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Dynamics of Perceptual Learning in Visual Search

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Summary

The present work is concerned with a phenomenon referred to as *contextual cueing*. In visual search, if a searched-for target object is consistently encountered within a stable spatial arrangement of distractor objects, detecting the target becomes more efficient over time, relative to non-repeated, random arrangements. This effect is attributed to learned target-distractor spatial associations stored in long-term memory, which expedite visual search. This Thesis investigates four aspects of contextual cueing:

Study 1 tackled the implicit-explicit debate of contextual cueing from a new perspective. Previous studies tested explicit access to learned displays by applying a recognition test, asking observers whether they have seen a given display in the previous search task. These tests, however, typically yield mixed findings and there is an on-going controversy whether contextual cueing can be described as an implicit or an explicit effect. The current study applied the new perspective of metacognition to contextual cueing and combined a contextual cueing task with metacognitive ratings about the clarity of the visual experience, either of the display configuration or the target stimulus. Bayesian analysis revealed that there was an effect of repeated context on metacognitive sensitivity for configuration, but not target, ratings. It was concluded that effects of contextual memory on metacognition are content-specific and lead to increased metacognitive access to the display configuration, but not to the target stimulus. The more general implication is that from the perspective of metacognition, contextual cueing can be considered as an explicit effect.

Study 2 aimed at testing how explicit knowledge affects memory-guided visual search. Two sets of search displays were shown to participants: explicit and implicit displays. Explicit displays were introduced prior to the search experiment, in a dedicated learning session, and observers should deliberately learn these displays. Implicit displays, on the other hand, were first shown in the search experiment and learning was incidental through repeated exposure to these displays. Contextual cueing arising from explicit and implicit displays was assessed relative to a baseline condition of non-repeated displays. The results showed a standard contextual cueing effect for explicit displays and, interestingly, a negative cueing effect for implicit displays. Recognition performance was above chance for both types of repeated displays; however, it was higher for explicit displays. This pattern of results confirmed – in part – the predictions of a single memory model of attention-moderated associative learning, in

which different display types compete for behavior and explicit representations block the retrieval of implicit representations.

Study 3 investigates interactions between long-term contextual memory with short-term perceptual hypotheses. Both types of perceptual memory share high similarities with respect to their content, therefore the hypothesis was formulated that they share a common memory resource. In three experiments of interrupted search with repeated and non-repeated displays, it was shown that contextual cueing expedites performance in interrupted search; however, there was no interaction of contextual cueing with the generation or the confirmation of perceptual hypotheses. Rather, the analysis of fixational eye movements showed that long-term memory exerts its influence on search performance upon the first glance of a given display, essentially affecting the starting point of the search process. The behavior of approaching the target stimulus is then a product of generating and confirming perceptual hypotheses with these processes being unaffected by long-term contextual memory. It was concluded that long-term and short-term memory representations of the same search display are independent and exhibit additive effects on search performance.

Study 4 is concerned with the effects of reward on perceptual learning. It was argued that rewarding repeated displays in a contextual cueing paradigm leads to an acceleration of the learning effect; however, it was not considered whether reward also has an effect in non-repeated displays. In these displays, at least the target position is kept constant while distractor configurations are random across repetitions. Usually this is done in order to account for target position-specific probability learning in contextual cueing. However, it is possible that probability learning itself is modulated by reward. The current experiment introduced high or low reward to repeated and importantly, also non-repeated displays. It was shown that reward had a huge effect on non-repeated displays, indicating that rewarding certain target positions, irrespective of the distractor layout, facilitates RT performance. Interestingly, reward effects were even larger for non-repeated compared to repeated displays. It was concluded that reward has a strong effect on probability-, and not context learning.

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1. General Introduction

Looking for objects in the world that are currently of interest – like the keys before leaving the house, or a certain book in the shelf – is one of the most prominent visual tasks the human visual system has to cope with (Wolfe, 1998). Visual search behavior is controlled by a number of distinct mechanisms that roughly fall into two categories: bottom-up capture or top-down control of visual attention (e.g. Yantis, 1993). While most of the processing in both types of attentional guidance is based on the physical properties of the current stimulus or task relevance of certain features, observers' expectations based on past experience play a significant role in goal-directed visual selection and in a stable visual environment, it is beneficial for the visual system to learn its properties that are predictive for the target stimulus. For example, looking for a certain book in the bookshelf for the first time is characterized by knowledge about the target stimulus (the book of interest), like its title, the color of its binding, its thickness, etc. In subsequent searches for the same book in the same bookshelf however, there is another source of information available, that is the knowledge that the book should be on the second shelf from above, around the other books with a similar topic. Long-term memory of the context, in which a target stimulus is embedded, incorporates stable features of surrounding objects which are therefore predictive for relevant attributes of the target. More specifically, this Thesis is concerned with perceptual learning of spatial configurations – formed by the positions of non-target, distractor objects – predicting the location of the target stimulus. While it is relatively uncontroversial that contextual memory expedites visual search (Chun, 2000), there are still several open questions regarding basic properties of the cueing effect and interactions with other cognitive processes. The Thesis investigates the following four issues:

i) metacognitive access to contextual memory (chapter 2)
ii) the memory architecture underlying context-guided visual search (chapter 3)
iii) the relationship between long-term contextual memory and short-term perceptual hypotheses (chapter 4)
iv) the effects of reward on context learning (chapter 5)

The first part of the introduction (1.1) provides a description of the central paradigm used to study contextual memory and summarizes the most important findings regarding the influence of learned spatial context on visual search. Subsequently, the second part of the introduction (1.2) outlines the on-going implicit-explicit debate in contextual cueing, which is concerned with the question whether contextual memory is available for conscious processing.

Third, and connected to the question of implicit and explicit processing, the memory architecture underlying contextual cueing is discussed (1.3). In the fourth part, another form of perceptual memory is introduced and contrasted to contextual memory: short-term perceptual hypotheses (1.4). In part five, the effects of reward and difficulties in its study posed by different forms of perceptual learning are discussed (1.5). Last, the sixth part of the introduction outlines the aims of the current thesis (1.6).

1.1 Contextual cueing of visual search

One of the most commonly used paradigms to investigate long-term memory guided visual search is the contextual cueing paradigm (e.g. Chun & Jiang, 1998; Chun, 2000; Conci & von Mühlenen, 2009; Geyer, Baumgartner, Müller, & Pollmann, 2012; Peterson & Kramer, 2001). The contextual cueing effect was first described by Chun & Jiang (1998) who wanted to describe systematically the influence of a coherent and stable visual context in visual search, which has previously been described in natural scenes (e.g Biederman, Mezzanotte, & Rabinowitz, 1982). Participants were required to search for a T-shaped target stimulus among L-shaped distractor elements. The spatial layout of these L-shaped distractors defined the global context embedding a target stimulus; and while in real world scenes the identity of objects is of course meaningful, this laboratory setting allowed for the isolated study of spatial information, provided by the distractor configuration[1]. In a block of 24 trials, half of them contained constant target-distractor arrangements, i.e., the positions of all distractors and the target were kept constant. The other 12 trials of one block contained random, non-repeated displays with a newly generated distractor configuration at every presentation. Importantly, also in non-repeated displays the target position was kept constant. This is crucial because if some positions in a search display are more likely to contain the target than others, this statistical information can also be exploited by the visual system. As a consequence reaction times are faster in trials with a high target position probability – an effect termed *probability*

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[1] Note that in this dissertation the terms contextual cueing and contextual memory always refer to memory of spatial configurations and not memory of object identities, unless stated otherwise. Contextual cueing based on object identities is termed object cueing (see e.g. Chun & Jiang, 1999; Chun, 2000; van Asselen, Sampaio, Pina, & Castelo-Branco, 2011)

cueing (Geng & Behrmann, 2005; Jiang, Swallow, & Rosenbaum, 2013). Therefore, repeating target positions in non-repeated displays ensures that effects of probability cueing are equal in repeated and non-repeated displays and differences in performance can only be attributed to the constant distractor configurations. The central finding of Chun and Jiang's study is that after only a few (3-5) blocks – that means 3-5 repetitions of the same set of repeated displays (Chaumon, Schwartz, & Tallon-Baudry, 2009; Chun & Jiang, 1998) – reaction times for repeated displays are faster compared to new displays. This difference is called the *contextual cueing* effect (for an illustration of a typical contextual cueing effect, see Fig. 1-1)

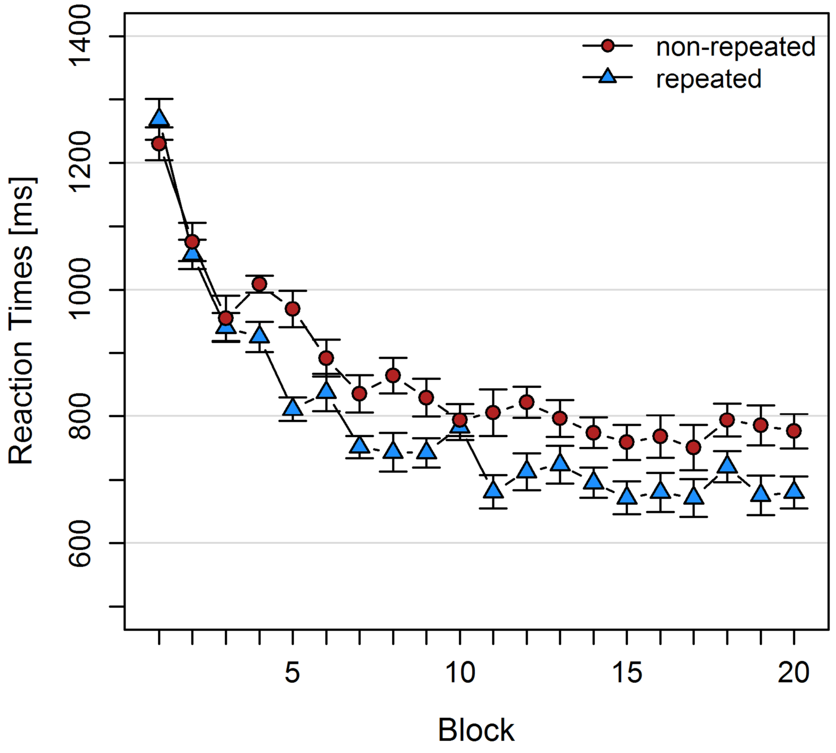

Figure 1-1. Simulated reaction time pattern of a typical contextual cueing experiment. Reaction times for repeated and non-repeated displays were estimated by a power function with the respective parameters taken from Chun & Jiang (2003, Experiment 1). The simulated sample size was $N = 20$, with normally distributed noise ($M = 0$, $SD = 125$) added to each individual value. As can be seen, after three repetitions (in block 4), repeated displays show faster reaction times compared to non-repeated displays.

Content of contextual memory. One of the central questions regarding the contextual cueing effect is what exactly is stored in contextual memory, that helps to guide visual search. As mentioned above, contextual cueing is based on coarse spatial information, i.e., spatial relations between the distractors and the target. Chun & Jiang (1998) demonstrated this by changing the identity of distractors across trials, leaving constant only their position in the display. Under these conditions contextual cueing was still observable, indicating that the effect is not based on repetition of the exact same visual context, or the detailed learning of distractor elements, but rather on the spatial association of distractors and the target. Note, that also the target identity cannot be part of contextual memory, since it always changes between trials and defines the response condition (e.g. observers have to indicate its orientation). However, changing the target position in a constant distractor configuration diminishes the contextual cueing effect (albeit it can be recovered given sufficient time and effort), since the distractors can no longer predict the target location (Chun & Jiang, 1998; Manginelli & Pollmann, 2009; Zellin, von Mühlenen, Müller, & Conci, 2014). While the spatial layout of distractors in a visual search display undisputedly drives the contextual cueing effect, there are two possibilities how this information is stored in contextual memory: via the absolute position of individual distractor elements or the global layout of distractors. Jiang & Wagner (2004) demonstrated that both types are learned in contextual cueing. In their first experiment, observers learned two sets of distractor configurations per target position. When those pairs of repeated displays were recombined in a transfer phase, which keeps individual distractor locations intact but disrupts the global configuration, observers still showed contextual cueing. The second experiment used rescaled and displaced variants of learned distractor configurations, which changed the absolute position of items in the screen while leaving the global configuration intact, and observers also showed contextual cueing in the transfer phase. Further developing the idea that individual distractor locations can drive contextual cueing Olson & Chun (2002) showed that it is not necessary to repeat the entire display in order to elicit contextual cueing. Repeating only distractors in the same hemifield as the target was sufficient for the effect to manifest, while distractors in the opposite hemifield were only able to elicit contextual cueing when there was no interfering random information from distractors between the repeated set and the target. Further evidence suggested that even only a small number of distractors in close spatial proximity to the target drives the effect (Brady & Chun, 2007). Developing a two-layer neural network model of contextual cueing, the authors could show that contextual cueing is based on pairwise associations between the distractor locations and the target location. In a subsequent study, Beesley, Vadillo, Pearson, and Shanks (2014) could show that the model can be further improved by implementing the learning of distract-distractor associations, which reflects configural learning in contextual cueing. In summary, contextual cueing is based on spatial associations between distractor locations and the target location, which can either be based on the absolute positions of few distractors around the target or the global configuration of distractors.

Contextual cueing in the cognitive architecture. Aside from the question which aspects of the visual scene constitute contextual memory, one also has to ask how search is affected by contextual memory, or in other words, which cognitive processes are affected by the presence of prior experience. Chun & Jiang (1998) suggested that repeated context guides attention towards the target, which is supported by evidence that repeated displays yield fewer overt attention shifts (Brockmole & Henderson, 2006; Peterson & Kramer, 2001; Tseng & Li, 2004), improve reaction times and accuracy performance in efficient pop-out search (Geyer, Zehetleitner, & Müller, 2010) and lead to an increase in the N2pc amplitude – an attentional marker of the event-related brain potential – ERP (Johnson, Woodman, Braun, & Luck, 2007). However, there is also evidence that contextual cueing rather affects later stages of response selection (Hout & Goldinger, 2012; Kunar, Flusberg, Horowitz, & Wolfe, 2007; M. A. Kunar, Flusberg, & Wolfe, 2008). Schankin & Schubö (2010) used electrophysiology (ERPs) to investigate both attentional and response-related processes in contextual cueing. They found that the N2pc component was larger in repeated compared to non-repeated displays; however, they attributed this result to the effects of contextual cueing on perceptual discrimination, rather than guidance. Specifically, the authors interpreted this result to indicate that repeated context aids attentional processes after target selection, that is, facilitation of the discrimination of the target from surrounding distractor objects. Regarding response-related effects, they found an earlier onset of the stimulus-locked LRP, which reflects faster mapping of a stimulus to a response. In summary, contextual cueing seems to affect both, early attentional and late response-related processes.

Attentional effects on contextual cueing. Irrespective of how contextual cueing affects attention, attentional mechanisms themselves have a strong influence on the manifestation of contextual cueing. If the distractor context is divided and some items are shown in an attended color (the color of the target), while others are shown in the unattended (ignored) color, contextual cueing manifests only for attended distractors (Jiang & Chun, 2001). This suggests that selective attention to the repeated context is a necessary prerequisite for eliciting memory effects in visual search. However, it is likely that the attentional effects do not hinder learning of the ignored context, but regulate its retrieval from contextual memory. If in a transfer phase, a previously ignored set of distractors is shown in the attended color, then contextual cueing can be observed for the ignored set. In the opposite case, when a previously attended set of distractors changes its color to the ignored set, contextual cueing is no longer observable (Jiang & Leung, 2005). This demonstrates that repeated context is learned even under the absence of attention, while on the other hand contextual information can only be retrieved from memory if selective attention is deployed to the repeated context. But even if selective attention is available for processing of distractors, there are several possibilities of how attention is deployed in a given search display. Lleras & von Mühlenen (2004) manipulated observers' focus of attention using different instructions: In the active search condition, observers should deliberately direct their attention to individual display items in the process of target detection. Therefore, their focus of attention could be considered as relatively narrow. In the passive search condition, participants were asked to be receptive and let the unique item "pop" into their minds, a strategy being accompanied by a relatively broad focus of attention. They found that contextual cueing was strongly reduced in the active search condition. Along similar lines, Kunar, Watson, Cole, and Cox (2014) used emotional stimuli in contextual cueing and found that negative stimuli, which were surmised as narrowing the focus of attention, also reduced the magnitude of the contextual cueing effect. In summary, attentional processes strongly affect contextual cueing and while selective attention in general is necessary in order to access contextual memory, the width of the focus of attention has a significant impact on the observed size of the contextual cueing effect.

1.2 The implicit-explicit debate

Implicit contextual cueing. Contextual cueing was introduced as a mechanism, where "incidentally acquired contextual knowledge forms a highly robust, instance-based, *implicit memory* for context" (Chun & Jiang, 1998). The assumption that contextual cueing is implicit, i.e., contextual memory is not available for conscious recollection, was tested with a so-called recognition test: at the end of a contextual cueing experiment, observers were presented with a set of random, non-repeated displays, in addition to the set of repeated displays they encountered during the previous visual search task. Note that repeated and non-repeated displays were shown in random order, so that each trial was equally likely to contain any of the two displays. For each display, they were asked to indicate whether they saw this particular display in the previous search task. Comparing the hit rates (correctly classified repeated display as seen before) with the false alarm rates (incorrectly classified non-repeated display as seen before) revealed, that observers were only at chance level when it comes to identifying learned display configurations (Chun & Jiang, 1998). This procedure has been adopted by many studies on contextual cueing as a proof-of-principle to show that the acquired contextual memory was implicit (e.g. Chun & Jiang, 1998, 1999; Conci & von Mühlenen, 2011; Geyer, Shi, & Müller, 2010; Manginelli, Langer, & Pollmann, 2013; Peterson & Kramer, 2001; Zellin et al., 2014). However, recognition tests also face some critique with respect to their applicability to contextual memory, as they might fail to be very sensitive to detect the kind of knowledge acquired in the context of a visual search task. Chun & Jiang (2003) argued that observers might have explicit access to the target location in a learned configuration without necessarily being aware of the repetition. In order to use an explicit test which engages processes that match those of the search task, Chun & Jiang (2003) applied a so-called generation task. In this test, observers were presented with displays, where the target was replaced by a distractor object and their task was to indicate which quadrant of the current display most likely contained the substituted target. The authors reported that also using this task, observers were unable to perform better than chance in guessing the correct target quadrant. Furthermore, even instructing participants that displays will be repeated in the course of the search task and that they should try to memorize them did not modulate the contextual cueing effect (Chun & Jiang, 2003). In a recent approach of testing contextual cueing in very large samples, it was observed that even in the presence of above-chance recognition, these cueing effects were uncorrelated with cueing effects on search reaction times, which is interpreted as evidence that contextual cueing is an instance of unconscious learning (Colagiuri & Livesey, 2016). Contextual memory also resembles other properties that are usually ascribed to implicit memory: it is long-lasting, as its effects are observable up to 1 week after they were acquired (Chun & Jiang, 2003; Jiang, Song, & Rigas, 2005) and it has a high capacity for up to 60 repeated displays (Jiang et al., 2005). In their review, Goujon, Didierjean, & Thorpe (2015) summarize that consciousness is no prerequisite of contextual cueing and that it is based on unconscious knowledge.

Explicit contextual cueing. Despite this evidence there are doubts about the implicit nature of contextual cueing which mainly stem from methodological concerns which raise doubts about the classical interpretation of awareness tests (Shanks & St. John, 1994). The main shortcoming of awareness tests in contextual cueing is their very low statistical power. The usual procedure of a recognition test in contextual cueing involves 24 trials, containing 12 repeated and 12 non-repeated displays. This very low number of trials stands in contrast to the hundreds of visual search trials, which form the basis of the behavioral contextual cueing effect on reaction times. Therefore, an effect of contextual memory on explicit recollection would have to be massive in order to be detected by such a weak test. Smyth & Shanks (2008) conducted a contextual cueing study and applied recognition and generation tests in order to measure awareness. The critical change to previous work was that the authors increased the number of trials in these tests by applying them not only at the end of the experiment but at several occasions during the search task. They found that simply by increasing statistical power, there were explicit effects of contextual memory in both awareness tests. Further evidence for the claim that contextual cueing might be explicit comes from the application of subjective measures. It was shown that contextual memory could increase visual preference for learned displays (Hirokazu Ogawa & Watanabe, 2011), as well as visual clarity and confidence in search decisions (Schlagbauer, Müller, Zehetleitner, & Geyer, 2012). There is yet another methodological issue concerning the classical approach to tests for implicit memory: the interpretation of null results. The absence of a significant difference in an awareness test between repeated and non-repeated display is often interpreted as evidence for implicit memory. However, non-significant results can only be interpreted as absence of evidence and not as evidence of absence (Dienes, 2015). In a meta-analytic approach to the question of explicit recollection in contextual cueing Vadillo, Konstantinidis, and Shanks (2015) included 73 studies of awareness in contextual cueing and found that despite the majority of studies support implicit memory, taken together there is overall evidence for an explicit effect of contextual memory on awareness. The reason for this is that most of the studies were in fact underpowered and the authors concluded that given sufficient statistical power, one is in fact able to detect the effects of contextual memory in classical awareness tests.

Memory systems in contextual cueing. The debate on implicit and explicit contextual cueing is directly linked to the question about the memory architecture underlying the effect. More specifically, contextual cueing might be based on a single memory system supporting performance in visual search as well as recognition in the awareness test, or two separate memory systems, supporting contextual cueing and recognition performance, respectively. Based on their meta-analysis of a number of contextual cueing studies, Vadillo et al. (2015) derived a simple model of the cueing effect and showed that it can best describe the available data by assuming one latent memory variable underlying effects of context on reaction times and recognition performance. However, there is also recent evidence pointing in the opposite direction. Colagiuri and Livesey (2016) directly derived from Vadillo et al's model that in the case of a single memory resource, there should be a small to medium, but nevertheless reliable correlation between contextual cueing effects on reaction times and recognition. They investigated this claim by collecting large samples (up to $N > 600$) which, according to the model, should be more than sufficient to observe a positive relationship between cueing and recognition effects. The results however showed no such relationship and instead provided evidence for the statistical independence of cueing effects and recognition performance (Colagiuri & Livesey, 2016). The authors therefore conclude that contextual cueing is a form of nonconscious learning, as the explicit effects of contextual memory are not connected to behavioral effects and thus contextual cueing does not rely on conscious access of long-term memory.

1.3 Interactions with short-term memory

Next to contextual memory (Chun, 2000), various other forms of memory have been shown to influence search performance. There are additional long-term memory effects like, e.g., object cueing (Chun & Jiang, 1999) or probability cueing (Geng & Behrmann, 2005), as well as short-term memory effects like, e.g., holding a particular target template in working memory (Duncan & Humphreys, 1989), memory of previously occupied target locations (Geyer, Müller, & Krummenacher, 2007; Maljkovic & Nakayama, 1996), or memory for checked locations in a search trial (Kristjánsson, 2000). Short-term memory in visual search is particularly important for the understanding of long-term contextual memory, since they may overlap both in function (Cowan, 1999) and the associated neural – i.e., hippocampal – structure (Axmacher et al., 2007; Chun & Phelps, 1999; Geyer et al., 2012). To investigate whether contextual cueing also requires short-term memory resources, the usual procedure is to add a secondary working memory task to the normal contextual cueing task (e.g. Vickery, Sussman, & Jiang, 2010). There is compelling evidence that spatial working-memory load interferes with contextual cueing, indicating that effects of long-term contextual memory depend on the involvement of a spatial short-term memory resource (Annac et al., 2013; Manginelli, Geringswald, & Pollmann, 2012; Manginelli et al., 2013). In a sense, short-term memory may be considered as the link between contents from long-term memory and the current search display. But this does not necessarily mean that contextual cueing itself can modulate the contents of short-term memory that are of relevance for performing the current search task.

Lleras and collaborators propose that the maintenance of short-term, perceptual memory is a ubiquitous process during visual search which is especially prominent and observable when a visual search trial is interrupted and later resumed (Lleras, Rensink, & Enns, 2005). Observers were required to perform a task similar to the contextual cueing task; however, the search display was presented only in short flashes (on-phase; e.g. 100 ms), interrupted by an empty screen for a longer period of time (off-phase; e.g. 900 ms). The analysis of reaction time distributions of either the first presentation of a given display or a later presentation revealed that the response pattern differed fundamentally. While there were no reaction times faster than approximately 500 ms following the first flash of the search display, the reaction time distribution of later presentations showed two peaks: the first peak reflected that a substantial number of times observers responded within 500ms, the second peak showed a similar characteristic as after the first presentation. The authors referred to this phenomenon of the fast picking up of an interrupted search as *rapid resumption* (Lleras et al., 2005) and attributed the effect to the fast confirmation of a perceptual hypothesis. According to a theory of reentrant processing, a perceptual hypothesis reflects the accumulated information of spatial relations in the visual scene (Di Lollo, Enns, & Rensink, 2000) and visual search is seen as an iterative process of generating and confirming / rejecting perceptual hypotheses. If a correct hypothesis was already generated on a previous encounter of the same display, this hypothesis just has to be confirmed upon reappearance of the display to elicit the response. This is substantially faster than engaging in the whole process of generation and confirmation and therefore gives rise to rapid resumption. In a number of experiments, it was shown that this effect was neither the result of a confirmation bias, leading observers to just withhold an answer until the next presentation (Lleras et al., 2005), nor a random effect of the target just reappearing by chance in the current gaze (Van Zoest, Lleras, Kingstone, & Enns, 2007). The crucial factor for observing rapid resumption was the stability of the visual display, indicating that if the reappearing display did not match the expectations from previous presentations, rapid resumption did not occur (Jungé, Brady, & Chun, 2009; Lleras et al., 2005; Lleras, Rensink, & Enns, 2007). By making changes to the display between the flashes of presentation and observing whether rapid resumption was preserved or diminished, it can be deduced which visual features are necessary for the effect to manifest and are therefore stored in short-term memory. Lleras et al. (2005) reshuffled the display between epochs – where one epoch refers to one cycle of on- and off-phase – leaving the global configuration intact but swapped positions of all items including the target. This led to an elimination of rapid resumption, indicating that the global context without any information on the items was not sufficient for rapid resumption. Lleras et al. (2007) investigated the importance of the target stimulus. If task relevant features of the target were changed between presentations, rapid resumption was eliminated. However, changes of task irrelevant target features did not influence the rapid resumption effect. Furthermore, they showed that the distractor context alone was insufficient to elicit rapid resumption, since if the target was presented from the second epoch on, rapid resumption was observed not earlier than the third epoch. Jungé et al. (2009) investigated which aspects of the distractor context were nevertheless crucial for rapid resumption. They found that if the locations of distractors in close proximity to the target were changed, rapid resumption was reduced, while changes of distractor positions farther away did not diminish the effect. Importantly, the identity of distractors was not relevant in any condition. Another factor of influence was selective attention: if a set of distractors was attended because it shared the target color, changing the locations of attended distractors affected rapid resumption, while changes of distractors in the unattended color did not modulate the rate of rapid resumption. Note that while Lleras et al. (2007) reported that only the target was relevant for rapid resumption and changing the distractor context did not produce any effects, Jungé et al. (2009) argued that this was due to the timing of the interrupted search task: Lleras et al. used an on-phase of 100 ms which might have led to a low resolution of perceptual hypotheses.

Just like long-term contextual memory is accumulated via the repeated exposure across several trials, perceptual hypotheses are generated via the repeated presentation of the same display within one trial. Also compared to the content of perceptual hypothesis, the content of long-term contextual memory shows strikingly similar characteristics, like the restriction to distractors close to the target (Brady & Chun, 2007; Olson & Chun, 2002), the relevance of spatial locations irrespective of distractor identity (Chun & Jiang, 1998) and task relevance by selective attention (Jiang & Chun, 2001; Jiang & Leung, 2005). This might indicate that both mechanisms involve a general memory resource underlying implicit processing in visual search (Jungé et al., 2009).

