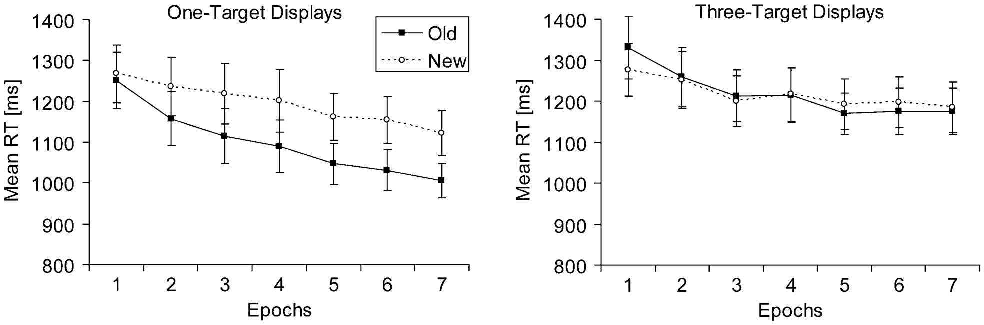

Fig. 5 Mean RTs (in milli seconds, with associated standard error bars) for old and new contexts (filled and unfilled symbols, respectively) as a function of epoch in Experiment 3, for displays paired with one (left panel) and with three (right panel) target locations

ANOVA with the factors Context (old, new), Targets (one, three), and Epoch (1–7) yielded significant main effects of context, *F*(1, 21) = 4.57, *p* < .05, targets, *F*(1, 21) = 16.35, *p* < .01, and epoch, *F*(2.65, 55.63) = 14.29, *p* < .001. RTs were faster for the old- as compared to the new-context displays (by 46 ms), and for one-target as compared to three-target displays (by 71 ms). The main effect of epoch was reflected in a decrease in RTs, by 160 ms, from the first to the last epoch. Furthermore, the Targets x Context interaction was significant, *F*(1, 21) = 7.52, *p* < .05, due to a strong contextual-cueing effect for one-target displays (95 ms) but not for three-target displays (−3 ms). The factors Context and Epoch also interacted significantly, *F*(2.95, 61.93) = 3.64, *p* < .05, with contextual-cueing effects increasing from −19 ms in Epoch 1 to 63 ms in Epoch 7. The interaction between Targets and Epoch was significant, *F*(3.91, 82.03) = 3.11, *p* < .05, with RTs decreasing more across epochs for one-target displays (by 195 ms) than for three-target displays (by 123 ms).

Recognition test Overall, the mean accuracy in the recognition test was 55.1%. For one-target displays, participants correctly identified old contexts on 60.6% of trials (hit rate), and this differed significantly from the false-alarm rate of 46.6%, *t*(21) = 2.59, *p* = .02, suggesting that participants were to some extent aware of the repeated contexts. For three-target displays, the rates of hits (53%) and false alarms (46.6%) were comparable and showed no evidence of explicit recognition, *t*(21) = 1.06, *p* = .30. To further qualify the explicit recognition performance in one-target displays, we examined whether the participants' ability to recognise repeated layouts was related to the size of the contextual-cueing effect. Individual sensitivity scores *d'* [*z*(hits) – *z*(false alarms)] were computed as a measure of explicit recognition and correlated with the contextual-cueing effect for one-target displays. This analysis produced no evidence of a correlation, *r* = −.03, *p* = .89; that is, recognition performance was not systematically related to the size of contextual cueing.

Analysis by separate target locations In a subsequent step, contextual cueing for all three-target displays was analysed separately for the dominant target location and the two minor target locations (see Experiment 2 above for details of the analysis procedure). Figure 6 illustrates that the mean contextual-cueing effect for the dominant target location was significantly larger than that for the two minor target locations (271 vs. –17 vs. –263 ms), *t*(21) = 11.28, *p* = .00, and *t*(21) = 14.64, *p* = .00, respectively. Contextual cueing for the minor target locations also differed significantly from each other, *t*(21) = 11.62, *p* = .00. Mean contextual cueing of the dominant target location was significantly greater than zero, *t*(21) = 8.02, *p* = .00, but contextual cueing of the minor target locations was equal to or less than zero, *t*(21) = −0.61, *p* = .55, and *t*(21) = −9.15, *p* = .00, respectively.