1.4 Reward in contextual cueing

Contextual cueing was shown to be an effect which can be modulated by a number of mechanisms like selective attention (Jiang & Leung, 2005), spatial working memory load (Annac et al., 2013), or perceptual grouping (Conci & von Mühlenen, 2011). It is however an open question whether incidental learning can be modulated by motivational factors. In a standard experiment, participants are not instructed about the repetition of displays and even if they are, this does neither increase nor decrease the amount of contextual cueing (Chun & Jiang, 2003). On the other hand, observers' intentions, i.e., search strategies, or emotional manipulations do affect the cueing effect (Kunar et al., 2014; Lleras & von Mühlenen, 2004). Another prominent motivational manipulation in cognitive research is monetary reward, which could also affect context learning. It has been shown that a reward schedule associated with perceptual features produces strong effects in visual search (Hickey, Chelazzi, & Theeuwes, 2010a, 2010b, 2011; Kristjánsson, Sigurjónsdóttir, & Driver, 2010). Hickey and colleagues associated high or low reward consistently with a specific color and found that observers' attention was drawn towards stimuli with the high-reward color. This led to faster reaction times when the target color was associated with high reward or the distractor color was associated with low reward. Analogously, reaction times were slower if the target color was associated with low reward or the distractor color was associated with high reward. Importantly this effect was independent of strategic effect since it still occurred although participants were aware that there was a more effective strategy available for them. Furthermore, electrophysiological evidence showed that reward modulated perceptual and attentional processing of the stimulus (Hickey et al., 2010a). Reward has also been shown to affect performance in effective pop-out searches (Kristjánsson et al., 2010). The authors showed that reward did not only affect performance in a given trial but it also led to an increase in inter-trial effects. Typically, observers perform better when target features are repeated in consecutive trials, an effect termed *priming of pop-out* (Gokce, Geyer, Finke, Müller, & Töllner, 2014; Maljkovic & Nakayama, 1994). This repetition effect, which was thought to be cognitively impenetrable, was also strongly enhanced if the target color was associated with high reward (Kristjánsson et al., 2010). Tseng and Lleras (2013) investigated whether reward was also effective in long-term contextual cueing. The authors paired certain target-distractor arrangements with either high reward (10 points), no reward (0 points), or a penalty (-10 points) in a way that after each trial participants would receive the respective outcome. The authors found that rewarded displays were learned faster, however as soon as an asymptotic level of cueing is reached, reward did not improve performance further. Interestingly, also a penalizing outcome associated with certain repeated display accelerated learning compared to no-outcome displays. Tseng and Lleras interpreted this as an effect of arousal following the negative outcome which led to faster learning compared to displays which were not associated with any outcome. In a second experiment the authors investigated the effects of expectancies in the associated reward. Repeated displays were either rewarded consistently with 5 points or variable between 12 points and -10 points. The results showed that displays that were consistently rewarded were learned faster than when the outcome was variable. However, an unexpected penalty on a given trial (-10 points) strongly increased the learning rate, leading to fast reaction times in the subsequent presentation. This finding further supports the notion that perceptual learning is strongly affected not only by positive reward but also by arousal elicited through penalizing outcome.

1.5 Aims of the thesis

This Thesis intends to contribute to the aforementioned debates and therefore leading to an advanced understanding of spatial long-term, perceptual learning. Four studies were conducted that investigated the relation between contextual cueing and explicit knowledge about repeated displays (studies 1 and 2); the relation between contextual cueing and short-term perceptual memory (study 3); and the relation between contextual cueing and monetary reward (study 4). In doing so, studies 1 and 2 used the novel approaches of metacognition (study 1) and explicit learning of visual search displays (study 2) to shed new light on the debate about the explicit vs. implicit character of the cueing effect. Study 3 combined a contextual cueing task with an interrupted search task in an attempt to reveal potential effects of contextual cueing on the contents of visual short-term memory. Study 4 selectively rewarded individual target locations vs. distractor configurations in an attempt to disentangle the contributions of monetary reward on probability vs. contextual cueing.

Study 1 taps into the debate about whether contextual cueing can be viewed as an implicit or explicit phenomenon. While previous studies mainly focused on the question whether explicit recollection of learned context is possible (Chun & Jiang, 2003; Smyth & Shanks, 2008), relatively little is known about whether contextual memory affects conscious perception of the learned spatial layouts. When participants are asked about the visual preference for a given display – i.e., the subjective impression of goodness, unity, sparseness, global form, etc. – predictive displays that were previously learned were rated higher (Hirokazu Ogawa & Watanabe, 2011). In another approach, if participants were asked to rate the perceptual clarity of the target stimulus and the confidence in their response in a masked localization task, again repeated displays lead to higher scores in the respective subjective scales (Schlagbauer et al., 2012). The existing evidence points in the direction that contextual memory elicits effects accessible for conscious evaluation. However, the question whether participants really have access to the processes underlying their task performance cannot be answered by forced-choice recognition or generation tests, since it is possible that implicit memory produces a response bias leading to above chance response behavior in these tests without ‘true’ recognition. An alternative approach is to measure metacognition, which describes the process of monitoring one’s own cognitive processing (Koriat, 2007). It is measured by subjective reports about visual features involved in deciding between response alternatives of the current task. While it is undisputed that contextual memory affects behavior in a visual search task, the question remains whether the effects of memory also inform metacognitive processes. In order to investigate whether observers have access to the representations underlying contextual cueing, metacognition of the display configuration and the target stimulus was measured, by asking participants to either rate the perceptual clarity of the display configuration or the target stimulus. It is important to note, that metacognition comprises of two aspects: sensitivity and bias. Metacognitive sensitivity is the ability of subjective reports to discriminate between correct and incorrect trials, while metacognitive bias is the tendency to report high or low confidence / perceptual clarity irrespective of behavioral accuracy (Fleming & Lau, 2014). The former is particularly interesting for the study of contextual memory, since a difference between repeated and non-repeated displays in metacognitive sensitivity of display configurations would indicate that contextual memory has an effect on metacognition, that is, observers' ability to consciously access the representation of the current visual search display increases as a function of contextual memory. On the other hand, an effect of repeated context on metacognitive sensitivity of the response-relevant target stimulus would indicate that participants have insight into their own search behavior.

Study 2 further investigates the implicit-explicit distinction in contextual cueing, however from the perspective of different memory systems. The usual rationale in studies on contextual cueing is to ask after the visual search task about recognition or generation and, based on a comparison of the hit and false alarm rates, make inferences about the explicitness or implicitness of contextual memory. Yet, it is problematic to assume that performance at chance level in a recognition test really indicates true implicit memory (Shanks & Berry, 2012). Even if a subset of participants is chosen based on their low performance in the recognition test, it is likely that their failure to recognize repeated displays is merely a statistical phenomenon rather than evidence for implicit memory. Vadillo et al. (2015) put forward a simple model of cueing effects using only one memory and two noise parameters for visual search and recognition performance, respectively. Importantly, the same memory parameter is used to estimate contextual cueing in visual search and explicit recognition and the simulation showed that 'unaware' participants still produced a cueing effect. By this, the authors demonstrated that it is problematic to select participants post-hoc by applying a cut-off on the awareness measure, since it cannot be concluded that this new sample comprises of participants with unconscious knowledge. In the current study, the distinction between explicit and implicit memory was therefore not inferred, but induced by an experimental manipulation. Prior to the search task, participants had to explicitly learn a set of search arrays until they were able to recognize these explicit displays with high accuracy. In the subsequent visual search task, the explicit displays were shown intermixed with repeated displays that have not been previously learned (implicit displays) and random non-repeated arrangements (new displays). A recognition test was administered at several points during visual search. Regarding the cueing and awareness effects, the predictions of four different models were tested: one memory system, two memory systems, transfer-appropriate processing, and associative learning, each using specific parameter settings for the visual search and recognition performance arising from explicit and implicit displays.

Study 3 was concerned with the effects of contextual memory on the contents of short-term perceptual hypotheses. Jungé et al. (2009) observed striking similarities between the two memory phenomena, suggesting that both mechanisms are linked by a common memory resource. Study 3 aimed at putting this hypothesis to the empirical test. In three experiments, interrupted search was combined with the procedure from contextual cueing studies to repeat half of the presented displays in the experiment. In the first part, a standard contextual cueing experiment was conducted for participants to learn the repeated displays. In the second part, they performed an interrupted search task, where the repeated displays from the first part were presented, together with random, non-repeated displays. If contextual memory and perceptual hypotheses shared a common memory resource, it was expected that the presence of long-term contextual memory affected performance in interrupted search by either interacting with the generation or the confirmation of perceptual hypotheses. Experiment 1a used the same timing of on- and off-phase in interrupted search as described in Lleras et al. (2005); the display was visible for 100 ms, interrupted by a blank screen for 900 ms. Experiment 1b was conducted as a control experiment and was identical to Experiment 1a except that the display was shown for 500 ms in interrupted search. This was done for two reasons: i) Following the reasoning of Jungé et al. (2009), short presentation times in interrupted search could yield perceptual hypothesis with only low spatial resolution, effectively leaving out information about the distractor context. ii) Display flashes of 100 ms might be too short in order for representations in contextual memory to become activated and retrieved. If one (or both) of these suspicions is true, Experiment 1b should yield a different pattern of results compared to Experiment 1a. Experiment 2 measured participants' fixational eye movements in order to gain insight into the process of how the target stimulus is approached in interrupted search. Eye movement behavior of both phenomena in isolation have been previously studied: It was shown that rapid resumption can be predicted by the distance of the current fixation to the target, up to two epochs prior to the response (Van Zoest et al., 2007). The analysis of eye movements in contextual cueing has revealed that the number of fixations in a given display is reduced if the display has been previously learned (Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004). In combination, the analysis of target-fixation distances in contextual cueing of interrupted search should yield insight into how contextual cueing fits into the iterative process of generating and testing perceptual hypotheses.

Study 4 was designed to re-investigate the study by Tseng & Lleras (2013) on reward effects in contextual cueing with an additional angle on study design and data analysis. In a standard contextual cueing experiment, a set of displays is shown repeatedly to investigate learning of spatial relations between distractors and the target stimulus. Therefore, both the distractor configuration and the target position are kept constant in a given display, so a reliable association can be formed between them. However, keeping the target position constant in a set of displays is in itself a statistical regularity that can be extracted by observers and used to make search more efficient. If some locations on the screen are more likely to contain a target, these locations receive a processing benefit and search is expedited if a target appears at one of these locations. This effect of statistical learning has been termed *probability cueing* (Geng & Behrmann, 2005; Jiang et al., 2013). In order to circumvent this effect in contextual cueing studies, the target position is also kept constant in non-repeated displays. For example, in an experiment with 12 repeated displays, there are in total 24 possible target locations, half of them associated with constant distractor configurations, the other half always shown with random distractor configurations. Tseng & Lleras (2013) applied different reward manipulations in their study (high reward, no-outcome and penalizing-outcome) and analyzed the reaction time data by comparing repeated displays with a distinct reward schedule to reaction times of non-repeated displays pooled together across reward conditions (providing only one baseline condition). This procedure is however unable to detect possible effects of reward on probability cueing. Since the target position is kept constant in non-repeated displays, a specific reward outcome could be associated to a target location and therefore lead to reward effects in non-repeated displays. Study 4 was conducted to investigate whether reward influences probability cueing and if so, whether this is problematic for the reported reward effects in Tseng & Lleras (2013).

2. Contextual cueing alters metacognition of spatial configurations

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Contextual cueing alters metacognition of spatial configurations.

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2.1 Abstract

Repeated exposure to display configurations facilitates visual search, an effect termed contextual cueing. While contextual cueing is usually attributed to implicit memory, more recent evidence suggests a link between explicit knowledge and the cueing effect. The present study investigated whether the memory trace acquired through contextual learning is able to modulate metacognitive representations of the visual context as well as the target stimulus. Metacognition was assessed by subjective reports of perceptual experience of the display configuration and the target stimulus in a masked localization task. Unbeknown to observers, half of the displays contained repeated target-distractor configurations. Bayesian analysis revealed that repeated search displays were associated with higher metacognitive sensitivity of reports about the display configuration, while there was no effect of repeated context on metacognitive reports about the target stimulus. We conclude that the effects of context on metacognition are content-specific, manifesting in increased metacognitive access to the display configuration but not visual search behavior.

2.2 Introduction

In everyday scenes, visual search targets do not appear in isolation, but are embedded within configurations of non-target or distractor objects. If observers encounter the target consistently within a stable spatial configuration of distractors, target detection becomes more efficiently over time, because incidentally learned configuration expedite visual search, an effect referred to as contextual cueing (Chun & Jiang, 1998, 1999; Chun, 2000). A controversial issue in research on contextual cuing is whether the effect is implicit or explicit (Chun & Jiang, 2003; Schlagbauer et al., 2012; Smyth & Shanks, 2008; Vadillo et al., 2015). In the present study, we investigate a property of contextual cueing being of key relevance to the implicit-explicit debate: the ability of the effect to influence metacognitive reports. Specifically, we ask whether contextual learning is able to impact on metacognition of display configuration processing and compare this effect to potential influences of contextual learning on metacognition of target processing.

2.2.1 The contextual cueing effect

In their pioneering study, Chun & Jiang (1998) let their observers search for a T-shaped target amongst L-shaped distractor items. The spatial configuration of targets and distractors was repeated in half of the trials, while in so-called non-repeated displays – shown in the other half of trials – only the locations of targets were kept constant. Thus, target location repetition effects were equated across the two types of displays and differences in search performance could only be attributed to the effects of repeated distractor configurations (for the effect of target repetitions, see e.g. Jiang, Swallow, & Capistrano, 2013; Schlagbauer, Geyer, Müller, & Zehetleitner, 2014). Reaction times (RTs) decreased with more practice on the experimental task but this effect was larger for repeated compared to non-repeated displays (contextual cueing effect). Interestingly, observers' ability in explicitly recognizing the repeated displays was only at chance level. It was thus concluded that contextual cueing is an implicit effect.

2.2.2 The implicit-explicit debate in contextual cueing

Following Chun and Jiang's (1998) proposal of implicit contextual cueing, the question whether the effect is inaccessible to awareness has become a controversial issue. The debate centers mainly around how implicit learning of display configurations should be measured (Chun & Jiang, 2003; Schlagbauer et al., 2012; Smyth & Shanks, 2008).

The original method used to assess implicit contextual cueing was a yes-no recognition test performed at the end of the search experiment. In this test, participants were presented with repeated and non-repeated, i.e., novel, displays and indicated whether they had seen these displays already during the search task. A large number of studies observed that hits (repeated displays correctly judged as "repeated") were not significantly more frequent than false alarms (non-repeated display misclassified as "repeated") (Chun & Jiang, 1998; Conci & von Mühlenen, 2011; Geyer, Zehetleitner, et al., 2010; van Asselen & Castelo-Branco, 2009). In an alternative approach, Chun and Jiang (2003) assessed awareness by a so-called generation test. In this test, repeated and novel displays were presented, but the target was replaced by an additional distractor item. Participants' had to indicate the quadrant of the substituted target. The generation test revealed no significant difference, which was interpreted as further evidence for implicit contextual cueing (Chun & Jiang, 2003).

Concerns have been raised whether these awareness tests were appropriate to detect explicit processing (Smyth & Shanks, 2008). First, in standard contextual cueing studies, recognition and generation tasks are usually performed only after the visual search task. However, an informative explicit test should be as close in time as possible to the implicit test (Newell & Shanks, 2014; Shanks & St. John, 1994). Second, the statistical power of previous recognition tests may have been insufficient to detect explicit learning in contextual cueing tasks (Smyth & Shanks, 2008).

In addition, the interpretation of previous recognition tests is limited by the problem of corroborating a null hypothesis by p-values: non-significant results should only be interpreted as absence of evidence, not as evidence of its absence (Dienes, 2015). In this regard, a Bayesian meta-analysis of recognition in contextual cueing suggested that the apparent absence of explicit recognition probably reflects false negatives (Vadillo et al., 2015; see also Supplementary Material). Vadillo and collaborators observed that although the majority of recognition tests in contextual cueing revealed no significant differences between hit and false alarm responses, the overall trend in these studies was that of above chance recognition of repeated display configurations. In fact, calculating Bayes factors for previous recognition tests revealed inconsistent findings: on the one hand, the majority of studies supported the notion of implicit contextual cueing, but the Bayesian evidence was only weak, while on the other hand, there was strong evidence for explicit cueing, but this came from only a few studies (Vadillo et al., 2015). To summarize, Bayesian inference appears necessary to evaluate claims about implicit learning, but the evidence provided by recognition tests in previous studies is inconsistent.

2.2.3 Contextual cueing and metacognitive reports

Notwithstanding the question whether participants are able to discriminate between new and old display configurations, the present study examines a new aspect of contextual learning of key relevance to the implicit-explicit debate: the effect of contextual cueing on metacognitive reports. Metacognitive reports are defined as participants' reports about their own performance in the task itself or about the contents relevant for making the decision between the response alternatives. There are two motivations for studying metacognitive reports in contextual cueing: first, anecdotal reports about the phenomenology of contextual cueing suggest a striking discrepancy between the observed changes in behavior and the participants' evaluation of their own performance. For example, Chun and Jiang (1998) reported that only few observers were aware of the display repetitions and their cueing effect was not larger than that of 'unaware' observers. They also noted that according to their own introspection, voluntarily attending to display repetitions did not improve search performance (Chun & Jiang, 2003). However, a thorough and systematic investigation of metacognitive reports is missing for a complete description of the contextual cueing effect. Second, in previous studies, awareness of display repetitions – or target locations – was ascertained based on performance in a forced-choice task. However, above-chance performance does not necessarily imply that participants were also aware of the mental contents underlying their task performance. This argument is at the heart of major theories of conscious awareness, such as global workspace theory (Dehaene & Naccache, 2001; Dehaene, 2010) and higher-order-thought theory (Dienes, 2008; Lau & Rosenthal, 2011; Lau, 2008). Thus, subjective reports may provide more stringent tests of awareness than mere yes-no recognition or generation tasks.

2.2.4 Metacognitive access to the display configuration and target identity

What representations are of relevance for metacognition during contextual cueing? Analogous to the relevance criterion for measuring awareness (Newell & Shanks, 2014; Shanks & St. John, 1994), we investigate if the memory representations that lead to performance benefits in visual search are also able to inform metacognition, i.e. if there is metacognitive access to the representations that facilitate visual search. Fig. 1-2 illustrates a hypothetical model of the processes involved in contextual cueing of visual search.

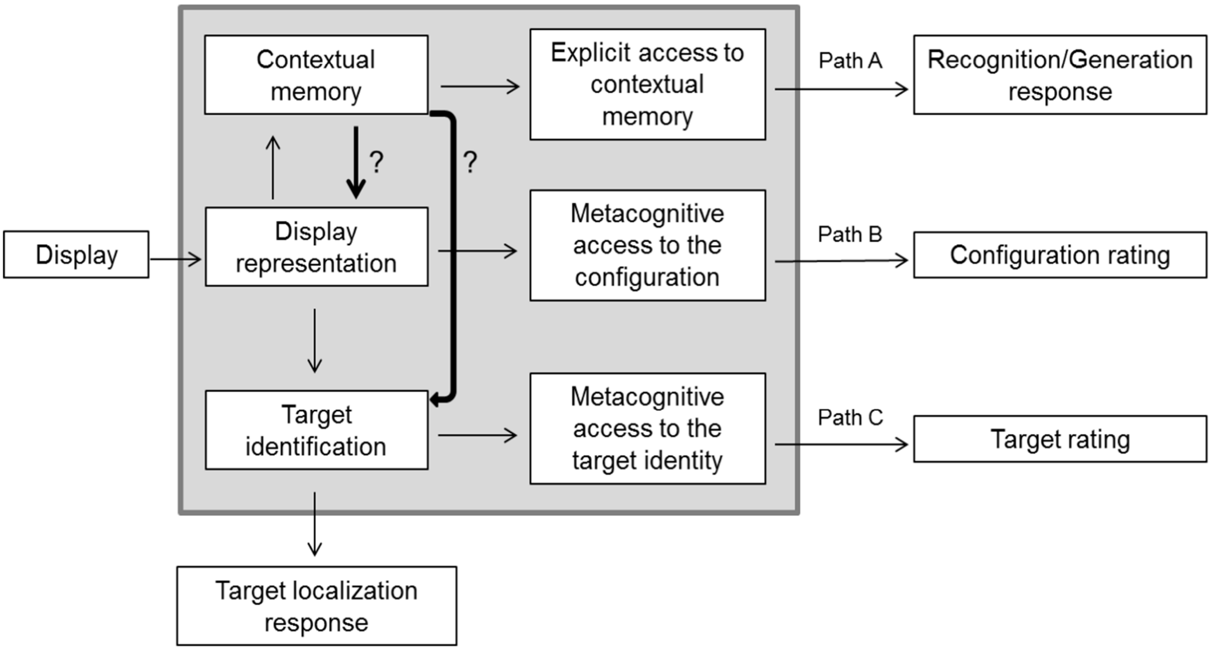

Figure 1-2. Hypothesized causal structure of processes in contextual cueing of visual search. Repeated exposure to the same display leads to recurrent display representations and the build-up of long-term, contextual memory which in turn expedites visual search, i.e., target localization. Previous investigations examined whether observers have explicit access to contextual memory (path A), using recognition or generation tests. In the present study, we investigate metacognitive access to the display configuration (path B) and target identity (path C). Metacognitive effects of contextual memory on either the display representation or target identification should manifest in configuration ratings or target ratings, respectively.

When exposed to a visual search display, the visual system creates a representation of the display, which is the prerequisite for identifying the target and giving a correct response. When a spatial configuration is encountered repeatedly, memory of the spatial layout is formed, which in turn influences visual search by altering the display representation and / or the process of target identification. Previous studies focused on measuring direct access to contextual memory by recognition and generation tests (see path A in Fig. 1-2). This however ignores the important test bed of visual search which serves both the acquisition, i.e., learning, and the expression, i.e., retrieval, of contextual memory. Therefore, in the present study we used visual search in order to investigate observers' metacognitive access to features relevant to this task.

The first source of input to metacognition is spatial memory. Given that contextual memory influences visual search it seems reasonable to investigate whether this memory also influences the displays representation of the current trial and whether this process is accessible to metacognition (see path B in Fig. 1-2). As metacognition is generally claimed to be closely associated with conscious awareness (Koriat, 2007; Lau & Rosenthal, 2011), an effect of context memory on metacognitive reports of the display representation could be considered as an indication of explicit contextual cueing.

There is a second source of input to metacognition. Even if observers are unable to access the memory underlying contextual cueing, they might still have insight into their own visual search behavior. As learned spatial layouts obviously improve participants' performance, participants could just notice the facilitation of their search. The response-relevant feature in visual search is always one of the target features (e.g. location, orientation, etc.) while the distractors are not informative in selecting an appropriate response. Thus, the experience of the target stimulus is crucial for giving a response, but should not be incorporated in contextual memory of the display, as the orientation of the target is always variable in repeated displays. Instead, contextual cueing may facilitate the identification of the target stimulus, for example, by expediting perceptual analysis of the target (Töllner, Conci, Rusch, & Müller, 2013) and/or facilitating response selection (Hout & Goldinger, 2012; Kunar, Flusberg, Horowitz, & Wolfe, 2007). If this is the case, contextual cueing may also enhance metacognitive access to the target stimulus (see path C in Fig. 1-2).

2.2.5 Measuring metacognition by subjective reports

When measuring metacognition, it is vital to distinguish between two aspects of metacognition (Fleming & Lau, 2014): Metacognitive sensitivity, and metacognitive bias. Metacognitive sensitivity, also called type 2 sensitivity (Galvin, Podd, Drga, & Whitmore, 2003), denotes the degree to which subjective reports differentiate between correct and incorrect trials. If participants had metacognitive access to the representations underlying their task performance, their subjective reports about the task should differentiate between correct and erroneous trials. Consequently, metacognitive sensitivity is often used as general measure of metacognition (Barrett, Dienes, & Seth, 2013; Fleming & Lau, 2014; Nelson, 1984). Metacognitive bias refers to participants' propensity to report high confidence irrespective of how accurate they performed. To distinguish between metacognitive bias and metacognitive sensitivity, mathematical tools from signal detection theory are available. Applied to the present study, assessing metacognitive sensitivity separately for repeated and non-repeated displays should provide insights into whether learned spatial configurations influence metacognitive processes.

Although two previous studies investigated the effect of repeated spatial configurations on metacognitive reports, none of them assessed metacognitive sensitivity. First, Ogawa and Watanabe (2011) investigated visual preference by asking participants to rate the “goodness of search displays”. Observers were free to use their own criteria for “goodness”; however, the scale was introduced with examples such as unity, sparseness, global form, and attractiveness of the search display. Participants rated displays as more favorable when display configurations were repeated and predictive of the target location, compared to non-repeated displays as well as repeated displays that were not predictive of the target location. In these displays, the target appeared at different positions while distractor positions were kept constant across repetitions. Consequently, mere repetition of display configurations is not sufficient to affect reports of subjective “goodness”; rather, the display configuration must also be predictive of the target location and lead to a contextual cueing effect. Second, Schlagbauer et al. (2012), using masked displays and verbal reports after each single trial, observed that repeated spatial context was associated with higher confidence in target localization judgments as well as clearer visual experience of the target stimulus. Taken together, both studies demonstrated that the learning of spatial configurations in a visual search task leads to a change of the subjective evaluation of perception. However, as no metacognitive sensitivity analysis was performed, it is still unclear whether the reported contextual cueing effect in the subjective ratings was due to a mere criterion shift.

2.2.6 Rationale of the present study.

The core question of the present study is whether spatial memory traces induced by the repetition of search displays affect metacognitive reports in visual search. Accordingly, we investigated the effect of spatial contextual learning on reports of the subjective experience of the display configuration and reports of subjective experience of the target stimulus.

The current experiment consisted of two parts: In the first part, participants had to localize a target letter “T” among distractor “L” letters under limited viewing conditions. To induce variation in visibility, search displays were masked shortly after the presentation of the search items (see Fig. 2-2). Half of the configurations were repeated and the other half non-repeated displays. The repeated condition consisted of 12 fixed, but differently arranged, target-distractor layouts, which were shown at random insertions throughout the localization task. Non-repeated, random displays were generated at the beginning of a given trial. We collected metacognitive reports after each single trial to measure metacognition as close in time as possible to the contextual cueing effect. A control condition was implemented without metacognitive reports, but otherwise identical procedure, to check whether contextual cueing was affected by the concurrent assessment of participants' introspection in each trial.

In a second, consecutive part of the experiment, participants performed a short, unmasked discrimination task, which is the standard procedure in most contextual cueing studies (for a revision see Goujon, Didierjean, & Thorpe, 2015). No rating questions were administered in the discrimination task and RTs were the dependent variable. The purpose of this task was to examine whether contextual memory obtained under limited viewing conditions transfers to an un-speeded discrimination task, also across conditions. An identical transfer would be indicative of similar learning processes in the different rating conditions.

We hypothesized that if there is any form of insight into contextual cueing of visual search, at least one of the two rating conditions should reveal increasing metacognitive sensitivity over the time course of the experiment for repeated display configurations. More specifically, if memory of display configurations is available to metacognitive processes, we expected an increase of metacognitive sensitivity of subjective reports of the display configuration for repeated displays over and above the behavioral contextual cueing effect. We predicted the analog for metacognitive sensitivity of subjective reports regarding target identity, if metacognitive access in contextual cueing is driven by subjective facilitation of search performance. Bayes factors were used to investigate the effect of context on metacognitive sensitivity, as both the presence and the absence of the effects are of theoretical interest. Of course, these two hypotheses are not mutually exclusive, as contextual cueing could well exert an influence on both metacognitive access to the display configuration and the target stimulus (see Fig. 1-2).

2.3 Experiment

2.3.1 Methods

Participants. A total of 45 observers took part in the experiment (11 male; 1 left-handed, mean age: 25.7 years). All participants reported normal or corrected-to-normal vision and provided written informed consent prior to the experiment. Participants received either €12 or course credit for their participation. The experiment was conducted according to the principles expressed in the Declaration of Helsinki (World Medical Association, 2013).

Apparatus and stimuli. The experiment was conducted in a dimly lit room and run on a PC under the Windows XP operating system. The experiment was programmed in Matlab with the Psychtoolbox extension for stimulus presentation (Brainard, 1997; Pelli, 1997). Participants were seated in front of a 19" CRT monitor (display resolution: 1024 x 768 pixels; refresh rate: 85 Hz [AOC, Amsterdam, The Netherlands]) at a viewing distance of approximately 60 cm. Search displays always consisted of one target T-shape among 11 distractor L-shapes. All 12 items in the search displays were dark grey (1.0 cd/m2, 0.47° × 0.47° in size) and presented against a light grey background (25.4 cd/m2). The items were scattered inside an area of 9.28° visual angle in a way that item density and display extension was as comparable as possible across search displays. Items were positioned at pseudo-randomly chosen locations on four (imaginary) concentric circles around the display center (radii: 2.32°, 4.64°, 6.96°, and 9.28°). The position of items was constrained by a minimum distance between two adjacent items of 2.32°, at least one item on each circle and an equal number of items in each quadrant. These restrictions ensured that search displays were comparable in terms of item eccentricity and item density and that there was no guessing bias regarding the target quadrant. The "T"-shaped target stimulus was oriented randomly either 90° or 270° from the vertical midline and always appeared on the third circle from the display center but never on the horizontal or the vertical midline. There were 24 possible target locations on the third circle, of which 12 were used with repeating display configurations and 12 for the random configurations. The eleven "L"-shaped distractors were positioned at random locations on the four circles (with the restrictions above) and tilted either 0°, 90°, 180°, or 270°. In part 1 of the experiment (localization task), the search displays were masked shortly after presentation by figure-8 shapes placed along 8 concentric circles around the display center, covering the whole area of possible item locations.

Task and procedure. The sequence of events in the experiment is illustrated in Fig. 2-2. Participants were randomly assigned to the configuration-, the stimulus- or the control condition. The conditions differed only in the type of metacognitive reports. The procedure of the experiment, the behavioral tasks, and their order was the same across the three rating conditions.

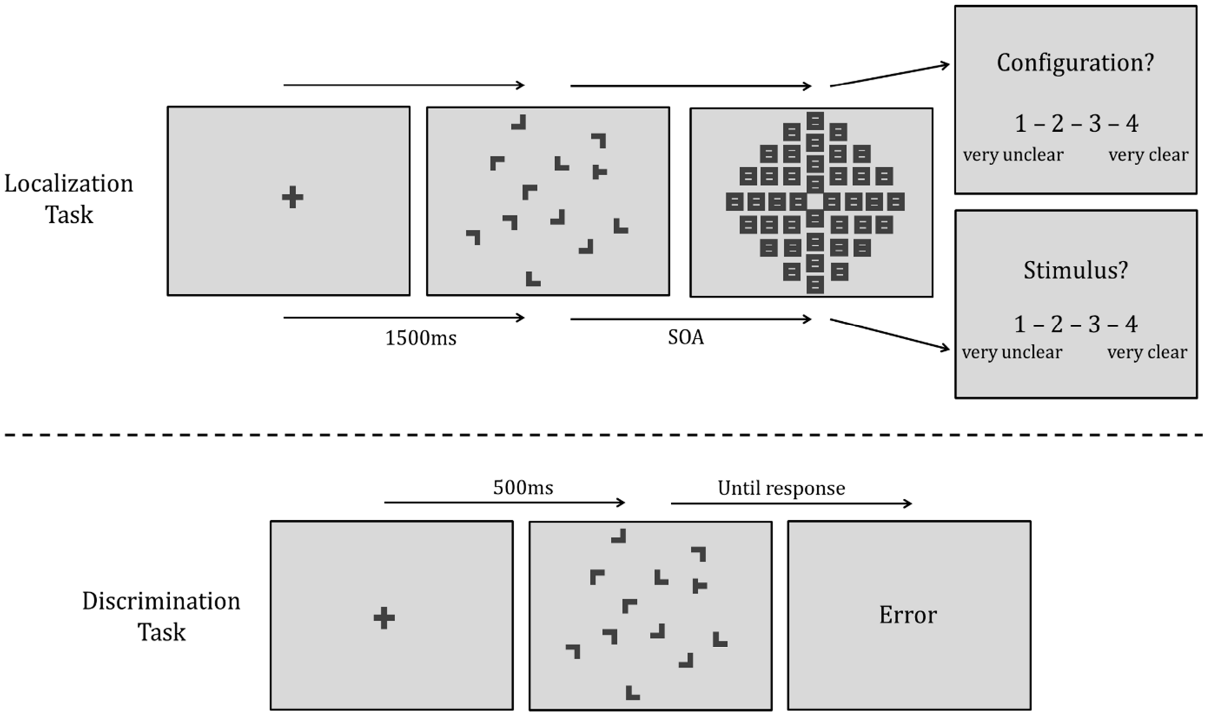

Figure 2-2. Sequence of events in the localization task (top panel) and discrimination task (bottom panel).

After each trial in the localization task, participants delivered a metacognitive report. The design of the experiment was a between-subject design, so each participant only had to rate either the display configuration or the target stimulus. This was done to avoid participants mixing up the rating questions and also to avoid interaction between the two ratings on the same trial. In the configuration condition, participants were asked to report the clarity of the configuration of the display after they gave their localization response. They were instructed that configuration refers to the general outline of the search array, its form or shape and that they should report how well they perceived the display as a whole entity. In the stimulus condition, participants were asked to report the clarity of the target stimulus. They were instructed that this refers to the letter T only and that they should report how clearly they perceived this item. In both conditions, participants were asked whether they understood the instruction and this was also double-checked at the end of the staircase procedure, when they already had an impression of how the displays and task looked alike. The control condition was identical to the other two conditions except that no rating questions were administered. The discrimination task was identical in all three conditions.

In part 1 of the experiment – the localization task – each trial started with the presentation of a fixation cross in the center of the screen for 1500 ms, followed by a blank interval of 200 ms. Next, the search display was presented for an individually adjusted stimulus onset asynchrony (SOA; see supplementary methods for the staircase procedure) until it was masked by the figure-8 shapes. Participants were asked to indicate in which quadrant of the screen the target was localized using the keys on the numeric key pad of a standard computer keyboard with their right hand ("1" for the lower left, "3" for the lower right, "7" for the upper left, and "9" for the upper right quadrant). Following participants' localization response and a blank interval of 200 ms, the rating question appeared on screen. In the configuration condition, participants were asked: "How clearly did you see the configuration"; in the stimulus condition participants were asked: "How clearly did you see the T?" The rating questions of both experimental conditions were presented together with a scale from 1 ("very unclear") to 4 ("very clear"). Metacognitive reports were given by participants pressing the corresponding key ("1", "2", "3" or "4" key) on the keyboard using their left hand. After the subjective report, the next trial started with a blank interval of 200 ms. No rating question was asked in the control condition, while the inter-trial interval was prolonged to 1000 ms. No feedback was given.

In part 2 of the experiment – the discrimination task – trials started with a fixation cross for 500 ms, followed by a blank interval of 200 ms. When the search display appeared, observers were asked to respond to the orientation (to the left or the right) of the target stimulus as fast and as accurate as possible by pressing the left or right arrow key using the corresponding index finger. After a correct response, the next trial started after a blank interval of 500 ms. An erroneous response resulted in the display of the word "Error" in the center of the screen for 1000 ms.

The localization task consisted of 480 trials, divided into 20 blocks of 24 trials each. In each block, 12 of the displays were repeated (repeated displays); the other 12 displays were generated randomly, with only the target position remaining constant across all trial blocks (non-repeated displays). The same repeated displays were used in the discrimination task, which consisted of 96 trials divided into 4 blocks of 24 trials each. Consequently, each repeated display was shown 20 times in part 1 and 4 times in part 2. Overall, the experiment took about 90 minutes.

Data analysis. The data of the localization task were collapsed into two epochs, which each epoch representing an average of 10 consecutive blocks, so as to obtain reasonably stable estimates of the contextual cueing effect and in particular metacognitive sensitivity. Each repeated display was shown once in a given block. Metacognitive sensitivity was assessed by the area under type-2 ROC curves (Fleming, Weil, Nagy, Dolan, & Rees, 2010, see Supplementary Methods for details), as type-2 ROC curves control for rating criteria unlike gamma correlation coefficients (Masson & Rotello, 2009) and logistic regression (Rausch, Müller, & Zehetleitner, 2015) and can be computed even when there are more than two response options, unlike meta-d’ (Maniscalco & Lau, 2012).

Localization accuracy, metacognitive reports, and metacognitive sensitivity were analyzed within three separate ANOVAs with condition as between-subject factor (three levels in ANOVA on accuracy: configuration, stimulus, control; two levels in ANOVAs on metacognitive reports and sensitivity: configuration, stimulus), context (two levels: repeated, non-repeated), and epoch (two levels: 1, 2) as within-subject factors. In addition, we computed equivalent Bayes factors using Bayesian linear models. The Bayes Factor of a given main effect or interaction is obtained by comparing a linear model including the effect of interest to a model which omits the effect. This procedure also allowed for the inclusion of covariates in the linear models (as implemented in the R package BayesFactor by Morey & Rouder, 2015). As priors, we used previously suggested default variance priors for linear models with a scale parameter of √2⁄(4) (Rouder & Morey, 2012). The presence (absence) of a main effect or interaction was considered to be substantial if its Bayes Factor was larger than 3 (lower than 1/3) (Wetzels et al., 2011).

As post-hoc tests, we computed t-tests with Holm-corrected p-values, as well as the Bayesian equivalent of a one-sided paired t-test comparing metacognitive sensitivity of configuration ratings between repeated and non-repeated displays. We assumed a Cauchy distribution of the standardized effect sizes with the scale parameter r = √2⁄(2) over the interval 0 to ∞, which was suggested as a default prior in Psychology (Rouder, Speckman, Sun, Morey, & Iverson, 2009).

In the discrimination task, incorrect responses were discarded from the analysis (overall error rate: 3.3%). Further, RTs were analyzed by means of a mixed-design ANOVA with the factors condition (configuration, stimulus, control; between-subject variable) and context (repeated, non-repeated; within subject variable). Bayes factors were calculated analogously to the analysis of the localization task.

2.3.2 Results

The data was analyzed using R (R Core Team, 2014) Bayes Factors were calculated with the package BayesFactor (Morey & Rouder, 2015). Descriptive statistics (mean values and standard deviations) are provided in the supplementary material.

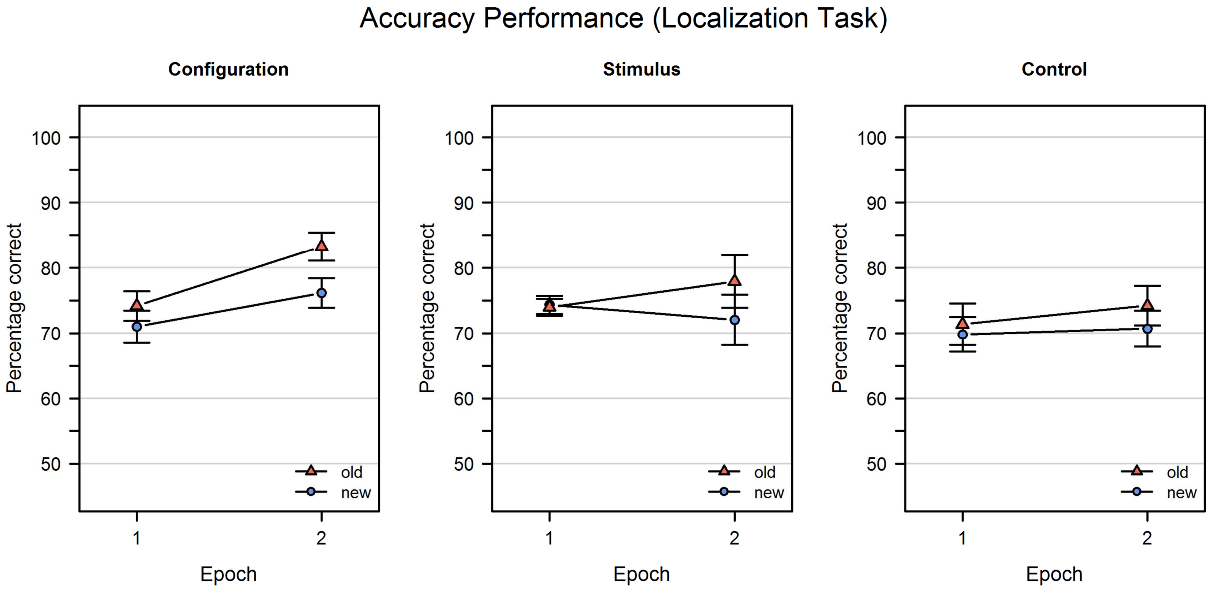

Figure 3-2. Mean localization accuracy performance as a function of epoch in the configuration (left panel), stimulus (middle panel), and control (right panel) condition.

Localization task – Accuracy. As can be seen in Fig. 3-2, task performance increased over time for both repeated and non-repeated contexts across experimental conditions; however, the increase was stronger when the context was repeated. The ANOVA and the corresponding Bayes factors of accuracy as dependent variable indicated main effects of both context [$F(1,42) = 19.8$, $p < .001$; $BF_{10} = 73.17$], and epoch [$F(1,42) = 6.4$, $p < .015$; $BF_{10} = 38.04$]. Their interaction was significant, although the Bayes factor indicated only anecdotal evidence [$F(1,42) = 12.6$, $p < .001$; $BF_{10} = 2.56$]. This could be due to the fact that the localization task was split into only two epochs involving 10 blocks, while contextual cueing usually emerges earlier, after approximately 4-6 repetitions (e.g., Chun & Jiang, 1998).

Importantly, there was substantial evidence against the interactions of condition and context [*F*(2,42) = 1.1, *p* = .333; BF_{10} =.19] as well as condition, context, and epoch [*F*(2,42) = 1.2, *p* = .319; BF_{10} =.17]. There was no conclusive evidence for a main effect of condition [*F*(2,42) = 1.0, *p* = .375; BF_{10} = 0.45] and the interaction of condition and epoch was not significant, although the Bayes factor indicated substantial evidence for it [*F*(2,42) = 2.3, *p* = .112; BF_{10} = 4.91]. In summary, we observed an effect of repeated spatial context on localization accuracy, which was not modulated by the experimental condition.

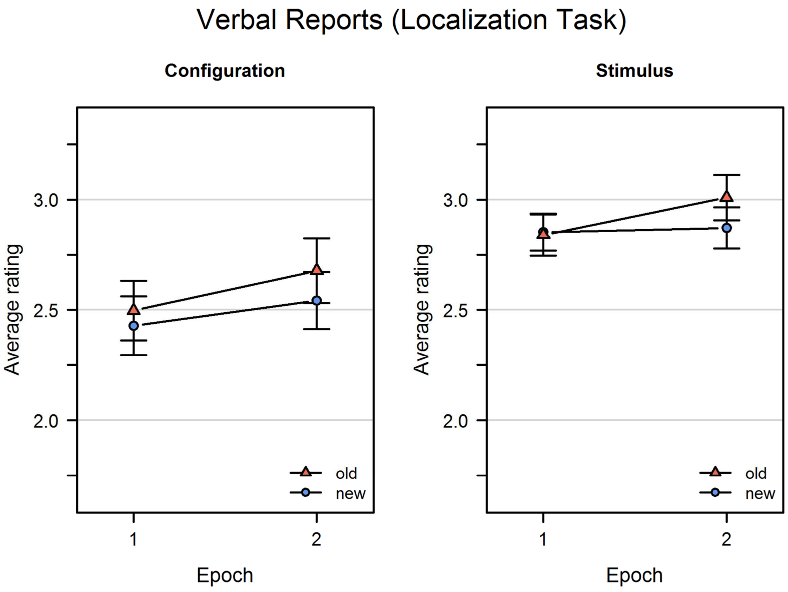

Figure 4-2. Mean verbal reports in the localization task as a function of epoch in the configuration (left panel) and the stimulus (right panel) ratings.

Localization task – Verbal Reports. The analogous analysis applied to metacognitive reports revealed significant and substantial main effects of context [*F*(1,28) = 6.5, *p* = .017; BF_{10} = 5.53] and epoch [*F*(1,28) = 10.3, *p* = .003; BF_{10} = 216.03]. There was a significant, yet non-substantial main effect of condition [F(1,28) = 5.2, p = .031; BF_{10} = 2.08], and an interaction between context and epoch [F(1,28) = 14.8, p < .001; BF_{10} = 1.28]. The analysis also revealed substantial evidence of absence of an interaction between condition and context [F(1,28) = .4, p = .551; BF_{10} = .11], as well as between condition and epoch [F(1,28) = .5, p = .485; BF_{10} = .13]. The three-way-interaction was not significant and inconclusive [F(1,28) = 2.33, p = .138; BF_{10} = .41]. Similar to the pattern of localization accuracy, there was an effect of context on metacognitive reports, which was – except from a potential three-way-interaction – unaffected by the experimental condition (see Fig.4-2).

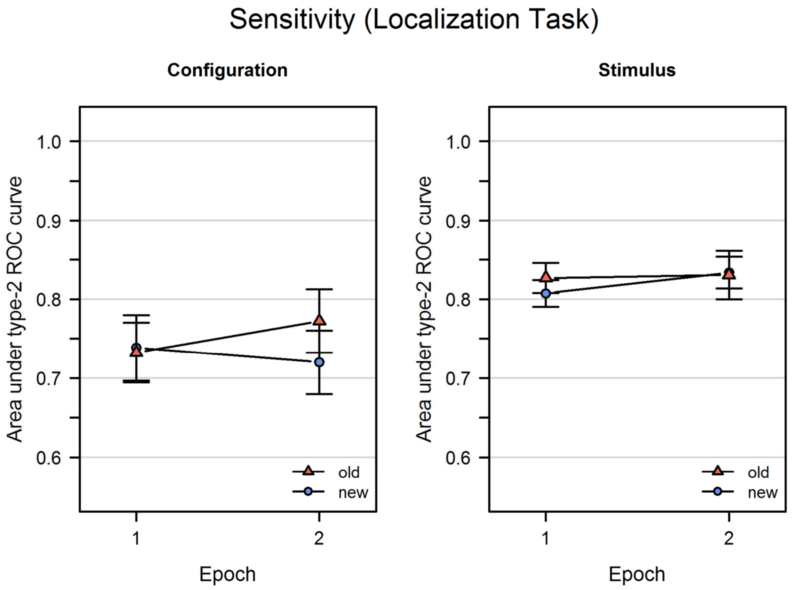

Figure 5-2. Metacognitive sensitivity in the localization task as a function of epoch in configuration (left panel) and stimulus (right panel) ratings – depicted as average area under the type-2 ROC curve for each participant.

Localization task – Sensitivity. The analysis of metacognitive sensitivity revealed that the only significant and substantial effect was a three-way-interaction of condition, context and epoch [F(1,28) = 6.7, p = .015; BF_{10} = 15.14]. All main effects were non-significant and inconclusive [Condition: F(1,28) = 3.9, p = .059; BF_{10} = 1.55; Context: F(1,28) = 3.0, p = .094; BF_{10} = .83; Epoch: F(1,28) = 1,2, p = .275; BF_{10} = .56], as well as the interaction of condition and context [F(1,28) = .7, p = .411; BF_{10} = .35] and context and epoch [F(1,28) = 1.3, p = .259; BF_{10} = .395]. There was substantial evidence against an interaction of condition and epoch [F(1,28) = .03, p = .859; BF_{10} = .27]. As depicted in Fig. 5-2, it appears that metacognitive sensitivity is greater in repeated compared to non-repeated displays only in the configuration condition. The post-hoc analysis for the stimulus condition revealed anecdotal evidence for a null effect of context in epoch 1 [one-sided: t(14) = 1.6, p = .210; BF_{10} = .71] and substantial evidence for a null effect of context in epoch 2 [one-sided: t(14) = -.2, p = 1; BF_{10} = .27]. For the configuration condition, there was substantial evidence for a null effect of context in epoch 1 [one-sided: t(14) = -.3, p = 1; BF_{10} = .27] and substantial evidence for an effect of context in epoch 2 [one-sided: t(14) = 2.7, p = .033; BF_{10} = 3.70], confirming that repeated context is associated with greater metacognitive sensitivity of display configuration ratings in epoch 2.

Control analyses. As metacognitive sensitivity depends on objective task performance, the effect of repeated context on metacognitive sensitivity could be just a by-product of the behavioral improvement in the task (Galvin et al., 2003). Recall that the above analysis was not conclusive whether localization performance differed between groups. It is thus possible that between-group differences in objective task performance have contributed to the pattern of metacognitive reports. As a first check, we repeated the analysis of metacognitive sensitivity with accuracy and reaction time as covariates. Although the localization task was un-speeded, reaction times were included in this analysis to control as many objective task parameters as possible in the determination of metacognitive performance As before, only the three-way interaction was significant and substantial [F(1,28) = 4.8, p = .036; BF_{10} = 4.84]. There was anecdotal evidence for a main effect of condition [F(1,28) = 4.1, p = .052; BF_{10} = 2.49] and the interaction of condition and epoch [F(1,28) = 1.1, p = .309; BF_{10} = .55]. Regarding all other effects, there was substantial evidence for the null hypothesis [F(1,28) < 1.1, p > .300; BF_{10} < .30].

As a second check, we performed a subset analysis in which we included only observers whose localization performance was within one standard deviation of the sample mean. This resulted in the exclusion of 11 subjects, reducing the sample standard deviation from 11% to 4%. The subset analysis was done in an attempt to examine metacognitive sensitivity in participants who displayed more consistent accuracies across rating conditions (recall that we used a between-subject design). Mean accuracies in the three experimental conditions after exclusion were 75.0% in the configuration, 75.8% in the stimulus and 74.4% in the control condition. Performing then the analysis on this very homogenous set of observers confirmed the above results. Regarding localization accuracy, the new analysis revealed substantial effects of context [BF_{10} = 7189], epoch [BF_{10} = 165520], condition x epoch [BF_{10} = 3.35], and context x epoch [BF_{10} = 6.73]. Regarding all other effects, there was substantial evidence for the null hypothesis [BF_{10} < .22]. Regarding metacognitive sensitivities, the only substantial effect was the three-way-interaction of context x condition x epoch [BF_{10} = 7.70]. All other effects were inconclusive with anecdotal evidence for an effect of condition [BF_{10} = 1.56], context [BF_{10} = 2.35], epoch [BF_{10} = 2.02] and condition x epoch [BF_{10} = 2.31], while there was anecdotal evidence for the null hypothesis in the case of condition x context [BF_{10} = 0.59] and epoch x context [BF_{10} = 0.53].

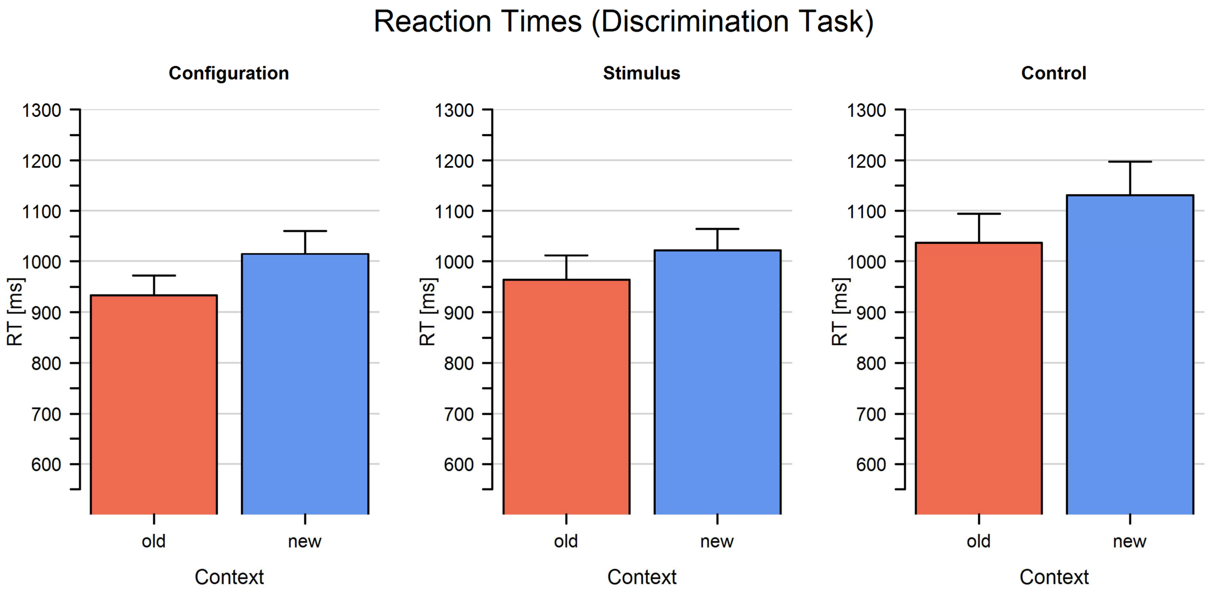

Figure 6-2. Mean RTs in the discrimination task as a function of context (old vs. new) in the configuration (left panel), stimulus (middle panel) and control (right panel) condition.

Discrimination task – Reaction times. The analysis of RTs revealed a significant and substantial main effect of context [F(1,42) = 20.1, p < .001; BF_{10} = 441.62], as well as substantial evidence for the absence of an interaction of condition and context [F(2,42) = .3, p = .726; BF_{10} = .09]. The main effect of condition was inconclusive [F(2,42) = 1.5, p = .238; BF_{10} = .73]. Overall, this pattern of results shows that the contextual cueing effect transferred to the discrimination task and there was no systematic modulation of the context effect depending on the experimental condition (see Fig. 6-2).

2.4 Discussion

2.4.1 Content-specific modulation of metacognition

The present experiment investigated the effect of contextual cueing on metacognitive reports about display configurations and target identity. Consistent with the hypothesis that contextual memory affects metacognition, we observed that configural learning was associated with an increase of metacognitive sensitivity during the course of the experiment when the report had to be made about the perceptual clarity of the display configuration. This effect persisted even when localization accuracy and RTs were used as covariates in the analysis as well as when the analysis of metacognitive sensitivity was limited to a more homogenous set of observers, indicating that the difference in metacognitive sensitivity was not a by-product of improved task performance and / or the between-subject design. However, we found substantial evidence that contextual memory did not have an effect on perceptual clarity of the target stimulus. These findings demonstrate that the display representations acquired during contextual learning are not necessarily restricted to visual search. Instead, these representations are able to modulate at least one additional higher-order cognitive function, namely metacognition. This effect cannot be attributed to a mere criterion shift, as revealed by SDT measures of metacognitive sensitivity. However, metacognitive sensitivity increased only for reports about the configuration, but not for reports about the target stimulus (cf. Fig. 1-2). Given this, and consistent with previous studies, the observed degree of metacognitive insight strongly depended on the content of metacognitive reports, i.e. what metacognitive reports were about (Charles, Van Opstal, Marti, & Dehaene, 2013; Rausch & Zehetleitner, 2016; Zehetleitner & Rausch, 2013).

2.4.2 Do metacognitive reports change visual search behavior?

Although the configuration and the stimulus condition were identical except for the metacognitive ratings, the question remains whether the specific instruction may have interfered with the way participants encoded, i.e., learned, the repeated configurations.

As a first possibility, it may be speculated that metacognitive reports moderated search behavior itself. The Bayesian analysis showed that the rating condition had an effect on procedural, i.e. context-independent, learning, revealed by a substantial interaction of condition and epoch. In contrast, the magnitude of contextual cueing, indexed by the difference between repeated and non-repeated configurations, was comparable between the rating groups, measured by means of both accuracy performance in the localization task and RT performance in the discrimination task. In addition, the Bayesian analysis of observers' localization performance provided substantial evidence for the absence of a condition-by-context interaction, further supporting the idea that the magnitude of the contextual cueing was not affected by the rating condition. In summary, it is possible that the rating task modified learning in visual search but this effect was apparently restricted to procedural – not contextual learning.

As a second possibility, asking observers to report specific perceptual contents may have affected their encoding strategy, i.e. the way how they performed the visual search. Specifically, when observers rated the clarity of the display configuration, they might have adopted a more broad attentional focus while on the other hand, when reporting the clarity of the target, the attentional focus could have been narrower. This possibility is critical, because contextual cueing has been shown to be modulated by the focus of attention induced by either emotional stimuli (Kunar, Watson, Cole, & Cox, 2014) or by the search strategy (Lleras & von Mühlenen, 2004). In the latter study, participants were instructed to either carefully search the display per item (active search), or to apply a strategy of observing the display as a whole, letting the target stimulus "pop into their mind" (passive search; Lleras & von Mühlenen, 2004, p. 475). They found that contextual cueing was reliable only in passive search, when observers had to adopt a wide attentional focus. Both studies imply that if the content of metacognitive reports influenced search strategies, there should be differences in the magnitude of contextual cueing effects. However, in contrast to this prediction, we did find comparable effects of context on localization accuracy and RTs in all three conditions. As the two rating groups produced different contextual cueing effects only in terms of metacognitive sensitivities, it seems that the effect of group on cueing-induced metacognitive sensitivity is due to the content of the reports instead of search strategies.

Of course, there is a third possibility, namely that instructing participants to report their experiences changes the nature of the underlying learning process. According to this view, only configural representations acquired during the concurrent assessment of localization performance and introspection are accessible to metacognition. On the contrary, the representations learned in standard contextual cuing experiments may not be accessible to metacognition. As the accuracy in the localization task and RTs in the discrimination task show the same cueing effect – the former performed with and the latter without rating questions –

these two learning processes would be highly similar and equally effective. Consequently, there is no evidence in favour of this view, but also no evidence against it. However, positing two contextual cuing processes does not appear to be the most parsimonious explanation. In sum, while the present (behavioural) measures support a view of contextual cueing being a single learning process that is not confounded by the concurrent assessment of observers' conscious reports, further (neuroscientific) work is required to elucidate whether different forms of contextual cueing possibly engaged by accompanying rating questions can lead to an improvement in visual search.

2.4.3 Metacognition of early and late processing stages

Metacognitive reports of targets and configurations may reflect contextual cueing effects on two different processing stages of visual search. According to two-stage models of visual search, participants need to direct spatial attention to a certain display item to make a discrimination judgment about whether this item is a target or distractor stimulus (Moran, Zehetleitner, Müller, & Usher, 2013; Wolfe, 1998). These models suggest that visual search is guided by pre-attentive processing of the display, which is governed by bottom-up, top-down, and memory influences (Wolfe, 1998, 2006). Regarding contextual cueing, there is evidence that learned display configurations guide attention (Geyer, Zehetleitner, et al., 2010; Johnson et al., 2007) but also speed-up selection of a discrimination response (Hout & Goldinger, 2012; Kunar et al., 2007). Metacognitive reports about distractor configurations may be sensitive to early guidance of attention by contextual cueing, while reports about the target stimulus may be linked to later cueing effects, such as identifying the target item and/or choosing an appropriate response. The present study suggests a dissociation of the two processes, indicated by effects of repeated displays on metacognitive reports about the perceived display configuration, but not target stimulus clarity. There are at least two possibilities why there was no effect on metacognition of the target stimulus: First, it is possible that contextual memory indeed speeded up response selection, but participants do not have metacognitive access to this late component of contextual cueing. Second, it is also possible that specific features of the current task led to a diminishing influence of response-related processes on contextual cueing: masking of the displays and the localization task could have induced a search behavior where post-selective processes were rather minimal for accurate task performance. Consistent with this hypothesis, recent ERP studies suggest attentional effects on processing the target identity in addition to attentional effects on target selection. The latter ”post-selective” attentional effects are reduced in localization tasks, relative to discrimination tasks, as processing target identity is not necessary for giving a localization response (Töllner et al., 2013; Töllner, Rangelov, & Müller, 2012). Future research may examine whether there is a contextual cueing effect on metacognitive reports about the target stimulus in discrimination tasks.