In order to compare the contextual-cueing effects for the dominant and minor target locations (three-target displays) to the corresponding effects in the baseline condition (one-target displays), analogous to the analysis in Experiment 2, triplets of one-target displays were randomly selected (for each participant), and then each triplet was sorted by the largest (dominant), the second largest (Minor 1), and the smallest contextual-cueing effect (Minor 2) to obtain a baseline ranking for the three-target displays. Not surprisingly, in the baseline, the dominant contextual-cueing effect (331 ms) was greater as compared to both minor effects (109 and −139 ms,

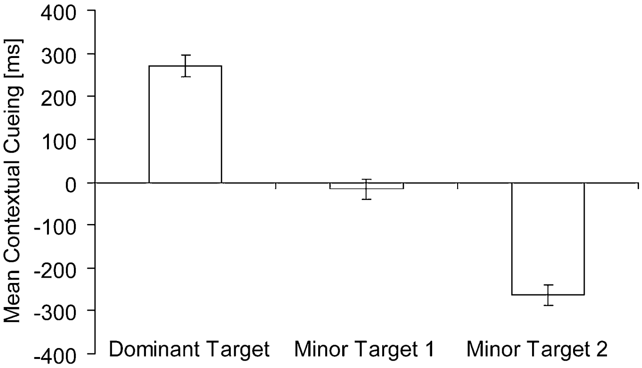

Fig. 6 Mean contextual cueing (in milliseconds, with associated standard error bars) for dominant and minor target locations in displays with three possible target locations (Experiment 3)

respectively) [*t*(21) = 7.73, *p* = .00, and *t*(21) = 9.91, *p* = .00, for the two comparisons], and the latter two effects also differed reliably from each other, *t*(21) = 7.70, *p* = .00. Less trivially, each dominant and minor baseline contextual-cueing effect also differed significantly from zero [*t*(21) = 7.5, *p* = .00; *t*(21) = 3.2, *p* = .00; and *t*(21) = −4.07, *p* = .00, respectively].

Next, dominant and minor contextual cueing in the baseline condition were compared to contextual cueing of dominant and minor target locations in the three-target displays. As in Experiment 2, dominant contextual cueing was comparable between one-target displays (331 ms) and three-target displays (271 ms), *t*(21) = −1.56, *p* = .13. But contextual cueing of minor target locations (−17 and −263 ms) was significantly smaller compared to minor contextual-cueing effects in the baseline (109 and −139 ms) [*t*(21) = −2.82, *p* = .01, and *t*(21) = −3.22, *p* = .00, respectively]. In sum, the dominant contextual-cueing effect in the baseline was similar to that for dominant target locations in three-target displays. By contrast, minor target locations in three-target displays showed no contextual-cueing effect, or even a contextual cost, whereas minor effects in the baseline still reflected a reliable contextual benefit (at least for the Minor 1 category). Thus, minor target locations in three-target displays were associated with significant contextual costs beyond the smallest effects in the baseline.

Between-target distance analysis Again, the influence of spatial distance in three-target displays between dominant and minor target locations (range = 2.5º–21.5º of visual angle) on contextual cueing for the minor target locations was analysed. Overall, contextual cueing for the minor target locations was reduced with greater distance from the dominant location, *r* = −.335, *p* = .00, and *r* = −.331, *p* = .00, respectively (correlations were partially controlled for distance between minor target locations). In a further step, RTs for three-target displays were sorted into three groups, according to whether (above-zero) contextual-cueing effects were obtained for all three target locations (13.6% of the data), for two target locations (30.3%), or for one target location (40.9%; or for none of the target locations). A one-way ANOVA revealed that the mean distance differed significantly between groups, *F*(3, 128) = 6.84, *p* < .001 [with a significant linear trend: *F*(1, 128) = 11.10, *p* < .01]. Mean distances were 10.7º, 9º, and 7.6º for contextual cueing of one, two, and three target locations, respectively, suggesting that the integration of multiple target locations into a learned context was only possible with smaller between-target distances. When two target locations were successfully cued, the average effect was 394 ms for the dominant target location and 163 ms for the minor target location (−238 ms for the "uncued" location; all *p*s < .001). When three target locations exhibited contextual cueing, the average effect was 441 ms for the dominant target location, and 319 and 155 ms for the first and the second minor target locations, respectively (all *p*s < .001).