2.5 Conclusions

The present study suggests that the display representations acquired during contextual cueing are not restricted to visual search behavior; but are able to modulate metacognitive representations of the display configuration in the present trial. However, the metacognitive representation of the target seemed to be largely unaffected from contextual cueing, indicating that the effects of memory on metacognitive processes during visual search are content-specific. These observations are consistent with the view that contextual cueing is an explicit effect; even if more stringent criteria for explicit processing than above-chance recognition performance are applied. Assuming that metacognitive reports of different contents are linked to different processing stages, we suggest that metacognitive reports with appropriately chosen content may be a promising tool for delineating task-specific processing stages that are modulated by perceptual learning.

2.6 Supplementary Material

Staircase Procedure. In order to adjust SOAs individually for each participant, an adaptive 1-up 2-down staircase procedure with the same task was applied. The staircase started with an initial SOA value of 600 ms and was adjusted stepwise until the first reversal point was reached (i.e., a correct trial after an error trial, or vice versa). During the first four reversals, SOA values were modified by step sizes of four frame durations (~48 ms at 85 Hz) to step sizes of one frame duration (~12 ms) for the last eight reversals. The SOA step size was doubled (increased) following an error response trial. The staircase procedure stopped after the 12 reversal points. The whole procedure was repeated four times in order to account for procedural-learning effects and also to allow participants to become familiar with the task. From the last staircase procedure, the mean of the last six reversals was calculated and taken as SOA for part 1 (the localization task) of the experiment. The average SOA obtained by this procedure was 492 ms (SD = 117 ms). Only non-repeated search displays were used in the staircase procedure.

Bayesian statistics. In general, orthodox statistics may bias in the investigation of implicit learning, since absence of evidence is often misinterpreted as evidence for implicit processing. A solution to this problem is provided by Bayesian statistics, because Bayes factors quantify evidence for both the null and the alternative hypothesis (Dienes, 2015; Rouder et al., 2009). A Bayes factor indicates how the prior odds in favor of one over another hypothesis need to be adjusted in light of the data: For example, a Bayes factor of 10 for the hypothesis that there is an effect (H1) vs. the hypothesis the effect is null (H0) means that, according to the available data, researchers should increase their belief about the odds of the two hypotheses by a factor of 10. A particular strength of Bayes factors is that in contrast to a non-significant result, which does not allow for deducing that the data supports the H0, a Bayes factor is also informative whether the result is just inconclusive or whether the data supports the null hypothesis. In other words, Bayes factors can provide evidence of absence.

Type 2 receiver operating characteristics. Type 2 receiver operating characteristics were used to estimate metacognitive sensitivity, the degree to which subjective reports differentiated between correct and incorrect localization responses (Fleming et al., 2010). The purpose of type 2 ROC analysis is to differentiate between metacognitive sensitivity and participants' propensity to report high visual experience. The receiver-operating characteristic is a method from signal detection theory that allows to quantify participants' sensitivity to distinguish between two events irrespective of criteria (Macmillan & Creelman, 2005). The advantage of ROC curves over others methods is that no assumptions about the distributions of evidence in correct and incorrect trials is made (Fleming & Lau, 2014).

To construct type 2 ROC curves, type two hit rate and type 2 false alarms are computed. The type 2 hit rate h is defined as proportion of high experience trials when the participant is correct and type 2 false alarms rate f as the proportion of high experience trials when the participant is incorrect (Galvin et al., 2003). However, with four category ratings, each two adjacent rating categories can be treated as criterion that separates high from low experience. For instance, there is a liberal criterion that assigns low experience = 1 and high experience = 2 – 4, then there is a higher criterion that assigns low experience = 1 and 2 and high experience = 3 and 4, and so on. For each split of the rating data, h and f are calculated and plotted to obtain a type 2 ROC curve (see Fig. 7-2). The area under the type 2 ROC curve can then be used as a measure of metacognitive sensitivity and was computed using the function somers2 implemented in the R library Hmisc (Harrell, 2014). An area under the curve of 1 indicates perfect sensitivity to differentiate between correct and incorrect trials and thus perfect metacognition; when the area is of .5 indicates metacognitive sensitivity at chance level.

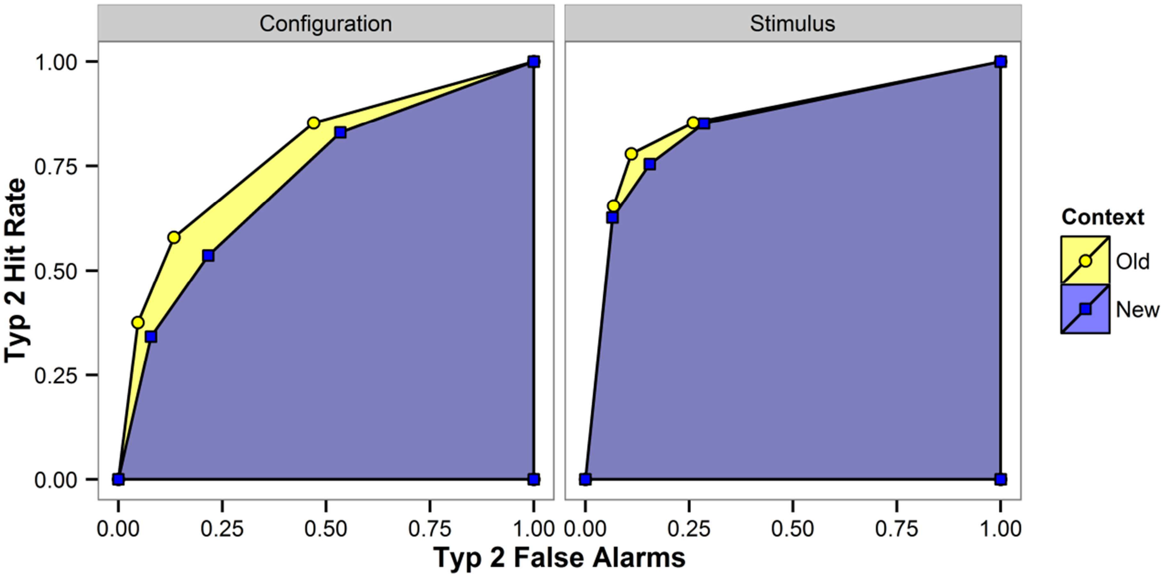

Figure 7-2. Receiver operating characteristics as a function of context (old vs. new) in the configuration (left panel) and stimulus (middle panel) condition in epoch 2.

2.7 Author Contributions

Bernhard Schlagbauer, Manuel Rausch and Thomas Geyer conceived the research question and the experiment; Bernhard Schlagbauer programmed the experimental routine and collected the data; Manuel Rausch conceived and conducted the analysis of metacognitive sensitivity; Bernhard Schlagbauer analyzed accuracy and reaction time data; Bernhard Schlagbauer, Manuel Rausch, Michael Zehetleitner, Hermann J. Müller and Thomas Geyer co-wrote the manuscript.

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3. Explicit knowledge blocks access to implicit contextual memory in visual search

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Schlagbauer, B., Kröll, L., Müller, H. J., & Geyer, T. (*unpublished manuscript*). Explicit knowledge blocks access to implicit contextual memory in visual search.

3.1 Abstract

Repeated presentation of display arrangements leads to an improvement of visual search. This contextual cueing effect is attributed to incidental learning of distractor configurations. Since findings are mixed concerning observers' in-/ ability to explicitly recognize repeated displays, there has been a controversy about the memory architecture underlying the cueing effect. The current study induces explicit learning prior to the visual search task to investigate the relation between explicit knowledge and contextual cueing. The approach is twofold: first, we derived predictions from four different memory models and, second, we tested these predictions in a visual search experiment. The results showed that explicitly learned displays elicit a contextual cueing effect but at the same time engender reaction time disadvantages for implicitly learned displays. This may suggest that contextual cueing is a form of 'classical' associative learning.

3.2 Introduction

A central capacity of the human visual system is extracting statistical regularities from encountered scenes (e.g. Draschkow, Wolfe, & Vo, 2014). For example, if the target in a search task is consistently located within an invariant configuration of distractors, observers can learn these arrangements, or distractor-target associations, and use them to improve their search – an effect termed contextual cueing (Chun & Jiang, 1998). There is an ongoing controversy whether cueing is supported by a single – explicit – memory system (e.g. Vadillo, Konstantinidis, & Shanks, 2015) or whether it is more appropriate to assume two independent – implicit and explicit – memory systems supporting contextual cueing and recognition performance, respectively (e.g., Colagiuri & Livesey, 2016). The current experiment induced explicit knowledge about spatial arrangements to investigate how this affects contextual cueing and to test which memory model is most likely to explain the observed effect.

3.2.1 Explicit memory in contextual cueing

In their seminal study, Chun & Jiang (1998) proposed that contextual cueing is an implicit effect – though this has become a controversial issue on both theoretical and methodological grounds (Chun & Jiang, 2003; Colagiuri & Livesey, 2016; Schlagbauer et al., 2012; Smyth & Shanks, 2008; Vadillo et al., 2015). While 'standard' tests typically fail to find explicit recognition of repeatedly encountered displays (e.g., Chun & Jiang, 2003), increasing the test power has been shown to be sufficient for yielding above-chance recognition performance (Smyth & Shanks, 2008). Furthermore, a meta-analysis by Vadillo et al. (2015) showed that even though single studies do not show explicit recognition of repeated search displays, the overall evidence points to above-chance recognition performance, again indicating that individual tests are hampered by lack of statistical power. Accordingly, Shanks and collaborators concluded that contextual cueing is based on a single, explicit memory system. However, this view has been challenged recently by Colagiuri & Livesey's (2016) investigation of contextual cueing in very large samples. They found no relationship between cueing and awareness, leading them to conclude that contextual cueing is based on non-conscious learning and that cueing and recognition are driven by two independent memory systems. Arguably, though, all these studies, and their discrepant conclusions, suffer from one shortcoming: the absence of an active manipulation of explicit knowledge. While previous work examined for explicit recognition of repeated displays only after participants performed (at least parts of) the visual search task, the present experiment induced explicit knowledge of repeated displays prior to visual search to test predictions derived from different memory models that assume in-/dependence of implicit and explicit processing.

3.2.2 Rationale of the present study

The current study was designed to investigate two main questions: Does explicit memory affect contextual cueing? And how can the memory architecture underlying contextual cueing be characterized? Accordingly, the experiment consisted of two parts: First, participants were instructed to actively memorize a set of six target-distractor arrangements (‘explicit displays’). Then, they moved on to a visual search task in which explicit displays were shown together with another set of six repeated but not previously learned configurations (‘implicit displays’), as well as non-repeated (‘baseline’) displays. Recognition tests were administered in-between four blocks of search trials (cf. Smyth & Shanks, 2008).

In total, participants were to learn 12 repeated displays during the experimental procedure: half of them explicitly prior to the search task in a deliberate effort to recognize them, and the other half incidentally during the search task through repeated exposure. We expected that memory effects to manifest in both tasks to be performed: During search, access to learned configurations should yield shorter reaction times (RTs); in the recognition test, memory access should improve identification of repeated displays. Our particular focus was on how spatial memory for explicit displays would relate to memory for implicit displays.

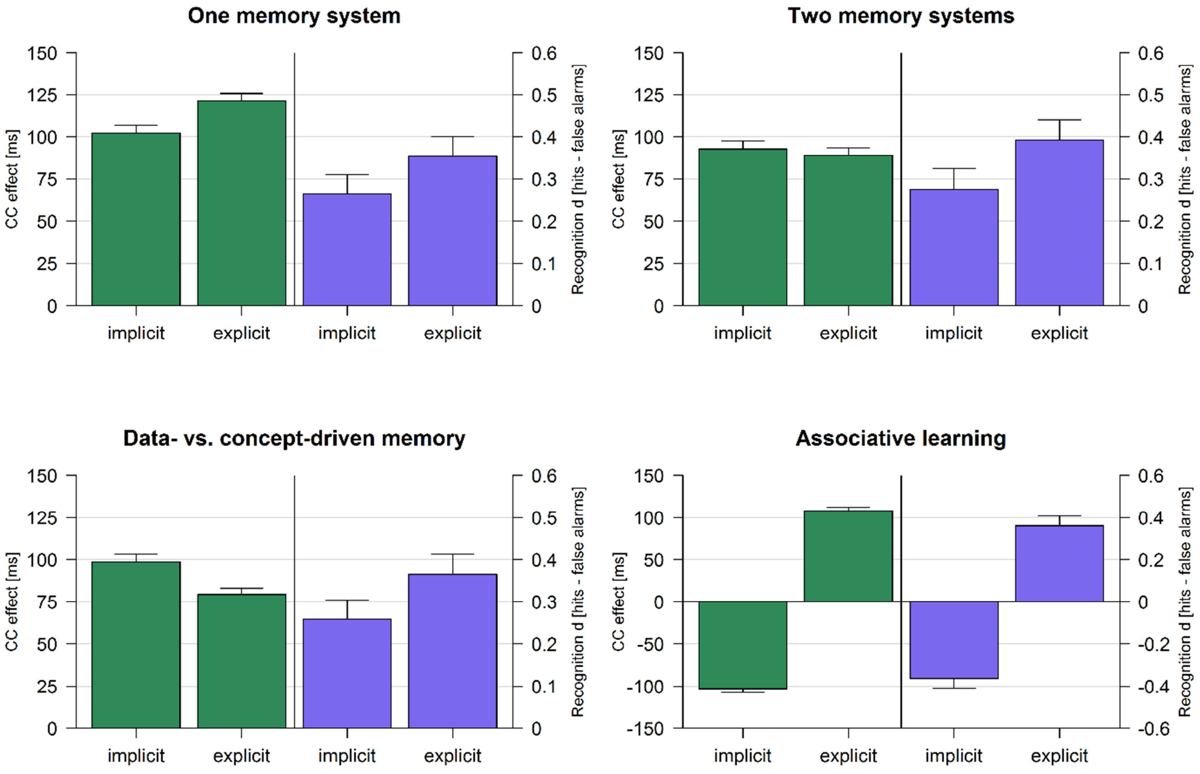
3.2.3 Model predictions

Different memory models make differential predictions with regard to the effects of explicitly versus implicitly learned configurations on visual search and recognition performance. To illustrate these predictions, we took the single-system model of contextual cueing proposed by Vadillo et al. (2015) and adapted Equations 1 and 2 to the predictions of four models.

$$\text{Equation 1:} \quad RT = w_{ss} * s + w_{es} * e$$

$$\text{Equation 2:} \quad d = w_{sr} * s + w_{er} * e$$

The memory strength parameter s is normally distributed with a mean and standard deviation (SD) of 1. Noise is quantified by the parameter e, which is normally distributed with a mean of 0 and a SD of 1. The estimated variable RT is the reaction time difference of non-repeated minus repeated displays (i.e., the contextual cueing effect). The effect size d in the recognition test is calculated by subtracting false alarms (non-repeated displays incorrectly judged as repeated) from hits (correctly recognized repeated displays). Weights – w – are assigned for each model parameter (memory strength [s], error [e]) and task (search [s], recognition [r]); e.g., wsr denotes the weight of the memory parameter in recognition). To predict RT and d in the current experiment, we varied the parameter s and its corresponding weights depending on theoretical assumptions about the in-/ dependence of explicit and implicit learning. Note that the default weights of s and e were chosen on the basis of Vadillo et al.'s estimations: wss = 100 and wes = 30 during visual search; wsr = .30 and wer = 1 during recognition. The simulation for each model was based on a sample of N = 500; the results are depicted in Fig. 1-3.


One memory system

Two memory systems

Data- vs. concept-driven memory

Associative learning

Figure 1-3. Simulated results for four different memory models. The panels show predicted contextual cueing effects, calculated based on the model of Vadillo et al. (2015), for one memory system (upper left panel), two memory systems (upper right panel), transfer-appropriate processing (lower left panel), and associative learning (lower right panel). The green bars depict estimated reaction time effects, the violet bars estimated effects on recognition performance. Both variables are difference values of non-repeated minus repeated displays either of explicitly or implicitly learned displays.

One memory system. The first account assumes the existence of a single memory system underlying both contextual cueing of visual search and recognition (e.g., Vadillo et al., 2015). On this view, the effects of learned contextual cues should be evident in both the search and the recognition task, with performance being based on the same memory strength s. In the current experiment, however, explicit displays have a (quantitative) learning advantage over implicit displays since observers saw them repeatedly in an initial session and went on to the search task only once they had learned to recognize them with high accuracy. To reflect this, the memory strength for explicit displays was increased by an (arbitrarily chosen) factor of 25%, yielding a mean of s in the explicit condition of 1.25 (implicit condition: s = 1). The expected results are illustrated in Fig. 1-3 (upper left panel). As can be seen, contextual cueing should be manifest in both visual search and recognition, with explicit displays yielding overall larger cueing effects.

Two memory systems. The second model assumes that contextual cueing is supported by two independent memory systems (e.g., Colagiuri & Livesey, 2016): one is implicit, driving contextual cueing in visual search, the other explicit, facilitating deliberate retrieval of context cues. On this model, the memory strengths of the two systems would be independent of each other, and, accordingly, the explicit learning phase in the current experiment should have no impact on search performance. Accordingly, both explicit and implicit arrangements should be equally encoded in implicit memory during the search task and thus yield similar memory strengths: mean of ssimplicit = ssexplicit = 1. However, during pre-experimental training on the explicit displays, the explicit memory trace should be elevated (by a factor of 25%), resulting in improved recognition performance for these compared to implicit displays: mean of srexplicit = 1.25; srimplicit = 1. The results of the simulation are depicted in the upper right panel of Fig. 1-3.

Transfer-appropriate processing. While the first two models focus on the encoding of context cues in different memory systems, the following two accounts emphasize the retrieval of contextual cues. Tulving & Thomson (1973) proposed that memory performance strongly depends on the mapping between learning and retrieval conditions (see also Roediger, 1990). Applied to contextual cueing, this would mean that memory effects are strongest if the context cues are retrieved under the same conditions as those applying during learning. For explicit displays, the mapping of learning and retrieval would be strong in the recognition task, but weak in the search task. Implicit displays, by contrast, are learned and therefore optimally retrieved during visual search, while the mapping and thus performance would be weak in the recognition task. Since this model emphasizes the role of memory retrieval, we chose to vary the weight rather than the memory strength itself in order to express varying degrees of access to contextual memory depending on retrieval conditions (see lower left panel of Fig. 1-3). Since transfer-appropriate processing assumes a single memory system (with regard to consciousness), the same memory strength s (mean = 1) was used for search and recognition, while its weight was adapted for explicit displays to reflect the reversed mapping of retrieval and learning conditions: for visual search, the weight for explicit displays was reduced by 25% to wss = 75; for recognition, the weight was increased by 25% to wsr = .375. The default values were used for implicit displays (wss = 100, wsr = .30).

Associative learning. The fourth model, which builds on an effect termed associative blocking, offers a possibility for an interaction between implicit and explicit displays. A basic principle of contextual cueing is that during learning, associations are formed between the distractor layout and the target position (Beesley, Vadillo, Pearson, & Shanks, 2014; Brady & Chun, 2007; Jiang & Wagner, 2004) One theory of associative learning is the Full model proposed by Kruschke (2001; Denton & Kruschke, 2006). In the current experiment, both explicit and implicit configurations predict the target location with equal validity and are thus, in principle, capable of facilitating search to a similar extent. The Full model involves strong assumptions about how successively encoded associations interfere with one another in a pattern known as associative blocking. Blocking occurs when a cue is consistently paired with an outcome while another cue has already been established as an equally valid predictor of that outcome (Kamin, 1968). As a result, the association between the second cue and the outcome is blocked. While Kamin (1968) attributed blocking to a failure to learn late cues, Denton and Kruschke (2006) proposed that late cues are actually learned but their expression is blocked by selective attention, due to the existence of already established memory for stimulus-response associations. Applied to the present experiment, we hypothesized that explicit displays would represent such a valid, search-guiding predictor of the target location and block the retrieval (expression) of implicit displays, although they would not interfere with the learning of the association between an implicit configuration and its target location (see Fig. 1-3, lower right panel). Note that blocking in contextual cueing may not necessarily require the two types of display to cue the very same target position. Instead, blocking may operate due to the high perceptual similarity between explicit and implicit arrangements and the requirement to shield the former – expressly learned – displays from interference from the latter. In terms of a formal implementation of blocking, we used the default weights for explicit displays (wss = 100 and wsr = .30) but reversed them for implicit displays (wss = -100 and wsr = -.30). In essence, the associative learning model assumes a cueing effect for explicit displays, while implicit displays should yield negative cueing effects, due to inhibitory blocking.

3.3 Methods

3.3.1 Participants and Setup

30 participants took part in the experiment (10 male; mean age: 28.0 years). All reported normal or corrected-to-normal vision and were naïve as to the purpose of the study. They provided written informed consent prior to the experiment and received either course credit or payment of 10 Euro (~11 USD). Participants were seated in a dimly-lit and sound-attenuated experimental booth in front of a computer screen (19-inch CRT monitor [AOC, Amsterdam, NL], with a refresh rate of 85 Hz) at an approximate viewing distance of 57 cm.

3.3.2 Stimuli and procedure

The experimental routine was purpose-written in C++. Search displays used in both the explicit learning and the search task contained one target and 11 distractors. The target was a T-shape, rotated by either 90° or 270°; distractors were L-shaped and rotated by either 0°, 90°, 180° or 270°. All stimuli were 0.55° of visual angle in width and height and were presented in black (1.00 cd/m^2) on a white background (25.40 cd/m^2). The items in search displays were placed on four concentric circles around the center (radii of 2.19º, 4.10º, 6.60º, and 8.80º, respectively), with three items in each quadrant and the target either on the second or third circle from the display center.

Explicit learning task. During the first phase of the experiment, participants were asked to memorize the spatial arrangement of a set of six displays. Each of the six displays was presented on screen until the participant continued to the next one via a button press. After each configuration was repeated four times, a recognition test was administered to check whether participants were able to reliably tell apart the six explicit displays from six novel configurations (non-speeded ‘seen before’ vs. ‘new’ discrimination without response feedback). If at least ten out of the twelve displays were classified correctly, participants moved on to the search task. Otherwise, they repeated the learning procedure.

Search task. The search task consisted of 480 trials, divided into 20 blocks of 24 trials. Each block contained three different types of search displays: 12 non-repeated displays, 6 explicit displays, and 6 implicit displays. The latter were generated at the beginning of the visual search task and repeated across the 20 blocks of this task. Non-repeated displays were generated anew on each trial. In order to equate target location repetition effects across the three conditions, the target was presented equally often at a fixed set of 24 locations: 12 locations were used for non-repeated, 6 locations for explicit, and 6 locations for implicit displays. After each four blocks of search, a recognition test was administered that now presented all three display types (12 non-repeated, 6 explicit, and 6 implicit displays) for classification; again, observers had to indicate whether or not they had seen a given display before. This yielded a total of 120 recognition trials. A search trial started with the presentation of a black fixation cross at the center of the screen for varying durations between 750 ms and 1250 ms. After a blank interval of 20 ms the search array was presented until a response was given, but for a maximum of 5000 ms. Participants were to respond as fast and as accurately as possible to the orientation of the target stimulus. If the target was rotated to the left (right) they pressed the left (right) arrow key of the keyboard with their left (right) index finger. A correct response resulted in a blank interval of 500 ms before the next trial. After an erroneous response, the word “Fehler!!!” (German for “error”) was presented for 1000 ms, followed by a blank interval of 1000 ms.

3.4 Results

Data analysis was performed using R (R Core Team, 2014). Bayes Factors were calculated using Morey & Rouder's (2015) *BayesFactor* package, assuming a Cauchy distribution of the standardized effect sizes with the scale parameter $r = \sqrt{2}/(2\ )$ over the interval 0 to ∞ (for the use of default priors, see Rouder, Speckman, Sun, Morey, & Iverson, 2009). We report the natural logarithm of a Bayes Factor (BF_{10}), with values larger than 1 [= *log(3)*] providing substantial and values larger than 2.3 [= *log(10)*] providing strong evidence for the alternative hypothesis (Wetzels et al., 2011).

The data of two participants had to be discarded from further analysis because of overall high error rates in the search task (> ±2.5 SD's of the sample mean). Furthermore, error trials and trials with extreme RTs (> ±2.5 SDs of the individual mean) were discarded.

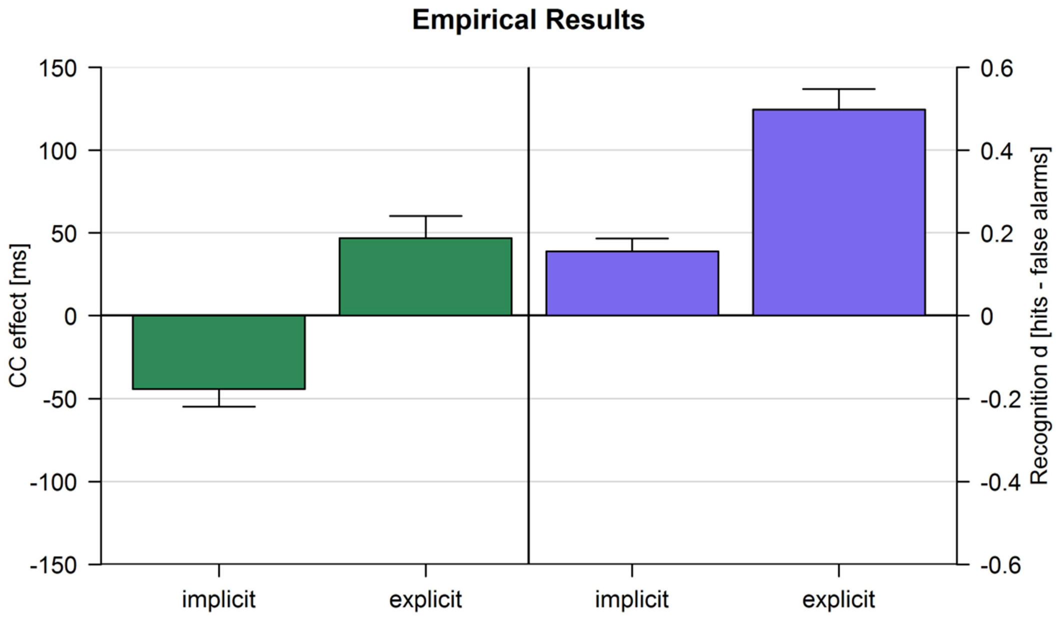


Figure 2-3. Empirical results. The green bars show contextual cueing effects, calculated by subtracting mean reaction times to implicit and, respectively, explicit displays from non-repeated displays. The violet bars show recognition performance, calculated by subtracting false-alarm from hit responses. Error bars indicate the standard error of the mean.

The contextual cueing effects (non-repeated displays – repeated displays) are depicted in Fig. 2-3. Both implicit and explicit displays elicited RTs that deviated substantially from the mean of non-repeated displays. However, implicit displays produced slower RTs [$t(27) = 3.84$; $p < .001$; $log(BF_{10}) = 3.87$], whereas explicit displays led to RT gains [$t(27) = 3.37$; $p = .002$; $log(BF_{10}) = 2.80$]. Naturally, both were also different from each other [$t(27) = 5.12$; $p < .001$; $log(BF_{10}) = 6.93$].

The analysis of recognition performance, as measured by hits – false alarms, revealed that recognition was above chance for both types of repeated displays [implicit: $t(27) = 4.72$; $p < .001$; $log(BF_{10}) = 5.97$; explicit: $t(27) = 9.91$; $p < .001$; $log(BF_{10}) > 17.90$]. However, recognition was superior for explicit over implicit displays [$t(27) = 6.76$; $p < .001$; $log(BF_{10}) = 10.92$].

3.5 Discussion

The present experiment investigated the effect of explicit learning on contextual cueing of visual search and recognition performance. Explicit knowledge was induced by having observers learn target-distractor arrangements prior to performing the search task. We observed that explicit displays elicited contextual cueing of visual search. By contrast, implicit displays, that also contained stable target-distractor arrangements but were introduced only in the search task, produced a negative cueing effect. Furthermore, both implicit and explicit displays yielded above-chance recognition performance.

3.5.1 Contextual cueing as an instance of associative learning

These findings favor the idea that contextual cueing is an instance of associative learning. Judging from RTs, explicit displays did in fact interact with contextual cueing in two ways: (i) they produced a reliable cueing effect and (ii) they interfered with contextual cueing from implicit displays. In line with the predictions of the fourth, associative-learning model, we conclude that the latter effect resulted from blocking. Importantly, for implicit displays, the cueing effect was negative rather than zero, while recognition was above chance level. This indicates that implicit displays were encoded in memory, but memory access was actively suppressed during visual search. One way how suppression may work is to assume separable memory representations, or categories, for explicit and implicit displays (e.g., Palmeri, 1997) and inhibitory tagging of the latter. Accordingly, upon detection of a repeated display of the implicit category, inhibitory tagging will slow the build-up of a search-guiding, overall-salience representation relative to non-repeated displays; for explicit displays, by contrast, the computation of such a representation would be expedited.

Blocking appears to be at variance with Beesley and Shanks (2012), who found no cue competition during contextual cueing of visual search. However, they only used incidental learning of different sets of target-distractor displays, while the current design included an explicit learning phase. Moreover, they paired different distractor layouts with the same target position, while in the current study each target position in explicit and implicit displays was consistently paired with the same distractor arrangement – arguably making both display types better distinguishable from each other and thus engendering strong cue competition.

Interestingly, blocking was not effective during (non-speeded) recognition. One reason for this might be that blocking shows up only when there is stress on response speed. – Taken together, the present results argue in favor of a functional separation of the cueing memory into explicit and implicit representations, rather than for distinctive memory systems.

3.5.2 Negative contextual cueing effects

The present finding that implicit repeated displays may lead to slowed RTs, rather than expedited search, is attributed to blocking of implicit displays. Interestingly, negative contextual cueing effects have also been reported in other studies. For example, Lleras and von Mühlenen (2004) reported contextual cueing effects to vary considerably across observers, with some participants even consistently producing slower RTs to repeated displays (see also Zellin, von Mühlenen, Müller, & Conci, 2014). Lleras and von Mühlenen (2004) also found that the proportion of observers who showed negative cueing could be reduced by changing the instruction: engendering a passive (‘receptive’) search strategy with a wide attentional focus led to more participants with positive contextual cueing effects, compared to an active strategy with a narrow focus of attention. Based on the present results, the mechanism behind this might be that in standard contextual cueing, a subset of displays is learned explicitly and hence blocks access to implicitly learned displays. This idea is supported by studies investigating contextual cueing at the level of individual displays, showing that some displays generate a cueing effect, while others even show negative contextual cueing (e.g., Schlagbauer et al., 2012; Smyth & Shanks, 2008, Colagiuri & Livesey, 2016). We conclude that future work should consider the possibility of blocking between repeated displays when observing negative cueing effects.

3.6 Author Contributions

Lisa Kröll and Thomas Geyer conceived the experiment; Lisa Kröll collected the data; Bernhard Schlagbauer provided the model predictions and conducted the model simulations; Bernhard Schlagbauer analysed the empirical data; Bernhard Schlagbauer and Thomas Geyer co-wrote the manuscript.

3.7 Acknowledgements

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4. Independence of long-term contextual memory and short-term perceptual hypotheses: Evidence from contextual cueing of interrupted search

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4.1 Abstract

Observers are able to resume an interrupted search trial faster relative to responding to a new, unseen display. This finding of rapid resumption is attributed to short-term perceptual hypotheses generated on the current look and confirmed upon subsequent looks at the same display. It has been suggested that the contents of perceptual hypotheses are similar to those of other forms of memory acquired long-term through repeated exposure to the same search displays over the course of several trials, that is, the memory supporting ‘contextual cueing’. In three experiments, we investigated the relationship between short-term perceptual hypotheses and long-term contextual memory. The results indicated that long-term, contextual memory of repeated displays neither affected the generation nor the confirmation of short-term perceptual hypotheses for these displays. Further, the analysis of eye movements suggests that long-term memory provides an initial benefit in guiding attention to the target, while in subsequent looks guidance is entirely based on short-term perceptual hypotheses. Overall, the results reveal a picture of both long- and short-term memory contributing to reliable performance gains in interrupted search, while exerting their effects in an independent manner.

4.2 Introduction

Searching for objects in the environment is one of the central capacities of the visual system and the underlying mechanisms are at the heart of many theories of visual processing (Treisman & Gelade, 1980; Wolfe, 1998). The role of memory, or past experience of visual information, in locating and identifying critical – target – items has long been debated, and it is now widely acknowledged that memory plays an important role in visual search (e.g., Enns & Lleras, 2008; Johnson, Woodman, Braun, & Luck, 2007; Kunar, Flusberg, Horowitz, & Wolfe, 2007; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; Schankin & Schubö, 2010). However, relatively little is known about the relationship between different forms of memory and, with it, the interaction between different attention guidance signals. The current study is concerned with two such memory mechanisms that are of relevance for visual search: long-term contextual memory of target-distractor arrangements (Chun & Jiang, 1998) and short-term perceptual hypotheses about target and distractor locations (Lleras, Rensink, & Enns, 2005). Prior research showed that there are uncanny similarities in the configural representations underlying the two memory types (Jungé, Brady, & Chun, 2009). Yet, no study so far has investigated the effects of contextual memory in a visual search task designed to study perceptual hypothesis testing, that is, interrupted search.

4.2.1 Rapid resumption of interrupted search

Interrupted search is a modified visual search task designed especially for the investigation of memory-based visual search. In their original study, Lleras, Rensink, and Enns (2005) used a search array consisting of a target letter T within a set of distractor letter Ls. The search display was presented in loops of on- and off-phases – the display being visible for 100 ms, followed by a blank display for 900 ms – until participants produced a response. Examination of the reaction time distribution resulting from interrupted search revealed that there were almost no (only approx. 4%) responses within 500 ms after the first presentation of the display. However, on the subsequent encounters, a substantial amount of responses did occur within 500 ms of the second, third, etc. presentation (some 30% – 50%). This effect has been referred to as ‘rapid resumption’ of visual search and is attributed to some short-term memory of the previous search display. In more detail, the notion of rapid resumption builds upon a theory of re-entrant processing (Di Lollo, Enns, & Rensink, 2000) and assumes that visual search involves an iterative process of generating and testing perceptual hypotheses.

Upon the presentation of a search array, a perceptual hypothesis relating to the target stimulus (e.g., its location) location is formed, which is then tested on the subsequent view of the display. If the hypothesis is confirmed, a response is elicited; if it is rejected, a new hypothesis is formed. Rapid resumption occurs when a perceptual hypothesis can be confirmed upon the reappearance of the display. In other words, if a correct hypothesis as to the target is generated, it may be confirmed rapidly in the following look at the display, leading to expedited reaction times.

Follow-on experiments addressed the issue of the contents of perceptual hypotheses by introducing changes to the search displays across successive presentations – the rationale being that if the changed attributes are part of the perceptual hypothesis, this should reduce the rate of rapid resumption (e.g., Jungé et al., 2009; Lleras, Rensink, & Enns, 2007). It was found that changing the location of distractors nearby the target strongly affected rapid resumption, while the location of distractors more distant from the target had no detrimental effect. Furthermore, changes of the target orientation, that is, of the response-relevant feature, had a negative effect on the rate of rapid resumption, but not changes of distractor orientation. Finally, rapid resumption was found to be modulated by task relevance, that is, feature-based attention: repositioning distractors that shared the target’s color interfered with the effect, while repositioning distractors of a different color left the rate of rapid resumption unchanged. Jungé et al. (2009) concluded that perceptual hypotheses contain information about the location, but not the identity, of distractors in close proximity to the target item, as well as information about perceptual attributes of the target. Furthermore, Junge et al. surmised that rapid resumption is modulated by task relevance, in that only distractors of the target’s color (set) are incorporated in the perceptual hypothesis. This pattern of effects strongly resembles findings from another line of research on the memory-based guidance of visual search: contextual cueing.

4.2.2 Contextual cueing of visual search

If a target object is consistently encountered within a stable spatial arrangement of task-irrelevant distractor objects, detecting the target becomes more efficient over time, relative to target detection in non-repeated arrangements. This contextual cueing effect is attributed to learnt target-distractor spatial associations stored in long-term memory, which come to guide the search (Chun, 2000; Chun & Jiang, 1998, 2003). Like in interrupted search, in typical investigations of contextual cueing, participants are required to find a target T amongst distractor Ls – however, with the display being visible until a response is issued. In a block of trials, usually 12 spatially different displays are presented repeatedly, that is, their arrangement is held constant across the experiment; the other 12 are non-repeated displays, consisting of random target-distractor arrangements. Note that target positions in non-repeated displays are kept constant to equate target position repetition effects across the two conditions; this way, the difference between repeated and non-repeated displays can be unequivocally attributed to contextual learning of distractor configurations (Chun & Jiang, 1998; Jiang, Swallow, & Rosenbaum, 2013). Numerous studies on the contents of contextual memory have revealed strong parallels to the findings of Jungé et al. (2009). For instance, Olson and Chun (2002) examined the spatial extent of contextual memory by repeating only half of the distractors in a given display, which was found to be sufficient to generate a contextual-cueing effect. Later on it was shown that essentially only the distractors in close proximity to the target give rise to contextual cueing (Brady & Chun, 2007). Regarding the identity of the distractors, it was shown that identity (i.e., orientation) changes of the target and distractors in repeated displays did not interfere with contextual cueing (Chun & Jiang, 1998). This suggests that what is stored in contextual memory are spatial target-distractor relations, but not target or distractor identities. In addition to spatial (proximity) factors and featural resolution, the third finding of Jungé et al. (2009) regarding the effects of featural attention in perceptual hypothesis testing also has analogue in contextual cueing: searching for a target of a predefined color among two sets of distractors of either the same color as the target or a different color did yield a reliable contextual-cueing effect when only the arrangements of the target-colored distractors were repeated (Geyer, Shi, & Müller, 2010; Jiang & Chun, 2001; see also Jiang & Leung, 2005). In summary, contextual memory and perceptual hypotheses exhibit striking similarities in terms of their spatial and featural properties, allowing for the possibility that the two mechanisms are linked by a common mnemonic representation.

4.2.3 Rationale of the present study

In three experiments, we examined for a relationship between contextual memory and perceptual hypotheses. Each experiment used repeated and non-repeated displays presented in an interrupted search task. First, in a normal visual search task, participants learned a set of (12) repeated displays. Subsequently, participants performed an interrupted search task with the same set of – now learnt – repeated displays, intermixed with random, non-repeated displays. In Experiment 1a, the display was visible for 100 ms and interrupted by a blank screen for 900 ms (Lleras et al., 2005). Experiment 1b was a replication of Experiment 1a, except that the on-phase was now prolonged to 500 ms. We manipulated the time available for processing the interrupted search displays because this factor has been shown to critically influence both the contextual-cueing and the rapid resumption effects. Regarding the former, there is ample evidence that the cueing effect is relatively sluggish in that it takes processing time for the effect to ‘kick in’ (Geyer, Zehetleitner, et al., 2010; Kunar et al., 2008; H. Ogawa & Kumada, 2008): cueing effects are larger when observers are provided with additional time for processing the displays. Applied to interrupted search, this could mean that although perceptual hypotheses based on the current search display and contextual cues from long-term memory may be linked via a common mnemonic representation, contextual cueing would simply be too slow to contribute to this representation and aid interrupted search. Regarding perceptual hypotheses, Lleras, Rensink, and Enns (2007) found that the task-relevant target feature alone is sufficient for rapid resumption to occur. However, Jungé et al. (2009) argued that this finding might be attributable to the timing implemented in the interrupted search task: Lleras et al. presented the display for (on-phases of) only 100 ms, which might limit the resolution, that is, the spatial extent/range, of perceptual hypotheses. The same might be true for our Experiment 1a, allowing for only relatively narrow perceptual hypotheses that lack information about distractor locations and thus decreasing potential effects of long-term – distractor – memory on perceptual hypothesis formation in interrupted search. Given this, Experiment 1b introduced extended presentation times of 500 ms in order to examine potential influences of this factor.

In Experiment 2 we recorded participants’ eye movements so as to gain further insights into potential effects of contextual cueing on perceptual hypothesis formation. Eye-movement analyses in interrupted search had revealed the distance of the fovea to the target to be a strong predictor of rapid resumption (Van Zoest et al., 2007): comparing the distance to the target on two looks prior to observers’ overt responses showed that, in case of a rapid-resumption response, fixations were closer to the target already on the second-to-last look.

4.2.4 Hypotheses

The presence of both types of perceptual memory – contextual memory and perceptual hypotheses – may result in either synergistic, interactive or independent, additive effects in interrupted search.

Synergistic effects. The high similarity of the memories underlying rapid resumption and contextual cueing, in terms of their spatial and featural characteristics (Jungé et al., 2009), may be taken to suggest that the two types of memory are integrated in a common, search-guiding representation. Conceivably, perceptual hypotheses, formed and held in short-term memory, integrate contextual cues retrieved from long-term memory with information extracted from the currently viewed search display. This may be an interactive process: information from the current search display would be required for retrieving context cues, which in turn might constrain the extraction of display information. In this way, contextual memory might expedite the generation of perceptual hypotheses, manifesting in an accelerated approach of fixational eye movements towards the target location and, thus, overall gains in search performance.

Alternatively, or in addition, the effects of contextual memory might become manifest at a later stage of the search process, namely: hypothesis confirmation. Contextual cueing has been shown to also facilitate processes of response selection (Kunar et al., 2007; Schankin & Schubö, 2010). If the target's response-relevant feature is already incorporated in the perceptual hypothesis (Jungé et al., 2009; Lleras et al., 2007), it is possible that contextual cueing particularly expedites the mapping of a stimulus onto a response during perceptual hypothesis confirmation, resulting in a higher rate of rapid resumption or faster reaction times in the epoch of response.

Independent effects. On the other hand, the relationship between perceptual hypotheses and contextual memory may be a fairly loose one, with both mechanisms exerting their effects in an independent fashion. For instance, owing to the nature of the interrupted search task, perceptual hypotheses may receive dominant input from the current visual search display: As the search display is available only for a short time, observers may focus their efforts on processing selected parts of the display. This may permit them to generate an already highly precise hypothesis as to the target based on the current look, which then cannot be further improved by guidance signals from long-term memory.

An alternative proposal is that perceptual hypotheses based on the current look occupy short-term memory resources, interfering with contextual cueing. This idea derives from recent findings that contextual cueing is substantially reduced when observers perform a demanding, secondary spatial working-memory task (Annac et al., 2013; Manginelli, Langer, & Pollmann, 2013). This is not to argue that the visual short-term memory underlying perceptual hypotheses is equivalent to working memory. However, there is evidence from both behavioral and neuroscientific investigations that visual short-term memory and working memory share functions and neural resources (e.g., Kristjánsson, Saevarsson, & Driver, 2013; Soto, Llewelyn, & Silvanto, 2012). The implications for interrupted search would be that the effects of contextual cueing on perceptual hypothesis formation and testing are weak, at best.

However, contextual cueing may nevertheless aid interrupted search by affecting parts of the search process that are unrelated to the formation and test of perceptual hypotheses. For example, in an oculomotor investigation of the cueing effect, (Peterson & Kramer, 2001) showed that the distance of the first fixation to the target and the angle of the first fixation from the target were smaller for repeated displays. Subsequent analysis showed that these effects were due to a higher proportion of initial fixations that were made directly to the target location. Peterson and Kramer took this to mean that contextual cueing is highly accurate in guiding attention to the target location (given successful recognition of repeated displays). Applied to interrupted search this could mean that cueing modulates the starting point of the search process in that it biases attention towards certain displays parts, effectively shortening the interrupted search process. These performance gains would impact search early, that is, before observers begin to search for the target in an iterative process of perceptual hypothesis generation and confirmation. Insofar, contextual cueing and the memory underlying perceptual hypothesis would exert their effects in an independent manner.

4.3 Experiment 1a – Short viewing time

4.3.1 Methods

Participants. 20 participants (5 male, 1 left-handed, mean age: 24.7 years) took part in Experiment 1a. All reported normal or corrected-to-normal vision. All participants provided written informed consent prior to the experiment and received 8 € (~8.9 USD) or course credit for their participation. All participants received standardized written instructions for the two parts of the experiment (cf. Fig. 1-4). Before the start of the experiment, participants performed two practice blocks, one with the visual search and one with the interrupted search task.

Apparatus and stimuli. The experimental routine was programmed in Matlab with the Psychtoolbox extension (Brainard, 1997; Pelli, 1997) and was run on a PC under the Windows XP operating system. Participants were seated in a dimly lit room in front of a 19inch CRT-Monitor (display resolution 1024 x 768 pixels; refresh rate: 85 Hz) at a viewing distance of approximately 50 cm. All items in a given search array were dark grey (1.0 cd/m2), extended 0.5° of visual angle in width and height, and were presented against a light grey background (25.4 cd/m2). A given search array always consisted of 11 L-shaped distractors and one T-shaped target. Item positions were chosen pseudo-randomly such that display extension and item density were comparable across displays. Distractors were positioned on four (imaginary) concentric circles around the display center (radii: 2.32°, 4.64°, 6.96°, and 9.28°), with a minimum distance of 2.32° from each other. At least one item was positioned on each circle and an equal number of items were positioned inside each quadrant of the display. The target was always located on the third ring from the center. There was a total of 24 possible target locations, 12 of which (3 in each quadrant) were used for repeated displays with constant distractor layout throughout the experiment. The other 12 target locations (3 in each quadrant) were used for non-repeated displays with random distractor arrangements. The T-shaped target was oriented randomly either 90° to the left or 90° to the right; the L-shaped distractors were rotated either 0°, 90°, 180° or 270°.

Task and procedure. The sequence of events in Experiment 1a (and Experiments 1b, 2) is depicted in Fig. 1-4. Participants first completed the visual search task, followed by the interrupted search task.

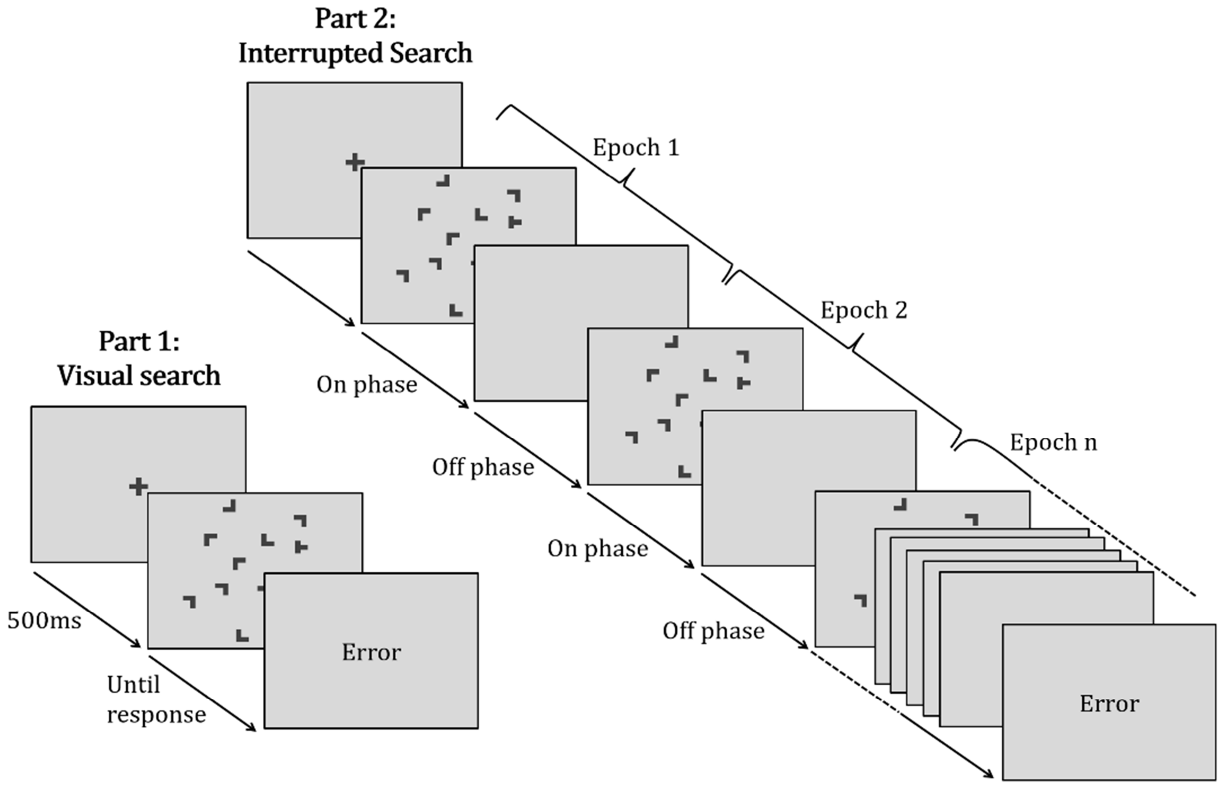

Figure 1-4. Sequence of events in a given trial of the visual search task (part 1) and interrupted search task (part 2). The procedure was identical for all experiments, except that part 2 differed with respect to the timing of the on- and off phase (on-phase, Experiments 1a, 2: 100 ms; Experiment 1b: 500 ms; off-phase, Experiments 1a, 1b: 900 ms; Experiment 2: 1500 ms). In interrupted search each displays was presented repeatedly for a short period of time (on-Phase) followed by a blank screen (off-Phase), until a response was given.

A visual search trial started with the presentation of a fixation cross (0.5° x 0.5°, 1.0 cd/m2) for 500 ms, followed by a blank interval of 200 ms before the search display was presented. Participants were instructed to respond as fast and as accurately as possible to the orientation of the target letter T. If it was tilted to the right (left), they had to press the right (left) arrow button on a computer keyboard with their corresponding index fingers. Following an erroneous response, the word “Fehler” (German for “Error”) appeared on screen for 1500 ms, followed by a blank inter-trial interval of 500 ms. A correct response immediately led to a blank screen, of 500 ms duration, before the start of the next trial. The visual search task consisted of 360 trials divided into 15 blocks of 24 trials each. Participants had the opportunity to take a short break between the blocks or continue directly with the next block. In each block, half of the trials contained repeated (old) displays with constant target-distractor arrangements. These 12 displays were generated randomly at the beginning of the experiment but the arrangement was held constant across the entire experiment. The other 12 trials contained non-repeated (new) displays with random distractor layouts (but constant target positions) generated anew on each trial. Trial order was randomized in each block. Target orientation was also a random variable.

An interrupted search trial started with the presentation of a fixation cross for 1500 ms, followed by a blank interval of 200 ms. The search display was then presented for brief looks (on-phase: 100 ms), separated by longer waits (off-phase: 900 ms). Note that in the following, cycles of on- and off-phases are labelled as epochs. Participants were instructed to respond at any time during the trial to the orientation of the target letter T, while being as fast and as accurate as possible. If no response was given after 10 epochs – or 10 repeated presentations of the same display – the trial was terminated and counted as error trial. If an error occurred, the word “Fehler” (German for error) was presented for 1500 ms followed by a blank inter-trial interval of 500 ms. A correct response immediately triggered the blank interval of 500 ms. The interrupted search task also consisted of 360 trials divided into 15 blocks of 24 trials each. The 12 repeated displays used in part 1 were also used in part 2, making up half of the trials in each block. The other half were non-repeated, random, displays with constant target positions (see above).

Data analysis. To acquire reliable estimates of contextual cueing, we collapsed 5 blocks into one set for analysis. Please note, that while most contextual cueing studies used the term epoch for aggregated blocks of trials (e.g. Chun & Jiang, 1998; Conci & von Mühlenen, 2009; Jiang & Chun, 2001; Peterson & Kramer, 2001), we tried to avoid confusion with terminology from the literature of interrupted search (e.g. Jungé, Brady, & Chun, 2009; Lleras, Rensink, & Enns, 2005; Van Zoest, Lleras, Kingstone, & Enns, 2007) and used the term epoch solely to describe one cycle of on- and off-phase in an interrupted search trial.

In order to conclusively test our hypotheses, it was necessary to also test for the absence of effects. Since non-significant results could only be interpreted as absence of evidence, we used Bayes factors which can also be interpreted as evidence of absence if they are sufficiently small (see, e.g., Dienes, 2015; Rouder, Speckman, Sun, Morey, & Iverson, 2009). We computed Bayes factors using Bayesian linear models, equivalent to an ANOVA design. The Bayes factor of a given main effect or interaction is obtained by comparing a linear model including the effect of interest to a model which omits the effect (as implemented in the R package *BayesFactor* by Morey & Rouder, 2015). Participant number was always included as random effect. We used suggested default variance priors for linear models with a scale parameter of $\sqrt{2}/(4\ )$ (Rouder & Morey, 2012). A main effect or interaction was considered to be substantial if the Bayes factor was larger than 3. A Bayes factor smaller than 1/3 was considered as substantial evidence for the absence of a main effect or interaction (Wetzels et al., 2011). Bayes factor in between the thresholds indicate that the evidence for or against an effect is inconclusive.

In visual search, error trials were excluded from further analysis. Reaction times were analyzed with main terms for context (repeated vs. non-repeated) and set (3 sets of 5 blocks each).

In interrupted search, error trials were excluded and we only analyzed trials with responses made within epochs one to six (see Lleras et al., 2005 for a similar procedure). Reaction times were analyzed with the same factors as in visual search (context: repeated, non-repeated; set: 1,2,3), but separately for the two dependent variables trial reaction times – measured from the first presentation of the display until response – and epoch reaction times – measured from the last presentation of the display until response. Additionally, we examined the average epoch of response as a function of context and set. The rate of rapid resumption was compared between repeated and non-repeated displays with a two-tailed paired Bayesian t-Test. We assumed a Cauchy distribution of the standardized effect sizes with the scale parameter $r = \sqrt{2}/(2\ )$ over the interval 0 to ∞, which has been suggested as a default prior in psychological research (Rouder et al., 2009). Responses with an epoch reaction time faster than the fastest individual reaction time in the first epoch but not slower than 500 ms were considered as rapid resumption responses (RR; cf. Lleras et al., 2005). Responses occurring later in an individual epoch were considered as normal search responses (NS).

4.3.2 Results

Data was analyzed using R (R Core Team, 2014), and Bayes Factors were calculated using the package *BayesFactor* (Morey & Rouder, 2015). The results of Experiment 1a are depicted in Fig. 2-4.

Visual Search. The analysis of reaction times in visual search revealed substantial effects of context ($BF_{10} = 27433$) and set ($BF_{10} = 3.144*10^{11}$), but no conclusive evidence for an interaction ($BF_{10} = 1.09$). The presence of a reliable contextual cueing effect suggests that repeated displays had been successfully learnt in the visual search task of Experiment 1a (see panel *a* of Fig. 2-4).

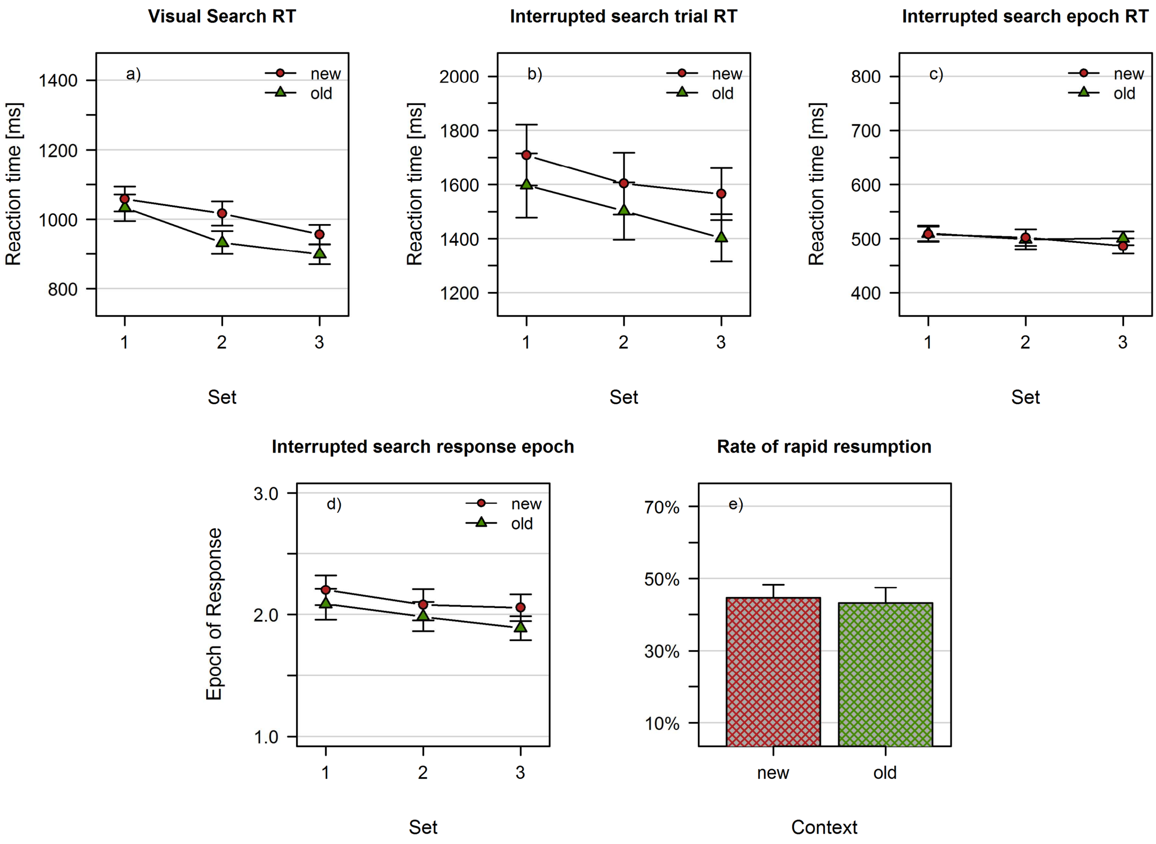

Figure 2-4. Results of Experiment 1a. Panel a: visual search task; panels b-e: interrupted search task. Panel a: mean reaction times. Panel b: trial reaction times (reference is the first display onset). Panel c: epoch reaction times (reference is the last display onset). Panel d: average epoch of response. Panel e: rate of rapid resumption trials. The data are shown separately for previously learned (old) and random baseline (new) displays.