Discussion

In Experiment 3, we compared contextual cueing between one-target displays (baseline) and three-target displays. Overall, only one-target displays, but not three-target displays, generated reliable contextual cueing (95 and −3 ms, respectively). In addition, search in three-target displays was slowed relative to one-target displays, which might point to extended inspection times due to the resolution of multiple associations between an invariant context and various target locations (see Brady & Chun, 2007). However, further analyses revealed that only a single, dominant target location was successfully cued by an invariant context with effects comparable to baseline, one-target displays. By contrast, the two remaining (minor) target locations did not show reliable contextual cueing and were associated with significant contextual costs when compared to the smallest effects in baseline displays. Of course, targets of three-target displays were presented fewer times than targets of one target displays which could have affected speed of learning, but had no influence on the overall contextual-cueing effect of the dominant target location. Therefore, the lack of observable contextual cueing for three-target displays can be attributed to single-target learning.

Moreover, as with two-target displays (Experiment 2), relative proximity between target locations facilitated contextual cueing for minor target locations and enhanced, to a certain extent, contextual cueing of two, or even all three, target locations by one and the same, invariant context. However, the size of contextual cueing for one or two proximal target locations never reached the same level as that for the dominant target location. This pattern of results again demonstrates that contextual cueing can index only a single target location (and its immediate surround) reliably, but fails to represent multiple target locations within an invariant context.

General discussion

The repeated presentation of invariant spatial item layouts facilitates visual search by guiding attention more directly to a learned target location. In the present study, invariant contexts were paired with multiple target locations (each presented on different trials) to investigate the adaptive properties of contextual cueing. Altogether, our results revealed that contextual cueing integrated only one target location successfully, but failed to reliably facilitate search for a second or third target location.

In line with previous results by Chun and Jiang (1998), contextual-cueing effects were obtained for repeated search displays paired with two target locations (Experiments 1 and 2). However, in comparison to one-target displays, contextual cueing for two-target displays was significantly reduced (101 vs. 33 ms, respectively; Experiment 2). Subsequent analyses showed that this reduction was caused by reliable learning of only one of two target locations (i.e., the dominant target; which was, however, not determined by order of presentation). Search for the remaining minor target locations did not benefit from the invariant context, but rather, in fact, showed contextual costs that were greater than the costs observed for inefficiently learned baseline displays. Furthermore, when a third target location was paired with a given, invariant context, there was no observable contextual cueing (−3 ms) overall, while there was reliable contextual cueing, of 95 ms, for one-target displays (Experiment 3). Again, closer inspection of the result pattern showed that the substantial reduction was caused by reliable cueing of only one of three target locations. By contrast, search for targets appearing at minor locations was again characterised by contextual costs that exceeded the costs observed for inefficiently learned baseline displays. However, additional analyses of all three experiments indicated that, in a subset of the repeated displays, larger distances between the dominant and the minor target locations were related to reduced contextual-cueing effects (or, in other words, increased contextual costs) for minor target locations. Conversely, proximity between target locations seemed to enable contextual cueing of two or even three locations. Nevertheless, the dominant target location still exhibited more contextual cueing than the proximal location(s).

In sum, the present study confirmed that contextual cueing could not adjust to multiple target locations, but rather indicated that it was limited to enhancing a single repeated target location—and possibly its immediate surround. Accordingly, the overall reduction of contextual cueing by multiple target locations was caused by averaging across cued and uncued target locations. For two-target displays, averaging occurred at a ratio of 1:1, at least halving the overall effect. For three-target displays, this ratio was reduced to 1:2, which explains why contextual cueing for three possible target locations appeared to be ineffective overall. Therefore, our results do not converge with models that proposed a reduction in contextual cueing due to multiple-target learning (see Brady & Chun, 2007).