Interrupted Search. In interrupted search, trial reaction times indicate the total duration of a trial (i.e., time from the first onset of a display until the response). As depicted in panel *b* of Fig. 2-4, there was substantial evidence for main effects of context (BF_{10} = 91.226) and set (BF_{10} = 84.503), in addition to substantial evidence for the absence of an interaction (BF_{10} = 0.171). Epoch reaction times indicate how fast participants responded after the last presentation of the display (i.e., time from the onset of the display in the epoch of response until the response; see panel *c* of Fig. 2-4). There was no conclusive evidence for a main effect of set (BF_{10} = 1.287), and substantial evidence for the absence of both an effect of context (BF_{10} = 0.264) and a context x set interaction (BF_{10} = .327). The analysis of the average epoch of response mirrored the pattern obtained from trial reaction times, with substantial evidence for main effects of context (BF_{10} = 99.179) and set (BF_{10} = 101.691), and substantial evidence for the absence of an interaction (BF_{10} = 0.180). Panel *d* of Fig. 2-4 illustrates the increased probability of repeated displays to yield responses in earlier epochs. The overall rapid resumption rate was at 43.88%, which was comparable between repeated and non-repeated displays (old: 43.12%, new: 44.64%; $BF_{10} = 0.241$) (see panel *e* of Fig. 2-4).

4.4 Experiment 1b – Long viewing time

20 Participants (8 female, all right-handed, mean age: 32.55 years) took part in Experiment 1b. Like in Experiment 1a, all participants provided written informed consent, reported normal or corrected-to-normal vision, and received 8 € (~9 USD) or course credit for their participation.

The procedure of the experiment was identical to Experiment 1a, except for the timing in the interrupted search task: the on-phase was extended to 500 ms, so the display was visible for a longer period of time compared to Experiment 1a. The off-phase was kept at 900 ms. Because of the extension of the on-phase, an epoch in Experiment 1b lasted 1400 ms.

4.4.1 Results

Visual Search. The analysis of reaction times in visual search revealed substantial evidence for main effects of context ($BF_{10} = 11.424$) and set ($BF_{10} = 228.638$) and for the absence of an interaction ($BF_{10} = 0.291$) (see panel a of Fig. 3-4).

Interrupted Search. As depicted in panel *b* of Fig. 3-4, trial reaction times in interrupted search yielded main effects of context ($BF_{10} = 1.014*10^6$) and set ($BF_{10} = 4.113$); evidence for the absence of an interaction was inconclusive ($BF_{10} = 0.483$). The analysis of epoch reaction times revealed inconclusive evidence for an effect of set ($BF_{10} = 1.287$), but substantial evidence for the absence of a main effect of context ($BF_{10} = 0.203$) and an interaction ($BF_{10} = 0.239$) (see panel *c* of Fig. 3-4). Analyzing the average epoch of response revealed a main effect of context ($BF_{10} = 72231$), while there was inconclusive evidence regarding a main effect of set ($BF_{10} = 1.675$) and an interaction ($BF_{10} = 0.358$). The overall rapid resumption rate was 28.06%, and there was substantial evidence for this rate being not different between old and new displays (old: 28.45%, new: 27.76%; $BF_{10} = 0.190$)

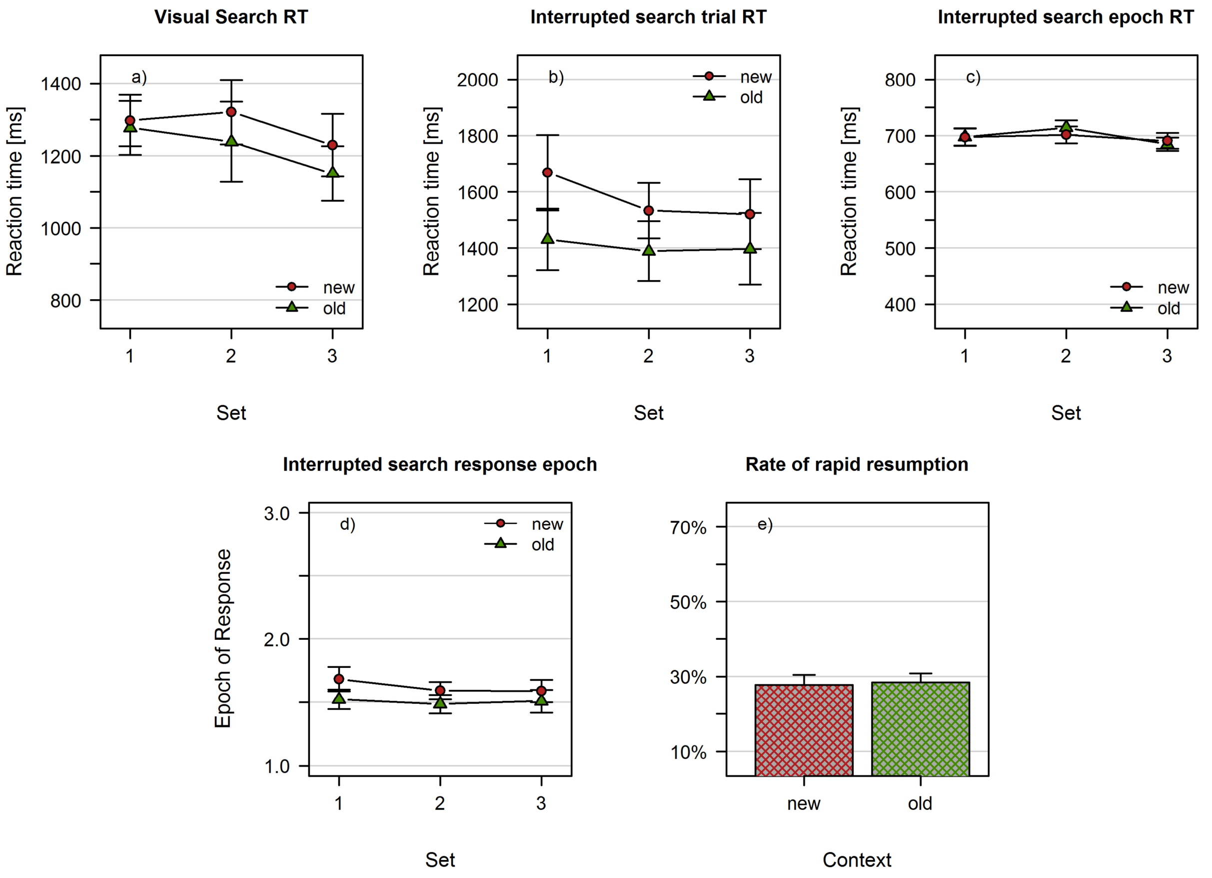

Figure 3-4. Result of Experiment 1b. Panel a: visual search task; panels b-e: interrupted search task Panel a: mean reaction times. Panel b: Trial reaction times (reference is the first display onset). Panel c: epoch reaction times (reference is the last display onset). Panel d: average epoch of response. Panel e: rate of rapid resumption trials. The data are shown separately for previously learned (old) and random baseline (new) displays.

4.4.2 Discussion

Experiments 1a and 1b combined interrupted search with contextual cueing by introducing previously learned spatial arrangements. In visual search (part 1), faster reaction times for repeated compared to non-repeated displays indicated that the stable target-distractor configurations were learned by participants and expedited visual search. This contextual cueing effect transferred to the interrupted search task (part 2), manifesting in overall shorter trial reaction times for repeated displays. However, analyses of epoch reaction times showed that the time after which observers executed a response in the last look at the search display was not affected by contextual memory. Instead, repeated displays elicited responses, on average, in earlier epochs. Furthermore, contextual memory did not affect the rate of rapid resumption. This pattern of results was identical for short and long viewing times (on-phases of 100 and 500 ms, respectively), making it unlikely that the non-finding of effects of contextual cueing on rapid resumption was confounded by viewing times (see Introduction). An unexpected finding was that the overall rate of rapid resumption in Experiment 1b was reduced compared to Experiment 1a (1a: 43.88%, 1b: 28.06%, $BF_{10} = 210$), as was the general level of performance, indicated by overall slower reaction times in the first, visual search part of each experiment (1252 ms in Experiment 1b vs. 983 ms in Experiment 1a: $BF_{10} = 1.018*10^9$). However, since the pattern of results concerning repeated and non-repeated displays was the same in Experiments 1a and 1b, we interpret this as baseline shift due to differences in the collected samples rather than the experimental manipulation.

In summary, the findings suggest that the memory underlying rapid resumption does not benefit from long-term context memory of the same spatial layout, although overall performance was improved by long-term memory. This finding is at odds with the proposal that perceptual hypotheses and contextual memory have interactive, synergistic effects. Had perceptual hypothesis testing benefited from information stored in spatial long-term memory, one would have expected to observe either an increase in the rate of rapid resumption or faster reaction times in the epoch of response. Still, it might be the case that repeated displays had an advantageous effect on the generation of perceptual hypotheses, which however could not be detected on the basis of observers' manual responses. This is because trial reaction times are agnostic as to whether contextual cueing boosted the starting point of the search process – by effectively bringing attention closer to the target location already in the first look of the display, or whether context effects become manifest during the trial, effectively leading to more rapid generation of the correct perceptual hypothesis in subsequent looks. For this reason, in Experiment 2 we recorded fixational eye movements (in addition to manual responses) in order to further explicate the processes during interrupted search and whether they are influenced by contextual long-term memory.

4.5 Experiment 2 – Eye movements

4.5.1 Methods

Participants. 30 participants took part in experiment 2. 4 participants had to be excluded because of technical problems in recording eye movements (3 participants) or an excessively high error rate outside 2 standard deviations of the sample mean (1 participant; error rate: 29%). The remaining sample consisted of 26 participants (10 male, 1 left-handed, mean age: 24.23 years). Participants reported normal vision and did not wear any glasses or contact lenses. They provided written informed consent prior to the experiment and received 12€ (~13.3USD) or course credit for their participation.

Apparatus and stimuli. The experimental setup was identical to Experiments 1a and 1b. Monocular eye movements of the dominant eye were recorded with an EyeLink 1000 system (SR Research, Canada), with a sampling rate of 1000 Hz and a spatial resolution of 0.1°. Head movements were minimized by a chin rest, situated 60 cm from the monitor. The experimenter operating the eye tracker during the experiment was seated outside the experimental booth.

Task and procedure. The task was identical to Experiment 1a, consisting of 15 blocks of visual search and 15 blocks of interrupted search. In interrupted search, displays were shown for an on-phase of 100 ms, with an interleaved off-phase of 1500 ms. Since Experiment 1b showed that an increase in viewing times did not further boost contextual cueing, one might speculate that retrieval from contextual memory might instead benefit from longer waits between display presentations. Therefore, the off-phase was prolonged to 1500 ms in Experiment 2 (Experiments 1a and 1b: 900 ms).

Data analysis. The behavioral data was analyzed analogously to Experiments 1a and 1b. Eye movement data was analyzed by custom software implemented in Matlab using a data-driven and velocity-based detection algorithm described by Nyström and Holmqvist (2010). Statistical analysis of fixations was then carried out with R and Bayesian linear models, as described above. The crucial dependent variable was the distance of a fixation to the target stimulus, analyzed as a function of context (old vs. new), search type (normal search (NS) vs. rapid resumption (RR)), and epoch as temporal factor. Fixation distance to the target was analyzed in two ways: (a) response-locked, including in the analysis the epoch of response (look) and two epochs before the response (look-1 and look-2; see Van Zoest et al., 2007), and

(b) stimulus-locked, including the first three epochs of a trial. An additional analysis was carried out in order to estimate across-look target approaching behavior by subjecting every trial to a linear regression. The fixation number (first, second, third fixation, etc.) was used to predict the distance of the fixation from the target. The resulting intercepts and slopes of every trial were then analyzed with a Bayesian linear model, with fixed effects of context and search type and participant number as random effect.

4.5.2 Results

Manual reaction time data. Behavioral results are depicted in Fig. 4-4. Panel a shows reaction times in visual search, which yielded substantial main effects of context (BF_{10} = 45.306) and set (BF_{10} = 6.399*1010), and inconclusive evidence for an interaction (BF_{10} = 2.483). In interrupted search, analysis of the trial reaction times (panel b of Fig.4-4) revealed substantial main effects of context (BF_{10} = 73.289) and set (BF_{10} = 7.132) and an absence of an interaction (BF_{10} = 0.142). As can be seen in panel c of Fig. 4-4, epoch reaction times produced substantial evidence for the absence of a main effect of context (BF_{10} =0.226) and of a context x set interaction (BF_{10} = 0.114), while evidence against a main effect of set was inconclusive (BF_{10} = 0.436). Regarding the average epoch of response (panel d of Fig.4-4), there was a substantial main effect of context (BF_{10} = 14.643), and substantial evidence for the absence of an interaction (BF_{10} = 0.124), while the evidence against a main effect of set was inconclusive (BF_{10} = 0.940). The overall rate of rapid resumption was at 46.47%. The test for a difference between old and new displays revealed substantial evidence for its absence (old: 47.21%, new: 45.80%; BF_{10} = 0.257), as can be seen in panel e of Fig.4-4.

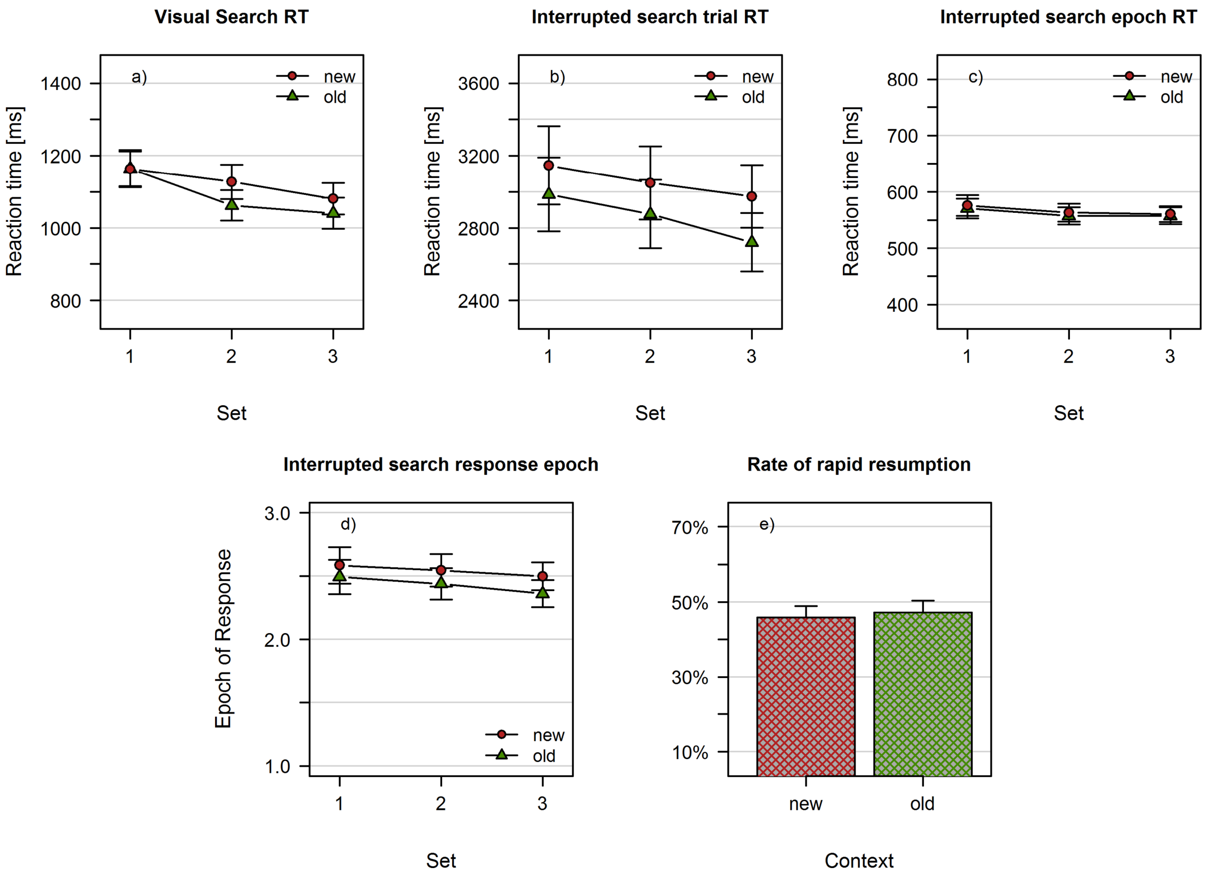

Figure 4-4. Results of Experiment 2. Panel a: visual search task; panels b-e: interrupted search task. Panel a: mean reaction times. Panel b: trial reaction times (reference is the first display onset). Panel c: epoch reaction times (reference is the last display onset). Panel d: average epoch of response. Panel e: rate of rapid resumption trials. The data are shown separately for previously learned (old) and random baseline (new) displays.

Eye movement data. Fixations in the interrupted search task were analyzed by calculating the distance of the first fixation in a given epoch, that is, the first fixation after the re-appearance of the display, to the target stimulus (see Fig 5-4, top row). As expected, fixations were closer to the target on each consecutive look (main effect of look: $BF_{10} = 6.697{*}10^{124}$). Furthermore, it was shown that rapid resumption responses were preceded by fixations closer to the target on three looks prior to the response (main effect of search type: $BF_{10} = 9.316{*}10^{33}$). Regarding spatial context, there was no difference between old and new displays (absence of a main effect of context: $BF_{10} = 0.152$). None of the interactions were substantial, there was anecdotal evidence against an interaction of search type and context ($BF_{10} = 0.372$) and substantial evidence for the absence of all other interactions ($BF\text{'s}_{10} < 0.298$).

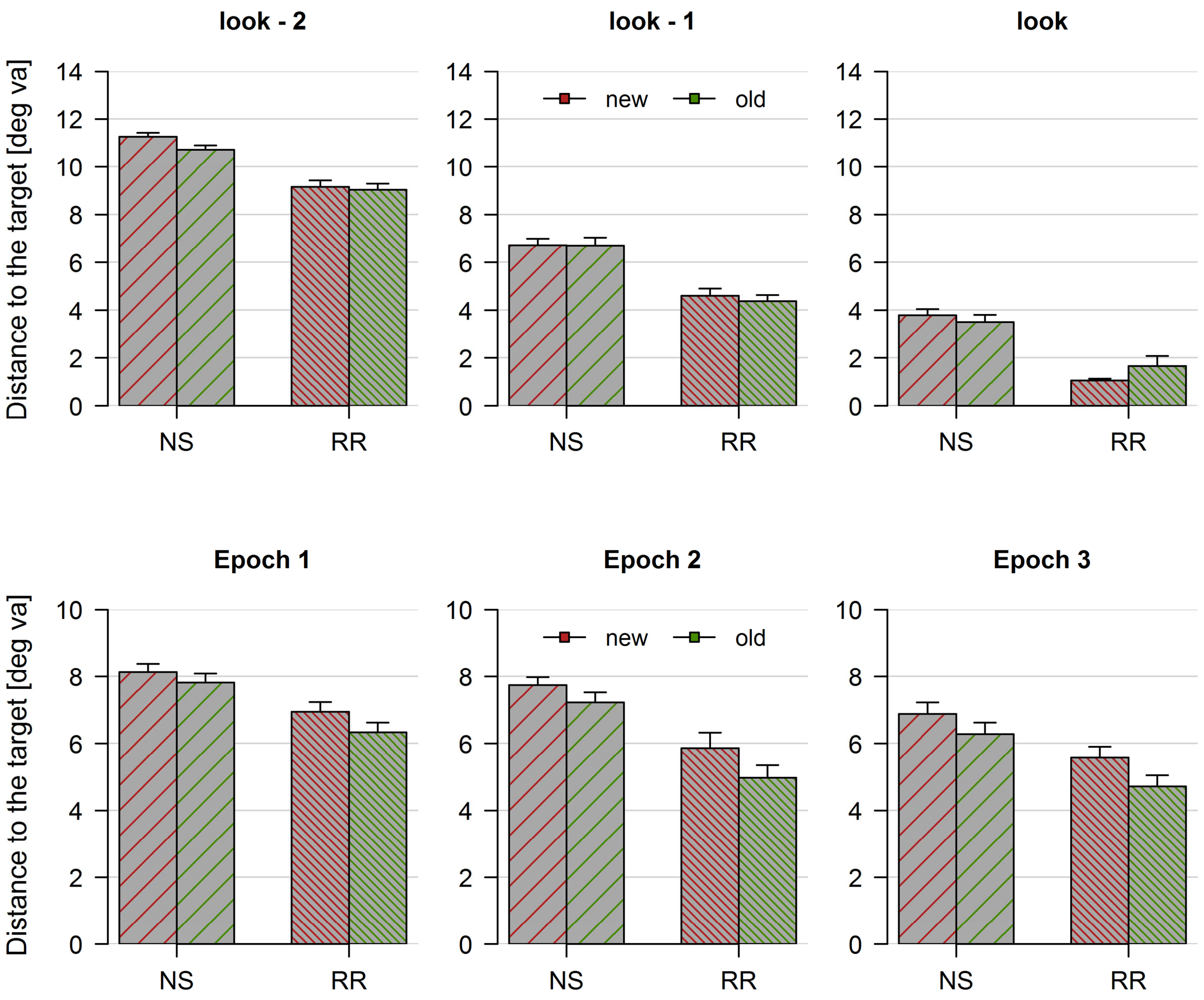

Figure 5-4. Results from Experiment 2. Distance in degrees of visual angle between the current fixation and the target, as a function of context (old vs. new) and search mode (normal search (NS) and rapid resumption (RR)). The upper row illustrates the response-locked analysis: fixations in the epoch of response and the two preceding epochs (look, look-1, and look-2). The bottom row illustrates the stimulus-locked analysis: fixations in the first 3 epochs of a given trial.

The stimulus-locked analysis, taking into account the first three epochs of each trial, revealed a different pattern of results. Again, search type ($BF_{10} = 1.245*10^{33}$) and epoch ($BF_{10} = 3.831*10^{10}$) yielded substantial main effects, indicating that the distance between the current fixation and the target was smaller for rapid resumption responses (main effect of search type) and that fixations came closer to the target in each consecutive epoch (main effect of epoch). However, now, there was substantial evidence for a main effect of context ($BF_{10} = 590.190$), indicating that fixations on trials with repeated displays were overall closer to the target location (see Fig.5-4, bottom row).

To further illustrate this relationship, fixational eye movements were analyzed by means of a linear regression, using fixation number as predictor and distance to the target as criterion (see Fig. 6-4). Subjecting the obtained intercepts to statistical analysis revealed that both search type ($BF_{10} = 1.196*10^7$) and context ($BF_{10} = 5.262$) had substantial effects, yielding reliable decrements in the intercept of the fixation number x distance function. Importantly, there was substantial evidence for the absence of an interaction ($BF_{10} = 0.304$), suggesting that contextual cueing exerted a comparable influence on both normal and rapid resumption trials. The analysis of slopes, by contrast, revealed substantial evidence for the absence of both main effects and the interaction ($BF\text{'s}_{10} < 0.295$).

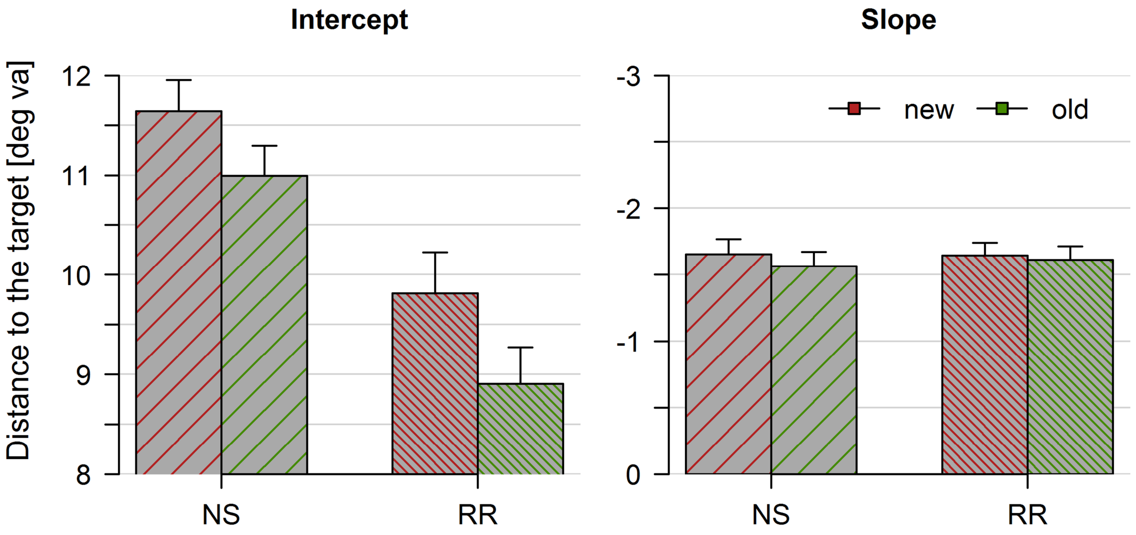

Figure 6-4. Comparison of regression parameters in Experiment 2. Slopes and intercepts were determined based on a linear regression of each trial with fixation number as predictor and distance to the target as criterion.

4.5.3 Discussion

Experiment 2 confirmed the results of Experiments 1a and 1b, demonstrating that contextual cueing and rapid resumption did neither interact in manual response nor oculomotor measures. As shown by Van Zoest et al. (2007), rapid resumption was evident in terms of closer fixations to the target already in the two epochs before the manual response; however, we could not replicate their finding that this was evident especially in the look prior to the response. Importantly, trials with repeated displays were statistically indistinguishable from trials with non-repeated displays when analyzing target-fixation distances relative to observers' manual responses. This indicates that the iterative process of generating and confirming perceptual hypotheses was not affected by long-term memory of the same spatial content. A contextual cueing effect was nevertheless expressed in the intercept of the function relating fixation number to the distance of the current fixation from the target location. This is indicative of an early, head-start effect of contextual memory in interrupted search, rather than an accelerated approach to the target during subsequent looks.

4.6 General Discussion

In three experiments, we investigated possible interactions between contextual long-term memory and short-term perceptual hypotheses, using the novel approach of presenting previously learned search displays in an interrupted search task. We observed both phenomena of contextual cueing and rapid resumption in isolation; however, we did not find evidence for joint effects. The behavioral results of all three experiments demonstrate that contextual memory was established during the visual search task and transferred to the interrupted search task. Yet, the rate of rapid resumption, as well as reaction times in the epoch of response were unaffected by contextual cueing. Instead, context effects became expressed through participants executing their responses in earlier epochs. Furthermore, the analysis of eye movements revealed that repeated and non-repeated displays were indistinguishable from each other in terms of the speed with which the eyes approached the target stimulus. Instead, there was an initial effect on the distance of a given fixation from the target stimulus for learned versus novel target-distractor arrangements: interrupted search began with a shorter distance to the target item in repeated displays, while the search process itself was comparable between repeated and non-repeated displays.

4.6.1 The relationship of contextual memory and perceptual hypothesis-testing

Past studies provided converging evidence for strong parallels between rapid resumption and contextual cueing of visual search in terms of both spatial and featural properties (Jungé et al., 2009; Lleras et al., 2005). There are two possible processing stages where long-term and short-term memory of spatial context could have interacted in interrupted search, namely: the generation and confirmation of a perceptual hypothesis.

Hypothesis Generation. During interrupted search, contextual memory of repeated displays facilitated search performance, expressed by responses occurring in overall earlier epochs. This effect may indicate that contextual memory facilitates the generation of perceptual hypotheses, for instance, by providing some sort of guidance signal that aids in the process of forming a correct perceptual hypothesis. However, the analysis of eye movements revealed that the eyes approached the target stimulus at an identical speed in repeated and non-repeated displays. If the generation of perceptual hypotheses – a process occurring iteratively over the course of the entire trial – was affected by contextual memory, one would have expected such effects to occur also within a trial. However, we observed an advantage for repeated contexts only when observers encountered the display for the first time. In the remainder of the trial, there was no evidence for contextual cueing to facilitate interrupted search. Therefore, we conclude that contextual memory influences only the very first generation of a perceptual hypothesis, providing a head-start for a search process which is then identical regardless of the presence or absence of long-term contextual cues. This is evidence against the idea of a synergistic relationship between contextual memory and perceptual hypotheses –as the effect of contextual cueing manifests only upon the first look, when there is no carry-over of visual information from previous encounters of the search display.

Hypothesis Confirmation. Although the contents of contextual memory and perceptual hypotheses are very similar, we did not observe any modulation of rapid resumption for previously learned displays. In three experiments, Bayes factors provided substantial evidence for the absence of an increase (or decrease) of the rate of rapid resumption as a function of context. Rapid resumption is described as an effect of confirming a perceptual hypothesis generated during the previous presentations of the same display. While it has been suggested that contextual memory may be an instance of a perceptual hypothesis stored in long-term memory (Jungé et al., 2009), in the present study, this long-term memory representation did actually not influence the process of confirming an already established hypothesis – which is also supported by the finding of reaction times in the epoch of response being identical for repeated and non-repeated displays. This may suggest that as soon as a strong search-guiding hypothesis is formed, long-term memory about this perceptual hypothesis is assigned a subordinate status. For instance, and as outlined in the Introduction, it is possible that bottom-up display cues and top-down context cues compete for limited resources in the memory underlying rapid resumption. If this memory was already filled with a perceptual hypothesis based on the current sensory input, less capacity would be left for hypotheses deriving from long-term memory. An alternative, though not mutually exclusive, view would be to assume that observers intentionally give priority to the processing of the current search display, for example, in an attempt to maximize information intake during the very limited viewing times. Future research may clarify why bottom-up, display cues seem to play a major role in the generation and confirmation of perceptual hypotheses.

4.6.2 Efficient vs. inefficient search

Our findings in Experiment 2 suggest that contextual memory influences the starting point of the interrupted search process and does not impact on the search process itself. Studies investigating eye movements in standard visual search usually report a reduction in the number of fixations owing to contextual cueing (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001), which goes along with a reduction in reaction times. Furthermore, Tseng and Li (2004) identified two stages of eye movement behavior in the contextual cueing of visual search: an initial phase of ineffective search and a phase of effective search, the latter characterized by the eyes systematically (monotonically) coming closer to the target item. They found that contextual memory of search displays led to a reduction of saccades only in inefficient search. Although an interrupted search task requires a different kind of search because the display is not constantly visible, the present pattern of results is strikingly similar to the 'ineffective-effective' distinction in normal visual search. We observed that the average distance between a fixation and the target two looks prior to observers' response were identical for repeated and non-repeated displays. On the other hand, contextual memory affected the intercept of the distance x fixation number function, with this parameter potentially reflecting the starting point for efficient search. Based on these findings, contextual cueing could be considered as mechanism that reduces the number of display items that would have to be inspected by attention in order to detect the target item. Therefore, our results support the findings of Tseng and Li (2004) in that long-term contextual memory has an early effect on the search trial, leaving the monotonic approach towards the target location unaffected. Applying this logic to the theory of reentrant processing (Di Lollo et al., 2000), context-based guidance of interrupted search could be described in the following way: The initial – inefficient – search is characterized by influences of long-term memory, setting up the starting point for the actual search process. Subsequently, this process continues by means of generating and confirming perceptual hypotheses, operating entirely on short-term visual memory of previous display exposures.

4.6.3 Conclusion

The present investigation revealed that contextual cueing and perceptual hypotheses are rather independent memory phenomena, despite their high similarity in terms of both spatial and featural properties. Contextual cueing effects were observed in interrupted search; however, the effect became manifest only in a modulation of the starting point of the search process, while leaving the process of iteratively searching an interrupted display unaffected. The finding of an early cueing effect in interrupted search resembles findings from standard visual search showing a distinction between inefficient and efficient search within a single trial, with the effects of repeated contexts particularly contributing to a reduction of the inefficient phase. More specifically, conceiving of visual search as a two-stage process with first a parallel visual analysis followed by closer scrutiny of individual display items (Buetti, Cronin, Madison, Wang, & Lleras, 2016), contextual cueing would help to reduce the number of display items to be processed in the first, parallel stage.

4.7 Author Contributions

Bernhard Schlagbauer and Thomas Geyer conceived the research question and experiment 1a and 1b; Bernhard Schlagbauer and Maurice Mink conceived experiment 2; Bernhard Schlagbauer and Maurice Mink programmed the experimental routines; Maurice Mink and Bernhard Schlagbauer set up the eye-tracking hardware; Bernhard Schlagbauer and Maurice Mink collected and analyzed the data; Bernhard Schlagbauer conducted Bayesian statistics; Bernhard Schlagbauer, Hermann J. Müller and Thomas Geyer co-wrote the manuscript.

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5. Rewarding distractor context versus rewarding target location: A commentary on Tseng and Lleras (2013)

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5.1 Abstract

The influence of reward on cognitive processes like visual perception, spatial attention, and perceptual learning has become an increasingly important field of study in the recent years. For example, Tseng and Lleras (2013) investigated whether reward has an effect on implicit learning of target-distractor arrangements in in visual search, i.e., contextual cueing (Chun & Jiang, 1998). They found that reward expedited the development of the cueing effect, i.e. the reaction times (RT) difference between repeated and non-repeated displays. However, their analysis did not account for potential effects of reward on the learning of individual target locations, i.e., probability cueing (Jiang, Swallow, & Rosenbaum, 2013). The current study was a replication of Tseng & Lleras (2013), taking into account reward effects on configural and locational learning as well. We found that reward lead to performance gains even in baseline ("new") displays, containing only repeated target, but not distractor, locations. Further, contextual cueing was smaller, and not larger, in high- relative to low-reward trials. We conclude that reward modulates probability, and not contextual, cueing and that this mechanism can account for the findings of Tseng and Lleras (2013).

5.2 Introduction

Humans are severely limited in their ability to process the entire perceptual array (Simons & Rensink, 2005). The mechanisms that are important for overcoming this limitation are reflexively, i.e., bottom-up, and intentionally, i.e., top-down, guided visual attention (Corbetta & Shulman, 2002), in addition to guidance based on motivational heuristics (Della Libera & Chelazzi, 2006). Thus, the central question is which particular aspects of a scene are worth looking at, and one of the most prominent motivational factors determining worthiness is reward. A number of recent studies have shown that currently rewarded items guide attention (Hickey, Chelazzi, & Theeuwes, 2010a, 2010b, 2011), or that items that were rewarded in the past can continue to have attention-attracting power even if they are no longer rewarded on current trials (Anderson, Laurent, & Yantis, 2011). These findings suggest that reward improves the deployment of visual selective attention by learning to associate stimulus features with high reward value.

Besides consistent reward, there are also other regularities in the visual environment that can be learned by an observer to facilitate search behavior. Especially spatial invariances in a visual scene are known to serve as cues to action-relevant objects. Two types of regularities are of particular interest in the present study: the spatial layout of non-target, or context, elements, i.e., contextual cueing (Chun & Jiang, 1998), and the probability for positional repetitions of target elements, i.e., probability cueing (Geng & Behrmann, 2005; Jiang, Swallow, & Rosenbaum, 2013). Probability cueing refers to the capability of the visual system to perform statistical inferences about the likelihood of a given target position. If the target in visual search (Wolfe, 1998a) is more likely to appear at a given location, this position is learned and prioritized over other locations. As a result, reaction times are faster on high relative to low target position probability trials (Jiang, Swallow, & Rosenbaum, 2013).

Contextual cueing refers to the observation of expedited RTs to repeated, relative to non-repeated, i.e. novel, target-distractor arrangements in visual search. Contextual cueing emerges after approximately five repetitions of a given repeated display (Chaumon et al., 2009; Chun & Jiang, 1998) and remains observable even after several days (Chun & Jiang, 2003). Although contextual cueing can lead to strong RT gains, participants are nevertheless unable to discern repeated from non-repeated displays (Chun & Jiang, 1998). The discrepancy in indirect (RT) and direct (explicit recognition) measures has led to the proposal of implicit contextual cueing (but see, e.g., Schlagbauer, Müller, Zehetleitner, & Geyer, 2012, or Smyth & Shanks, 2008, for discrepant views). Moreover, there is evidence that the cueing effect can exert its influences at various visual processing stages, including pre-attentive and post-selective stages, as well (pro pre-selective: Geyer, Zehetleitner, & Müller, 2010; Johnson, Woodman, Braun, & Luck, 2007; pro post-selective: Kunar, Flusberg, Horowitz, & Wolfe, 2007).

Although contextual cueing is an implicit, i.e., cognitively impenetrable effect, Tseng and Lleras (2013) recently asked whether motivational factors like the delivery of monetary reward would nevertheless influence the cueing effect. They hypothesized that rewarding the distractors' arrangement in a contextual cueing task may enhance configuration-specific learning. The authors used the "standard" contextual cueing paradigm, introduced by Chun and Jiang (1998), which requires observers to search for a T-shaped target letter among L-shaped distractor letters and subsequently report the target's orientation (left- vs. right-tilted). Importantly, half of the trials contained repeated target-distractor arrangements. Additionally, the authors introduced different levels of reward, namely, gaining points (reward condition), losing points (penalty condition), or no reward (no-outcome condition). Of relevance to the present study is the authors' finding of reward-based contextual cueing: for rewarded relative to non-rewarded target-distractor arrangements, the cueing effect became manifest in earlier experimental epochs (but reward did not increase the overall size of the cueing effect).

There is, however, one shortcoming in Tseng and Lleras' (2013) design. As elaborated earlier, there are two different types of spatial learning effects in repeated visual search: probability cueing and contextual cueing. One important methodological aspect of contextual cueing studies is to control for target location repetition effects and therefore to isolate effects of repeated distractor from repeated target positions (cf. Chun & Jiang, 1998). Since the repetition of a whole search display in the repeated-display condition includes both identically positioned target and distractor items, observers could use either of these cues to facilitate their search. Consequently, in standard contextual cueing experiments, target positions are kept constant across non-repeated displays as well, so the only crucial difference between search conditions is the spatial layout.

Tseng and Lleras (2013) compared repeated (old) displays associated with three different reward outcomes to non-repeated (new) displays, but with the latter averaged across the three reward conditions. Specifically, a given old display was either positively rewarded ('rewarding context': 6 out of 12 old displays), negatively rewarded ('penalizing context': 3 old displays), or not associated with any reward ('no outcome': 3 old displays) – importantly, with the reward association being kept constant across the entire experiment. A similar reward scheme was applied in the ‘new’, baseline condition (which consisted of 12 repeated target, amongst non-repeated distractor, locations); but for their data analysis, Tseng and Lleras (2013) merged all RTs on positive-, negative-, and neutral-reward trials into a single new (‘mean’) condition, because “… reward occurred after the response and new displays were never repeated” (p. 290). However, collapsing RTs into a single new condition is potentially problematic as this would (1) hide any effects of the reward manipulation on target probability learning in the new (‘mean’) condition and, thus, (2) confound the effects of reward on configural versus target probability learning in the old condition. Arguably, in order to isolate the effect of reward on the learning of distractor contexts (unconfounded by target probability learning), a full factorial design is necessary in which reward is also manipulated in the new condition and RT performance compared for corresponding levels of reward between the old and new conditions. Thus, given that Tseng and Lleras (2013) did not examine their data in this manner, it is possible that their reward manipulation had an effect on target location learning – in addition to, or instead of, configural learning.

To examine for an influence of reward-based target location learning in Tseng and Lleras' (2013) paradigm, we implemented a full factorial contextual cueing experiment manipulating context (old, new) and reward (high, low). In each one half of the trials, target locations were associated with high and, respectively, low reward. Orthogonal to this, distractor configurations were either repeated (old displays) or newly generated (new displays), independently of the level of reward associated with particular target locations. Thus, there were two levels of reward (targets appearing at locations associated with high vs. low reward) for both old and new displays. This allowed us to assess (1) whether reward influences target position learning (by comparing RTs between high- and low-reward trials of both the old and new conditions) and (2) whether reward influences configural learning (by comparing RTs between old and new displays of both high- and low-reward trials).

In summary, an effect of reward in the new condition would be attributable only to reward-based improvements of location-specific learning. However, if reward enhances configuration-specific learning in repeated visual search, as proposed by Tseng and Lleras (2013), then one would expect contextual cueing to be more marked, i.e., arise earlier, for high- relative to low-reward trials. Of course, the latter prediction does not exclude the possibility of reward effects on both configuration- and location-specific learning in repeated visual search.

5.3 Methods

5.3.1 Participants

As in Experiment 1 of Tseng and Lleras (2013), a total of 25 observers took part in the experiment (9 male; mean age: 25.4 years). All participants reported normal or corrected-to-normal vision and were naïve as to the purpose of the study. They provided written informed consent prior to the experiment and received payment depending on their performance in the experiment with a minimum of 8 € (~10.7 USD) for a one-hour experimental session.

5.3.2 Apparatus and stimuli

The experiment was controlled by a Dell PC running Matlab with the Psychtoolbox extension for stimulus presentation (Brainard, 1997; Pelli, 1997). Participants were seated in front of a 24” CRT monitor (Mitsubishi Diamond Pro; refreshed at a rate of 120 Hz), at a viewing distance of approximately 80 cm. Search displays consisted of 12 dark grey items (1.0 cd/m^2; 1 target and 11 distractors) presented against a light grey background (25.4cd/m^2). All stimuli extended 0.35° of visual angle in width and height. The items were arranged along 4 (invisible) concentric circles around the display center (radii: 1.74°, 3.48°, 5.22°, 6.96°), with the target always being positioned on the third circle from the display center. The “T” target was oriented randomly either 90° or 270° from the vertical midline (“L” distractors: 0°, 90°, 180° or 270°).

5.3.3 Trial procedure

Each trial started with the presentation of a fixation cross (0.35 x 0.35°, 1.0 cd/m^2) at the center of the screen for 500 milliseconds (ms) followed by a blank interval of 200 ms; thereafter, the search displays appeared. The participants’ task was to respond as fast and accurately as possible to the orientation of the target. When the target was oriented to the left (right), they pressed the left (right) arrow key of the computer keyboard. Displays were visible until a response was made or maximally for 2000 ms. Following observers’ search task response and another blank interval of 200 ms, error feedback and feedback indicating monetary reward was given. This information stayed on the screen until participants pressed the down arrow key (but at least for 750 ms), which triggered the start of the next trial (the blank inter-trial interval was 500 ms). Participants performed 20 blocks of 24 trials each, yielding a total of 480 trials.

5.3.4 Design

The 'old' condition contained 12 randomly arranged target-distractor configurations, generated at the beginning of the experiment. These were repeatedly presented on randomly selected trials throughout the search task, with the restriction that each repeated display was shown only once per block. Displays in the 'new' condition were generated online on a given trial. In half of the trials, an old arrangement was presented, and a new arrangement in the other half. To equate target location repetition effects between the two types of displays, the target appeared equally often at each of 24 possible locations throughout the experiment: 12 locations were used for repeated, the other 12 for non-repeated displays. Note that for both old and new displays, the target was equally likely to appear in any of the four display quadrants. Further, item density was kept constant across the four display quadrants (each quadrant contained three items).

Half of the displays were rewarded with 5 Cent (high-reward trials), the other half with 1 Cent (low-reward trials). After their search task response, participants received feedback about their current reward (5 Cent, 1 Cent, or 0 Cent in case of an error or timeout) and how much money they had gathered thus far. Participants were not informed – neither in the beginning, nor on a trial-by-trial basis – about the details of the experimental reward manipulation. Importantly, reward was assigned consistently: the very same 12 target positions were associated with high vs. low reward, 6 of them being embedded in a repeated distractor arrangement (old displays), the other 6 appearing in random distractor arrangements (new displays).

5.4 Results

Data analysis was performed using R (R Core Team, 2014). In order to obtain reasonable estimates of the contextual cueing effect, the data of 5 consecutive blocks were pooled into one 'epoch' (see Chun & Jiang, 1998), resulting in 4 experimental epochs. Incorrect trials (including erroneous responses and time-outs) were discarded from analysis (mean error rate: 5.98%). A 2 (context) x 2 (reward) x 4 (epoch) repeated-measures ANOVA (only) revealed the effect of epoch significant [$F(3,72) = 9.3$, $p < .001$, $\eta_p^2 = .280$; less response errors occurred in later epochs]. Furthermore, ‘extreme’ RTs outside ±2.5 standard deviations of the individual mean RTs were also excluded from analysis (overall 1.90% of trials).

5.4.1 Replication of Tseng & Lleras (2013)

First, we pooled reaction times across both reward conditions in the new displays and compared it with old displays, separately for the high- and low-reward conditions (Tseng & Lleras, 2013). A two-way repeated-measures ANOVA with the factors display type (old displays – high reward, old displays – low reward, new displays) and epoch (1-4) revealed main effects of both display type [F(2,48) = 6.1, p = .004, η_p^2 = .203] and epoch [F(3,72) = 41.7, p < .001, η_p^2 = .634]. Although the interaction was non-significant [F(6,144) = 1.5, p = .183], direct tests were conducted for each individual epoch (p-values were Holm-corrected for multiple t-tests) in order to track the time course of contextual cueing. As expected, high-reward displays yielded a contextual cueing effect already in the first epoch [44, 72, 90 and 104 ms in epochs 1-4; all p’s < .007]. For low-reward displays, there was at least some tendency for the cueing effect to develop later in time, though the effect faiued to reach significance in any of the four epochs [Epoch 1: 8 ms, t(24) = 0.3, p = .366; Epoch 2: 29 ms, t(24) = 1.6, p = .189; Epoch 3: 41 ms, t(24) = 2.0, p = .120, Epoch 4: 27 ms, t(24) = 1.1, p = .263].

5.4.2 Full design with rewarded new displays

Second, to analyze reward effects associated with repeated target positions (in addition to those resulting from repeated distractor contexts), RTs were analyzed by means of a three-way repeated measures ANOVA with the factors context (old vs. new), reward (high vs. low), and epoch (1-4). All main effects were significant: context [F(1,24) = 72.3, p < .001, η_p^2 = .751], reward [F(1,24) = 5.5, p = .028, η_p^2 = .185], and epoch [F(3,72) = 40.1, p < .001, η_p^2 = .626]. Furthermore, the interactions between context and epoch [F(3,72) = 3.1, p = .032, η_p^2 = .114] and, of most interest here, between context and reward [F(1,24) = 9.3, p = .005, η_p^2 = .280] were significant. Further analyses were carried out to explore the latter interaction. First, a comparison of mean RTs revealed that observers responded fastest to old displays with high reward (887 ms), intermediate to new displays with high reward (919 ms), and slowest to new displays with low reward [1013 ms; all p’s <.01 ; p-values Holm-corrected; see Figure 1-5, left panel; note that the difference in RTs between old displays with high reward vs. old displays with low reward and the difference between new displays with high reward vs. old displays with low reward only approached significance: both p’s>.20; see below).

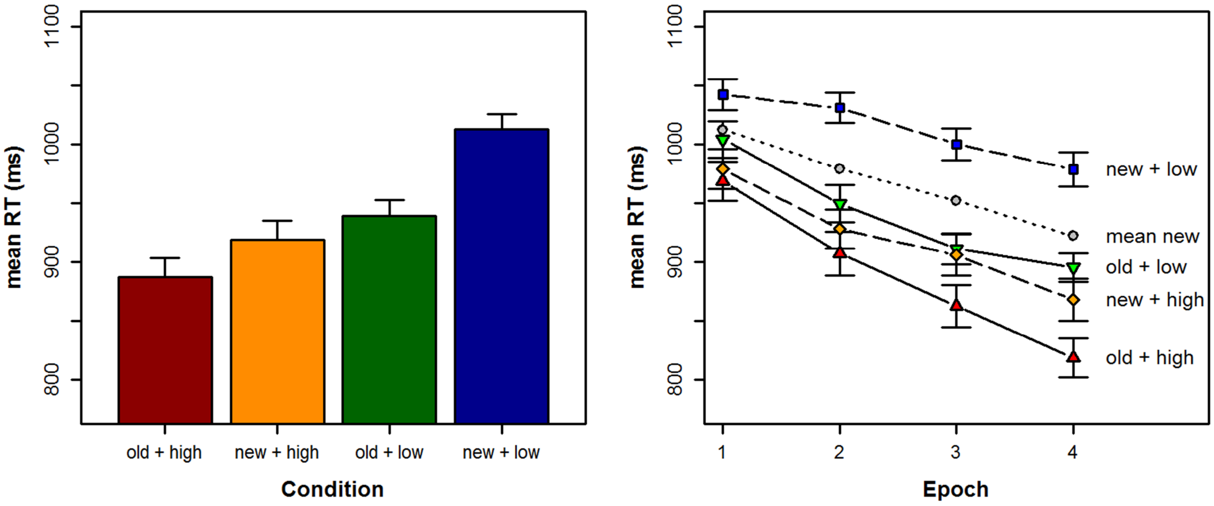

Figure 1-5. Reaction time performance. *Left panel*: mean reaction times (RTs.) as a function of reward (high, low) and context (old, new). The data are collapsed across all epochs. *Right panel*: mean RTs as a function of reward (high, low) and context (old, new), separately for epochs 1-4. Grey dots represent RTs to new displays averaged across the (high, low) reward conditions ('mean new'), following Tseng and Lleras (2013).

Second, a comparison of contextual cueing, i.e., RT new minus RT old display between high- and low reward trials (cf. Figure 1-5, right panel), revealed that for high-reward trials, the cueing effect was reliable from the third epoch onwards [Epoch 1: 10 ms, t(24) = 0.6, p = .264; Epoch 2: 21 ms, t(24) = 1.6, p = .119; Epoch 3: 43 ms, t(24) = 2.6, p = .022; Epoch 4: 50 ms, t(24) = 2.8, p = .020]. For low-reward trials, by contrast, the effect gained significance already in the first epoch [38, 82, 89 and 83ms in epochs 1-4, all p's < .020]. Third, perhaps the most apt analysis that is diagnostic with regard to the context x reward interaction is to compare the contextual cueing effect between high- and low-reward trials (left panel of Figure 2-5) as well as the reward effect, RT high- minus RT low-reward trials, between old and new displays (right panel of Figure 2-5). Figure 2-5 shows that while contextual cueing was overall larger in low- compared to high-reward trials, reward effects were more pronounced overall for new than for old displays. In essence, reward effects for new displays were significant throughout the entire experiment [63, 103, 94, and 111 ms in epochs 1-4, p's < .040], while the reward manipulation did not show an effect for old displays [36, 43, 49 and 77 ms in epochs 1-4, p's > .100].

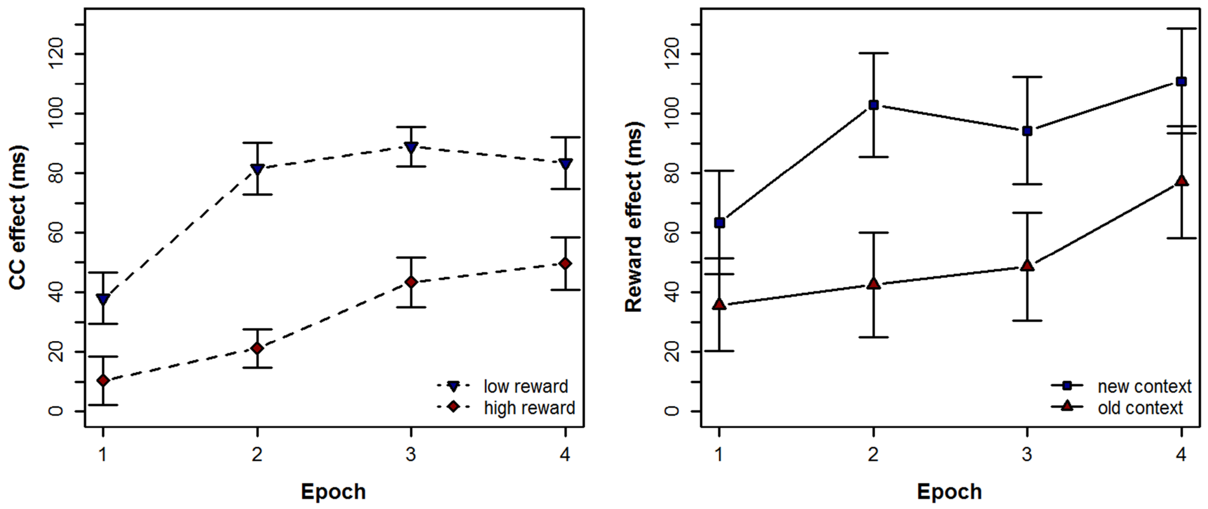

Figure 2-5. Interaction of context and reward. Left panel: Context effects calculated by subtracting individual mean RTs to old displays from RTs new displays, separately for high- and low-reward trials. Right panel: Reward effects calculated by subtracting individual mean RTs to high-reward displays from low-reward displays, separately for old and new target-distractor contexts.

5.5 Discussion

In accordance with previous studies, the current experiment replicated contextual cueing, as indicated by faster RTs to old relative to new displays. However, the most interesting results of the current study were that reward effects (1) were measureable also in new displays and (2) were actually smaller, rather than larger, in old displays. These results are difficult to explained by accounts assuming that reward enhances the learning of target-distractor contingencies, i.e., contextual cueing (Tseng & Lleras, 2013). Instead, the results support the view that reward facilitates target location learning, i.e., probability cueing (Jiang et al., 2013). This is not to say that there is no role of reward in contextual cueing. Rather, there are two possibilities for explaining the significant (context x reward) interaction.

First, guidance by learned target-distractor arrangements and individual target positions may be additive and reach a plateau after which RTs cannot be improved any further. Assuming that reward and contextual cueing occur at the very same time (a further analysis of RTs in the first epoch showed this to be the case: both effects emerged after just two cycles of presentation, i.e., in block 2 of the experiment), this would mean that once rewarded positions have been learned, contextual cueing cannot further improve visual search performance (or vice versa). The ultimate consequence is that context effects are smaller for high-reward trials.

Second, the effects of reward and contextual cueing could also be interpreted in the context of formal decision models, such as the Ratcliff-Diffusion-Model (RDM; Ratcliff, 1978). The model assumes that for binary decisions (e.g., left- vs. right-oriented target), evidence is accumulated over time until a decision boundary is reached, which is followed by response execution. The drift rate of such an accumulation process may be influenced by some experimental manipulation –in the present experiment: reward or repeated target-distractor context – and an increase of this parameter yields shorter RTs. Zehetleitner and Müller (2010) have shown that differences in response times due to a modulation of the drift rate are dependent on the overall duration of the decision process (modulations of the drift rate and associated performance gains are the larger the longer the overall decision process is). Applied to the current results, it is possible that contextual cueing has a smaller effect on high-reward trials, because overall RTs are shorter on such trials compared to low-reward trials.

However, and in conclusion, the finding of contextual cueing being smaller in high-reward trials may also be taken as evidence for a less direct relationship between contextual cueing and reward. That is, given the available evidence (Tseng & Lleras, 2013) and after controlling for target repetition effects (current investigation), it is far more plausible to say that there is no relationship between configural learning and reward. Instead, it is more likely that monetary reward influences the learning of individual target locations (Jiang et al., 2013).

5.6 Author Contributions

Bernhard Schlagbauer and Michael Zehetleitner conceived the experiment; Bernhard Schlagbauer collected and analyzed the data. Bernhard Schlagbauer, Thomas Geyer, Hermann J. Müller and Michael Zehetleitner co-wrote the manuscript.

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6. General Discussion

The present Thesis investigated four aspects of spatial contextual memory: metacognitive access to distractor configurations vs. the target stimulus, explicit knowledge about repeated displays, in-/dependence of short-term and long-term perceptual hypotheses, and reward effects in probability vs. contextual cueing. In the following, the findings of the four studies are discussed and an outlook is given with respect to future questions.