Previous studies had already reported that, following the learning of a first target location, the introduction of a second target location disrupted contextual cueing (Conci et al., 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009). These findings implied that the learned association between a given target location and a given invariant context hinders adaptation to a second target location. The present pattern of results replicated these findings even for displays that presented the possible target locations in alternating order (across blocks of trials), which was expected to provide optimal conditions for learning more than one target location. Consequently, changes in the context–target relation cannot be sufficiently adapted to or compensated for in contextual learning.

Nevertheless, within a relatively narrow spatial range, two-target and three-target displays revealed contextual cueing for multiple target locations, but contextual facilitation dissipated as the spatial distances among target locations increased (see also Makovski & Jiang, 2010, for similar findings). This could mean that contextual cueing establishes multiple memory-based associations between an invariant context and proximal target locations. However, the magnitude of contextual cueing still differed between the cued (dominant and minor) target locations, suggesting that contextual cueing of a second or third target was rather a side effect of contextual cueing of the dominant target. Computational models of contextual cueing (Brady & Chun, 2007) have assumed that observers build up associations between the target location and the invariant context in repeated visual search. In subsequent search, target locations are cued by a locally activated context, rather than the whole repeated display (see also Geyer, Shi, & Müller, 2010). Thus, a second or third target, located near the contextually activated dominant target location, automatically benefits from contextual cueing. Given this finding, contextual cueing of minor target locations is presumably a side effect of contextual cueing of a "primarily" cued target area. Similarly, the prominent contextual costs for distant minor target locations also result from (mis)guidance to the "primarily" cued target location.

From the present results, we conclude that observers orient attention primarily to the learned (dominant) target location, and if the target appears at its expected (i.e., learned) location, robust contextual-cueing effects occur. However, if the dominant target is absent, observers need to reorient attention to the unlearned (minor) target, which shows contextual cueing if it is located near the dominant target, but this facilitation dissipates, and even turns into considerable costs, with growing distance from the dominant location (see also Manginelli & Pollmann, 2009, who demonstrated comparable results based on eye movement measures).

Interestingly, single-target learning was equally effective even when three different target locations were paired with one and the same, invariant context. This demonstrates a remarkable degree of selective and noise-resistant (or interference-free) learning. Evidence for the resistance of contextual cueing to interference was already reported by Jiang and Chun (2001), who found contextual learning for a repeated set of nontargets presented among another set of unpredictably changing items (see also Endo & Takeda, 2005;

Olson & Chun, 2002). In addition, effective learning of repeated contexts occurred even when these were intermixed with a large number of novel display layouts on five consecutive days (Jiang, Song, & Rigas, 2005). Furthermore, once contextual cueing was established for a set of old-context displays, the subsequent presentation of noise (i.e., the presentation of new-context displays) no longer affected the learned associations (Jungé, Scholl, & Chun, 2007). In general agreement with these findings, in the present study, contextual memory for the learned (dominant) target location was equally strong whether it was associated with its repeated context in 100%, 50%, or only 33% of all cases. Thus, while contextual learning is rather inflexible in adapting to changing environments (e.g., when the target location changes), the learned associations between a repeated context and a target location are remarkably stable.

But what might be the advantage of optimising selectivity at the expense of flexibility? One tentative answer is that contextual learning is, in fact, particularly effective when an invariant context cues only one target region. By contrast, if three (or even more) target locations were learned to be associated with a single invariant context, the context would provide only a vague cue, with a 33% (or smaller) chance of directly guiding attention to the relevant location—thus substantially compromising the benefit of predictive surrounds. Consequently, preserving the functional role of predictability may be more valuable in repeated visual search than a high degree of flexibility.

In summary, our findings show that contextual cueing lacks the potential of multiple-target learning. However, other adaptive processes appear to be maintained in contextual learning—for example, when a given change preserves the context–target relation (Jiang & Wagner, 2004; Nabeta, Ono, & Kawahara, 2003) or when relational changes are predictable (Conci et al., 2011). Also, real environments typically contain much richer sources of information than the simple spatial relations in the contextual-cueing paradigm, and these, in turn, could facilitate multiple-target learning. For example, contextual learning would not be particularly useful if an environment, such as a kitchen, cued only the location of the toaster, but not that of the coffee machine. Hence, factors contributing to multiple-target learning in contextual learning remain a fruitful topic for future studies.

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