6.1 Metacognitive access to learned configurations

Synopsis of results. While classical contextual cueing studies mainly focused on the question whether incidentally learned search displays can be actively remembered / recognized, the current study investigated another aspect in the realm of implicit or explicit processing. In a masked localization task, observers were either asked to rate the visual clarity of the configuration or the target stimulus. It was observed, that metacognitive sensitivity of configuration ratings was increased in repeated displays, while metacognitive sensitivity of the target ratings was not different from non-repeated displays. Since contextual cueing is a behavioral effect, any phenomena associated with it can either be attributed to impacts from contextual memory or be interpreted as a by-product of the changes in behavior. This means, that changes in metacognition as a function of contextual cueing could either reflect direct memory effects or indirect effects, via improved search behavior. In the current case the former is more likely than the latter for a number of reasons: First, the task was to locate the target stimulus and no emphasize was put on processing the distractor configuration. If contextual cueing affected metacognitive access to response-related processes, these should be more connected to the experience of the stimulus eliciting that response (the target) than the stimuli irrelevant for solving the task (the distractors). Yet, no contextual cueing effect on metacognitive sensitivity of target ratings was found. Second, if expedited localization performance was the prime reason for increased metacognition, then this effect would not have been restricted to the configuration condition. Behavioral effects were comparable in both conditions, yet metacognitive effects were only observable in the configuration condition. This was further demonstrated by a control analysis, with accuracy in the localization task as co-variable, which yielded the same pattern. Third, the observed pattern beard close resemblance to the content stored in contextual memory: the distractor configuration is necessarily part of the memory representation (Jiang & Wagner, 2004), but importantly, the identity of the target is not. It was observed that metacognitive access to stimuli that match the content of contextual memory was affected, while metacognitive access to a stimulus not part of the memory representation was not affected. Therefore, only if observers are asked to rate parts of the visual scene that are also part of contextual memory, then metacognition is affected by contextual cueing. In sum, the findings demonstrate that a) contextual memory has a direct influence on metacognitive access to the display configuration; and b), from a methodological point of view, that it is imperative that the content of subjective ratings is chosen carefully with respect to the aspect under investigation (Rausch & Zehetleitner, 2016; Zehetleitner & Rausch, 2013). Another study which applied subjective measures in contextual cueing, showed that observers rate repeated displays higher on a scale of visual preference (Hirokazu Ogawa & Watanabe, 2011). In the instruction for participants, visual preference was described with the terms unity, sparseness, global form and attractiveness, which are all referring in one way or the other to the configuration of the display. The authors observed an increased subjective rating of visual preference for repeated displays, however only if those repeated displays were also predictive for the target location. This is further evidence for a clear relationship between subjective evaluation of the configuration and contextual memory. While the scale used by Ogawa an Watanabe (2011) is quite different from the perceptual clarity ratings in the present investigation, they both refer to the perception of the display configuration. Although visual preference additionally involved a process of evaluation of the percept, the effects of contextual memory on the perception of configurations was still observable.

In conclusion, the findings from subjective measures do not necessarily resolve the question whether contextual cueing is an explicit effect in a sense that observers are able to consciously recollect repeated configurations from contextual memory. But they demonstrate that there is subjective insight into the effects of contextual memory and in this regard, contextual cueing is an explicit effect.

Future directions. The assumed relationship between contextual memory and metacognitive processing relies heavily on the content of contextual memory. The current investigation used a spatial contextual cueing paradigm, yet context-guided visual search can also occur in the absence of repeated spatial layouts. If other features of the distractor context are repeated than their location, contextual memory should reflect this and therefore also affect metacognitive processes of non-spatial visual properties of the search displays. This can be put to the test by using other forms of contextual cueing, like object cueing (Chun & Jiang, 1999; van Asselen, Sampaio, Pina, & Castelo-Branco, 2011) or dynamic event cueing (Chun, 2000;

Chun & Jiang, 1999). In the case of object cueing, the perceptual clarity of configurations should not be affected by contextual cueing, as it relies solely on associations between the identity of distractors and the target. Therefore, ratings about the clarity of individual distractors should be affected. Analogously, in dynamic event cueing, the perception of the motion of distractors should be modulated as a function of contextual cueing.

Related to this, it is also an open question how task modalities influence the effects of contextual memory on metacognition. According to good practices in examining implicit memory, it is important to measure access to the memory representation under conditions which are comparable to the context they were acquired in (Newell & Shanks, 2014). In the case of contextual cueing, explicit access to contextual memory should be measured in the context of a visual search task. However, if task relevance is critical in the assessment of explicitness, different task requirements should also yield differences in contextual memory. The current task used a masked localization task, which required observers to detect the target stimulus, but not necessarily process its visual features in greater detail. If a discrimination task was used, maybe this would also affect the contextual cueing effects on metacognitive ratings of the target stimulus, simply because the visual clarity of the target would be more important in the current task. There is extensive work on the question whether contextual cueing affects early attentional or late response-related processes and there is evidence for both (Schankin & Schubö, 2010). Consequently, depending on the task, contextual cueing might exert its effects to different degrees at different stages of the search process. In a localization task, attentional processes might be affected by contextual cueing, in a discrimination task, processes involved in identifying the target and eliciting the response might be affected. On a second level, metacognitive access in contextual cueing might reflect the locus of contextual cueing in the cognitive architecture. Depending on whether contextual cueing in the given task is more of an early or a late effect, metacognitive access might be increased for early or late processes, respectively. Future research might determine whether different task requirements do in fact modulate the effects of contextual cueing in the cognitive architecture – stages of visual search – and whether metacognitive access is also modulated by this.

6.2 Blocking of implicit memory

Synopsis of results. The implicit-explicit debate revolves around the question whether contextual memory can be accessed in a recognition or generation task. Evidence for explicit cueing is given when the hit rates are reliable larger than the false alarm rates, that is: when observers perform above chance level. Yet, context learning is in any case incidental and not intended, as memory is build up through repeated exposure to identical target-distractor arrangements. In the current study, explicit memory is actively induced to investigate how this affects contextual cueing and whether it interferes with classical, 'implicit' contextual cueing. It was shown that if both kinds of display representations are present – explicitly and implicitly learned displays – only explicit displays elicit contextual cueing, while implicit displays lead to negative cueing effects and their retrieval is potentially suppressed by explicit memory about repeated displays. However, recognition performance was above chance in both conditions with hit rates reliably larger for explicit displays. The results from the recognition test were not surprising, since explicit displays were learned with the goal to be explicitly remembered. The fact that implicit displays also passed the threshold of chance performance is regularly reported if the recognition test has sufficient power (Smyth & Shanks, 2008; Vadillo et al., 2015). However, the finding that implicit displays exhibited negative contextual cueing needs further elaboration. Negative cueing effects are rarely reported and if so, they are treated as outliers on an individual level (e.g. Schlagbauer et al., 2012). Lleras and von Mühlenen (2004) reported that the number of participants exhibiting contextual cueing varies as a function of search strategies. If an active search strategy of deliberate attentional deployment was used, the number of participants with a positive cueing effect dropped, while more of them showed no or negative cueing effects. The opposite is true if a passive search strategy is applied, where observers let the target 'pop into their mind', perceiving the displays more as a whole. The current results offer a complementary interpretation of inter-individual differences in the contextual cueing effects. Assuming that observers have in principle two possible learning mechanisms available, via explicit remembering or implicit / incidental encoding, different observers might apply them to a different extent. Negative cueing effects would stem from a mixture of explicitly and implicitly learned displays, where a few explicitly learned displays lead to cueing but block access to implicitly learned displays and yield, on average, a negative cueing effect. Applying then different search strategies might modulate the way displays are learned: passive search could foster implicit learning, while active search is more prone to lead to the explicit encoding of single displays.

With respect to the question whether there is one or two memory systems underlying contextual cueing, the current results favor a single memory system. Assuming an implicit and an explicit memory system would imply that the learning history of explicit and implicit displays in visual search is equal. Both kinds of displays are repeated during visual search and should therefore be encoded in implicit memory. However, if only a single memory system underlies both explicit and implicit display representations, the memory trace of explicit displays should be stronger, since more time was spent in learning these displays. Furthermore, there is evidently competition between the two representations, leading to the negative cueing effects. Initially, the single memory system account predicted stronger cueing for explicit displays, but nevertheless positive cueing effects also for implicit displays. Therefore, the view of contextual memory has to be extended by the notion, that depending on the learning history, some representations are able to block access to other representations. Importantly, the learning of implicit displays was not hindered by explicit displays, since recognition of implicit displays was above chance, indicating contextual memory. Additionally, if implicit displays had not been learned, cueing effects should have been around zero, and not consistently negative.

Future directions. An argument could still be made that the observed effects in the current study stem from two distinct but interacting memory systems. Input from explicit memory could suppress input from implicit memory in a race-like competition model of memory access. Functional imaging of the associated brain regions could answer the question whether different structures are active during blocking or access of contextual memory. It was found that contextual cueing is associated with activity in the hippocampus (e.g. Chun & Phelps, 1999) and surrounding medial temporal lobe structures (e.g. Preston & Gabrieli, 2008). Furthermore it was shown that BOLD-activity to repeated displays varied as a function of whether observers were able to explicitly recognize a given display (Geyer et al., 2012). Therefore, it would be promising to examine the current question of associative blocking in explicit contextual cueing with neuro-imaging methods, as they could answer whether the same or different structures are involved in explicit and implicit contextual cueing.

Another unresolved issue is why blocking occurred only in visual search and not in recognition. A possible reason could be the different task requirements of search and recognition: in visual search, observers were asked to respond as fast as possible, in recognition, they had as much as time as needed. Therefore, it was not necessary for the system to prioritize the content of contextual memory, since there was enough time available to check all categories of display representations. Blocking could be understood as a safe-guard against false-alarms of memory recollection and if a stimulus activated memory retrieval but does not match a template from the set of explicit displays, retrieval is blocked. This would mean that content in contextual memory is prioritized, either by the explicit learning or simply by the fact that explicit displays were learned first. Future experiments could put this hypothesis to the test by either changing the order of learning or by any other manipulation suitable to de-prioritize explicit displays in the hierarchy of contextual memory.

6.3 Early contextual memory effects

Synopsis of results. According to theories of reentrant processing in visual search (Di Lollo et al., 2000), search behavior can be described as an iterative process of generating and testing perceptual hypotheses about the target stimulus. The content of these perceptual hypotheses is very similar to the content of long-term contextual memory (Jungé et al., 2009), which leads to the question whether both mechanisms share a common memory resource and therefore, whether their effects on visual search performance interact. In the current study, the first two experiments were conducted to investigate behavioral contextual cueing effects in interrupted search. While it was shown that performance was expedited for repeated displays in interrupted search, the rate of rapid resumption, as well as reaction times in the epoch of response (that is, the reaction time measured from the last onset of a given display in interrupted search) were not affected by contextual cueing. Rather, contextual cueing was manifest in observers responding overall in earlier epochs for repeated compared to non-repeated displays indicating that contextual cueing led to less repetitions of the hypothesis cycle. This means that the number of hypotheses that are on average generated and tested in a given search trial was reduced for repeated displays, while the process of confirming a hypothesis was itself unaffected by long-term, contextual memory. This leaves two possibilities of how contextual cueing could contribute to short-term hypothesis generation: Hypothesis generation could have been overall more accurate, so each individual hypothesis that was generated in a given trial had a higher chance of being a correct one. Alternatively, contextual memory could have altered the starting point of the search process – e.g. by excluding irrelevant parts of the display from search, or by deprioritizing items farther away from the target – so that less steps were on average necessary to converge on the correct perceptual hypothesis. Note that in a strict sense the latter would be equivalent of saying that contextual cueing does not contribute to the process of hypothesis generation (and hypothesis confirmation).

In the third experiment, fixational eye movements were recorded in order to investigate the processes that lead to the contextual cueing effect in interrupted search. The distance of each fixation to the target was taken as a measure of how the eyes approached the target stimulus over the course of a given trial. It was shown that the distance to the target decreased gradually for each successive fixation, however this decrease happened at the same speed for repeated and non-repeated displays. The crucial difference between the two display conditions was in the intercept, not slope, of the function relating target-fixation distances to the number of consecutive fixations in a given trial. There was an overall benefit for repeated displays, in a way that fixations were closer to the target, while target approaching behavior was identical between repeated and non-repeated displays. This pattern of results demonstrates that contextual memory leads to a head-start of the search process and does not affect the processing of perceptual hypotheses during the time course of a trial. Initially, when the display is seen for the first time, contextual memory aids visual search, while during the course of the trial the cycle of perceptual hypothesis generation and test takes over and is carried out unaffected by long-term memory. The finding that contextual cueing exerts its effects early in an interrupted search trial supported by other studies investigating eye movements in a standard visual search / contextual cueing task. Generally, contextual cueing is found to be associated with a reduction of fixations necessary to find the target (Peterson & Kramer, 2001). Close examination has revealed that this reduction happens in an initial phase of ‘ineffective’ search, which is followed by ‘effective’ search, which is characterized by a monotonic approach of fixations towards the target (Manginelli & Pollmann, 2009; Tseng & Li, 2004). This confirms the notion raised in the current study that contextual cueing offers a head start for visual search in repeated displays. In other words, the finding of a reliable contextual cueing effect in interrupted search may suggest that cueing facilitates the transition from an ineffective to an effective search phase, even when search displays are shown only for very short flashes. Another interpretation of the findings would be that contextual memory can in fact be understood as a form of long-term perceptual hypothesis, which is used when there is no perceptual hypothesis available from previous encounters of the same display. However, as soon as online-information from the actual stimulus is available to form a short-term perceptual hypothesis, input from long-term contextual memory is discarded. Therefore, contextual memory has this positive effect on the starting point of the search process compared to trials which do not have this initial source of information available. In summary, the current study demonstrated that contextual memory and perceptual hypotheses do not interact despite their similarities. Rather, contextual memory exerts an early effect on search performance, while generation and test of perceptual hypotheses characterize later stages of the search process.

Future directions. An alternative approach to investigate how contextual cueing is affecting performance in interrupted search is by formulating a Ratcliff Diffusion Model (RDM; Ratcliff, 1978; Zehetleitner & Müller, 2010). In an RDM, evidence is accumulated over time in order to exceed the response threshold of a binary decision (e.g. orientation of the target). The decision time is then a product of the general drift rate of the random walk and the response threshold. In interrupted search, some modifications have to be made to the standard diffusion model in order to reflect the different characteristics of the search task. Evidence in interrupted search cannot be accumulated until the response threshold is reached, as the search display is only visible for a short period of time. Therefore, the time axis would have to be restricted in an RDM of interrupted search, so the accumulation process is terminated after a fixed amount of time, reflecting one epoch (on/off cycle). The accumulation process begins anew in the next epoch, however some evidence that was accumulated in the previous epoch can be carried over, which is reflected in a lowering of the response threshold. This series of RDMs is then continued until a decision is reached. First (own) attempts in creating a set of model parameters that produces a reaction time distribution comparable to real empirical data (see e.g. Figure 1b in Lleras et al., 2005) were promising, however it proved to be challenging to achieve stable model behavior. Even smallest changes to single parameters of the model could yield an entirely different outcome. Yet, if it can be achieved to formulate an RDM for interrupted search, it could be investigated which parameters have to be adjusted to mimic contextual cueing in interrupted search. This would further shed light on the relationship of long-term and short-term perceptual hypotheses and also which parameters give rise to the rapid resumption effect.

Although there was no interaction observable in the current study between contextual memory and perceptual hypotheses, there could still be a connection that was not addressed. Jungé et al. (2009) hypothesized that contextual memory is established via the consolidation of frequently used perceptual hypotheses. If the same perceptual hypotheses proved to be accurate on a number of trials in the experiment, this hypothesis might be encoded into long-term memory, forming contextual memory of the same content as the corresponding perceptual hypothesis. However, in order to test this theoretical stance, behavioral measures are not sufficient and it would be necessary to identify neuronal markers of interrupted search and perceptual hypotheses. Since the cycle of hypothesis test and generation is very fast and interrupted search consists of events on a short time scale, the application of EEG during interrupted search would probably be most promising. If it is possible to associate the processes of hypothesis generation and confirmation with ERP-components, then it could be further tested what happens when the same configurations are shown repeatedly and therefore encoded in contextual memory.

6.4 Rewarding probability cueing

Synopsis of results. In their study on reward effects in contextual cueing, Tseng and Lleras (2013) reported that the learning of repeated spatial contexts was accelerated when these contexts were associated with a reward outcome. The current experiment investigated an alternative explanation to this result: whether the reward manipulation might have affected probability cueing, which is statistical learning of target location probabilities (Jiang et al., 2013). The same paradigm was used as in Tseng & Lleras (2013) and a reward manipulation of low (1 cent) and high reward (5 cent) was associated with repeated and importantly, also non-repeated displays. When the data of the current experiment were analyzed as in Tseng and Lleras' experiment 1 – i.e., RT performance was collapsed across all reward levels in the non-repeated condition – their results were fully replicated and faster learning of high reward repeated displays was observed compared to low reward repeated displays. However, when reaction times were analyzed separately for high and low reward in non-repeated displays, the pattern of results changed dramatically. Now reward had a huge effect in non-repeated displays and reaction times were faster for high reward displays. This reward effect can only be attributed to an enhancement of probability cueing. A non-repeated display is in fact associated only with a constant target position while the distractor background is variable and reward is applied only after a response with no pre-cue given to observers to predict the outcome. Therefore, the only constant in a given non-repeated display that could be associated with reward was the location of the target object. Importantly, target positions are constant in repeated displays as well, which implies that it is likely that probability cueing was also affected when rewarding repeated displays. This poses the question whether the rewarding of constant distractor layouts had any effect at all or whether it could all be attributed to probability cueing. The current results further revealed that if contextual cueing effects were calculated within a certain reward condition (e.g. high reward repeated displays vs. high reward non-repeated displays), cueing effects were smaller in the presence of high reward compared to low reward displays. An explanation of this surprising reduction in contextual cueing could be that of different levels of reaction time performance in the reward conditions. Given high reward and its effects on probability cueing, performance is already expedited and might not benefit from further advantageous effects, like contextual cueing. This could be due to the fact that, according to the logic of RDMs (Ratcliff, 1978; Ratcliff, Smith, Brown, & Mckoon, 2016), effects of the drift rate on reaction times depend on the overall decision time. If the decision time is reduced, changes in the drift rate also have smaller effects on reaction times (Zehetleitner & Müller, 2010). In summary, contextual cueing provides an additive bonus to reaction time performance on top of and importantly, independent of reward effects on probability cueing. This leads to the conclusion that it is more likely that reward affects the learning of individual target locations in a contextual cueing paradigm, rather than the learning of repeated distractor configurations.

Future directions. Although the present experiment demonstrated reward effects on target repetition, this does not rule out that in principle spatial learning can be enhanced by a reward manipulation. It is however difficult with a standard contextual cueing paradigm to investigate this, since spatial learning is always confounded with target repetition learning. An alternative approach in order to isolate context learning from probability cueing would be to investigate the learning of distractor-distractor associations, rather than investigating target-distractor associations, as in classical contextual cueing. Beesley, Vadillo, Pearson, and Shanks (2014) investigated whether observers learn these distractor-distractor associations by pre-exposing their observers to repeated displays, however without a fixed target position. When the target was then kept constant in the transfer phase of their experiment, cueing was stronger for these pre-exposed displays compared to a novel set of repeated displays. This suggests that even though cueing was not elicited, configurations were learned and increased contextual cueing later on. Adapted to the current question, manipulating the reward outcome to pre-exposed repeated displays could reveal whether contextual cueing is stronger in a transfer phase for pre-exposed displays associated with high reward, compared to pre-exposed displays with low reward.

Alternatively – or additionally – the pre-exposure phase could also reveal whether reward affects learning of distractor-distractor arrangements, even in the absence of behavioral cueing effects. In their study on reward effects on perception and attention, Hickey et al. (2010a) identified that the P1 ERP component, as a marker of perceptual facilitation, and the N2pc, as a marker of attentional deployment, are affected by rewarding certain stimulus features. However, these components are enhanced, contralateral to the stimulus associated with reward and the distractor configurations of contextual cueing normally span the whole display area. In order to investigate electrophysiological markers towards repeated distractor configurations of different reward outcome, displays in such an experiment could be generated by repeating only one half of the display. It was shown that repeating only distractors in the same hemifield as the target is enough to elicit contextual cueing (Olson & Chun, 2002). Therefore, it should in principle be possible to investigate ERP activity contralateral to repeated configurations of differing reward outcome and therefore develop an electrophysiological marker of reward in perceptual learning.

6.5 Conclusion

One of the central capacities of the human visual system is to extract regularities from scenes even without conscious intentions. These regularities strongly increase the predictability of the visual world and make visual processing more efficient, e.g. in the context of a visual search. One such regularity is the spatial configuration of objects and repeated exposure leads to the formation of contextual memory which subsequently expedites visual processing. This dissertation investigated four different aspects of contextual memory and yielded the following main results:

i) Contextual memory increases metacognition of spatial configurations

Contextual cueing is widely regarded as an implicit effect, which implies that effects of contextual memory are cognitively impenetrable and not accessible for conscious evaluation (Chun & Jiang, 1998, 2003). It was shown however, that subjective reports about the configuration of displays were affected by contextual memory of these displays. This demonstrates that metacognition – a measure for observers' insight into their own performance (Koriat, 2007) – was enhanced by contextual memory. Therefore, contextual cueing is not an unconscious phenomenon.

ii) Explicit contextual memory blocks access to implicit knowledge

In standard contextual cueing experiments, displays are learned incidentally via repeated exposure in a visual search task (Chun, 2000). This study used explicit memorization of search displays to investigate the relationship between explicit knowledge and contextual cueing. Explicit displays turned out to elicit a standard contextual cueing effect; however, reaction times to implicit displays were even slower than reactions times to baseline, non-repeated displays, suggesting a negative contextual cueing for implicit displays. The relationship between explicit and implicit displays could be best described as blocking of implicit from explicit displays. With regard to memory systems, the results support the idea that cueing is supported by a single memory system; however, within this system, explicit and implicit displays are processed in functionally different ways (facilitation vs. suppression of memory retrieval, respectively).

iii) Contextual cueing does not impact the generation or test of perceptual hypotheses

Visual search can be described as an iterative process of generating and testing perceptual hypotheses, which can be observed using the paradigm of interrupted search (Lleras et al., 2005). The content of perceptual hypotheses was shown to be very similar to the content of contextual memory with respect to spatial extent, featural resolution and task relevance (Jungé et al., 2009). However, in the current study no interaction was found between contextual cueing and perceptual hypothesis generation or confirmation. Effects of both mechanisms were shown to be additive and to be effective at different stages of the search process. While contextual cueing provided an initial advantage to search, it had no accelerating effect on approaching the target and therefore did not impact the processing of perceptual hypotheses. This is evidence for a very early effect of contextual memory.

iv) Reward in contextual cueing affects target probability learning, not spatial configuration learning

It was argued that reward in a contextual cueing paradigm speeds up the learning of spatial configurations, leading to a faster development of contextual cueing (Tseng & Lleras, 2013). However, it was not taken into account, that rewarding repeated displays does not only associate reward with the repeated distractor context, but also with the repeated target location. Target repetition effects in general have been shown to affect performance in visual search, leading to an effect termed probability cueing (Jiang et al., 2013). The current study demonstrated that applying a reward schedule to non-repeated displays greatly improved performance, indicating that the outcome was associated with certain target positions, irrespective of the distractor layout. It was concluded that reward in contextual cueing primarily affects probability cueing of repeated target positions, rather than contextual cueing of repeated distractor configurations.

7. References (General Introduction and General Discussion)

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9. Curriculum Vitae

Education

Graduate School of Systemic Neurosciences (GSN-LMU), Planegg-Martinsried, Germany

Oct 2012 - present	PhD student in Systemic Neurosciences

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Oct 2011 - Oct 2012	M. Sc. in Neuro-Cognitive Psychology (final grade: 0.94)
Oct 2010 - Sep 2011	B. Sc. in Neuro-Cognitive Psychology (final grade: 0.95)
Oct 2007 - Sep 2011	Intermediate diploma in Psychology (final grade: 1.44)

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Sep 1998 – Jun 2007	Abitur (final grade: 1.0)

Professional experience

Nov 2012 - present	Research assistant at the Chair of General and Experimental Psychology, Ludwig-Maximilians-Universität München
June 2010 – Jan 2012	Student research assistant at the Excellence Cluster "Cognition for Technical Systems", Ludwig-Maximilians-Universität München

Scholarships

Apr 2011 – Sept 2012	Scholarship from the Max-Weber-Programm
May 2013 – May 2016	Graduate Scholarship from Universität Bayern "im Rahmen einer Graduiertenförderung nach dem bayerischen Eliteförderungsgesetz (BayEFG)"

Teaching

Summer semesters 2013-2016	Lecture and tutorial "Introduction into statistics" B. Sc. Psychology (minor)
Winter semester 2013/2014	Tutorial "Classical Psychological Methods: Reaction time and psychophysical methods", M. Sc. Neuro-Cognitive Psychology
Winter semester 2012/2013	Tutorial "Classical Psychological Methods: Reaction time and psychophysical methods", M. Sc. Neuro-Cognitive Psychology
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10. List of Publications

10.1 Manuscripts

Schlagbauer, B.*, Rausch, M.*, Zehetleitner, M., Müller, H.J., & Geyer, T. (*submitted*). Contextual cueing alters metacognition of spatial configurations. (Chapter 2 of this thesis)

Schlagbauer, B., Mink, M., Müller, H. J., & Geyer, T. (2017). Independence of long-term contextual memory and short-term perceptual hypotheses: Evidence from contextual cueing of interrupted search. *Attention, Perception & Psychophysics, 79(2),* 508-521. doi:10.3758/s13414-016-1246-9 (Chapter 4 of this thesis)

Schlagbauer, B., Kröll, L., Müller, H. J., & Geyer, T. (*unpublished manuscript*). Explicit knowledge blocks access to implicit context memory in visual search. (Chapter 3 of this thesis)

Schlagbauer, B., Geyer, T., Müller, H. J., & Zehetleitner, M. (2014). Rewarding distractor context versus rewarding target location: A commentary on Tseng and Lleras (2013). *Attention, Perception & Psychophysics*, *76*(3), 669–674. doi:10.3758/s13414-014-0668-5 (Chapter 5 of this thesis)

Schlagbauer, B., Müller, H. J., Zehetleitner, M., & Geyer, T. (2012). Awareness in contextual cueing of visual search as measured with concurrent access- and phenomenal-consciousness tasks. *Journal of Vision*, *12*(11), 1–31. doi:10.1167/12.11.25

10.2 Contributions to conferences

Oral presentations

Schlagbauer, B., Müller, H. J., Zehetleitner, M., & Geyer, T. (2013). Awareness in contextual cueing of visual search as measured with concurrent access and phenomenal conscious tasks. 55. *Tagung experimentell arbeitender Psychologen* (TeaP), Vienna, Austria.

Posters

Schlagbauer, B., Mink, M., Müller, H. J., & Geyer, T. (2015). The relationship of long-term and short-term perceptual hypotheses: Evidence from contextual cueing of interrupted visual search. *18th European Conference on Eye Movements (ECEM)*, Vienna, Austria

Schlagbauer, B.*, Rausch, M.*, Zehetleitner, M., Müller, H. J., & Geyer, T. (2015). Contextual cueing of visual search alters conscious perception of spatial configurations. *19th Annual Meeting of the Association for the Scientific Study of Consciousness (ASSC 19)*, Paris, France.

Schlagbauer, B., Müller, H. J., Zehetleitner, M., & Geyer, T. (2012). Awareness in contextual cueing of visual search as measured with concurrent access and phenomenal conscious tasks. *Visual Search and Selective Attention III,* Holzhausen am Ammersee, Germany.

Schlagbauer, B., Medina Hernandez, J. R., Koropouli, V., Vlaskamp, B. (2011). Anticipatory Eye Movements when Observing Point-Light Animations. *Munich Multisensory Perception Symposium*, Holzhausen am Ammersee, Germany.

11. Affidavit / Eidesstattliche Versicherung

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation „Dynamics of Perceptual Learning in Visual Search“ selbstständig angefertigt habe, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

I hereby confirm that the dissertation “Dynamics of Perceptual Learning in Visual Search” is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

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Ort/place Datum/date Unterschrift/signature

Bernhard Schlagbauer

12. Declaration of author contributions

Contextual cueing alters metacognition of spatial configurations

Bernhard Schlagbauer, Manuel Rausch and Thomas Geyer conceived the research question and the experiment; Bernhard Schlagbauer programmed the experimental routine and collected the data; Manuel Rausch conceived and conducted the analysis of metacognitive sensitivity; Bernhard Schlagbauer analyzed accuracy and reaction time data; Bernhard Schlagbauer, Manuel Rausch, Michael Zehetleitner, Hermann J. Müller and Thomas Geyer co-wrote the manuscript.

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		Manuel Rausch, shared first author

Explicit knowledge blocks access to implicit context memory in visual search

Lisa Kröll and Thomas Geyer conceived the experiment; Lisa Kröll collected the data; Bernhard Schlagbauer provided the model predictions and conducted the model simulations; Bernhard Schlagbauer analyzed the empirical data; Bernhard Schlagbauer and Thomas Geyer co-wrote the manuscript.

Independence of long-term contextual memory and short-term perceptual hypotheses: Evidence from contextual cueing of interrupted search

Bernhard Schlagbauer and Thomas Geyer conceived the research question and experiment 1a and 1b; Bernhard Schlagbauer and Maurice Mink conceived experiment 2; Bernhard Schlagbauer and Maurice Mink programmed the experimental routines; Maurice Mink and Bernhard Schlagbauer set up the eye-tracking hardware; Bernhard Schlagbauer and Maurice Mink collected and analyzed the data; Bernhard Schlagbauer conducted Bayesian statistics; Bernhard Schlagbauer, Hermann J. Müller and Thomas Geyer co-wrote the manuscript.

Rewarding distractor context versus rewarding target location: A commentary on Tseng and Lleras (2013)

Bernhard Schlagbauer and Michael Zehetleitner conceived the experiment; Bernhard Schlagbauer collected and analyzed the data. Bernhard Schlagbauer, Thomas Geyer, Hermann J. Müller and Michael Zehetleitner co-wrote the manuscript.

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