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Systemic Neurosciences
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Bi-directional relationship between attention and long-term context memory

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Dissertation
der Graduate School of Systemic Neurosciences
der Ludwig-Maximilians-Universität München

München
30th of October 2017

Disputation date:
18th of April 2018

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Acknowledgements

Five years spent in Ph.D. was a highly challenging process. In this time period, I have also challenged myself to do the best I could by learning new methods and techniques to be able to define myself as a ‘cognitive neuroscientist’. On this journey, there are a couple of people I would like to thank for helping me to shape my doctoral career:

I would like to express my sincere gratitude to my two supervisors Prof. Dr. Thomas Geyer and Prof. Dr. Hermann J. Müller who have provided me both scientific and non-scientific support on my Ph.D. career. Especially, I would like to thank my ‘Doktorvater’ Thomas who gave me a chance to do Ph.D. under his supervision and supported me not only as a principal investigator but also as a responsible supervisor by providing me his valuable insights about how to walk on this journey. I would also like to thank my external supervisor Prof. Dr. Stefan Pollmann for his support as part of my thesis advisory committee. Besides my supervisors, I would like to thank my colleagues Markus Conci and my office mate Bernhard Schlagbauer, for all our scientific discussions and for all their help during my Ph.D. Likewise, I thank my colleagues; Ahu, Anna, Artyom, Leonardo, Linda, Marian, Melanie, Ondrej, and Siyi for all the things we shared on Ph.D. My sincere thanks go to GSN and RTG 2175 for their enormous support during my Ph.D.; especially to Prof. Dr. Benedikt Grothe, Maj-Catherine Botheroyd-Hobohm, Prof. Dr. Christian Liabold, and Verena Winkler.

I thank my Munich family (gang); Ebru, Idil, Jairo, Kacha, and Kelsey who made my outside Academy life wonderful and meaningful. Also, special thanks to Ross for all his love and positive encouragement that have kept me always motivated during my Ph.D.

Last but not least, I owe my loving thanks to my dear family. First I would like to thank my father, who passed away eight years ago, for his support in my education and for his philosophy on being patient and moving forward. He couldn’t see any of my graduations but I believe he would have been so proud to have a daughter who was able to finish Ph.D., as the first one of our family. Many thanks to my dear brother for always making me feel his support and love together with his positive attitude. Finally, I am grateful to my mother for her endless love and admirable efforts to make me a strong, educated woman, and a scientist. Without her determination, patience, and loving support, it would have been impossible to complete my Ph.D.

Efsun Annaç,
October 2017

Summary

This dissertation presents four empirical studies investigating the link between visual attention and long-term memory. Long-term memory in visual search is acquired by repeated exposure to invariant spatial configurations and expressed by expedited visual search in repeated over non-repeated displays (i.e., contextual cueing paradigm). The memory of repeated (invariant) displays is considered to be implicit. The present studies aimed to contribute to a better understanding of how visual attention and long-term context memory interact with each other using reaction time and eye tracking measures.

Study 1: Previous studies revealed that unpredictable target location changes impair contextual cueing, and the cueing-related gains in reaction times recover slowly with extensive training on the relocated displays. Study 1 examined whether other forms of attention guidance i.e., spatial grouping, play a role on the adaptation of context memory. For this reason, after the learning of target-distractor arrangements, we re-positioned the target in two different local contexts: local-sparse (consisting of one distractor item around the target) or local-dense (consisting of three distractors around the target) contexts. The results revealed successful adaptation to a new target location when the target was replaced in local-sparse, but not local-dense, regions. It was concluded that spatial grouping of the dense items makes this region salient in a sense that bottom-up attention is effectively guided towards the target region. The lack-of-adaptation of contextual cueing reported in earlier studies reflects not a mere inability of the cueing memory for adaptation. Instead, it suggests that both stimulus- and memory-based processes contribute to target detection.

Study 2: The dependency and independency of contextual cueing from a secondary working memory (WM) load was investigated in Study 2. In former studies, it was shown that contextual learning is independent of divided attention. Study 2 re-investigated the role of divided attention in both context learning and the expression of learned contexts, and further examined whether the influence of WM load is due to the load on spatial or executive WM

capabilities. In the experiments, in order to distinguish between different stages of learning, a visual search task was combined with a secondary WM load either in the early or in the late phases of the experiments. To test whether disadvantageous WM effects result from spatial or executive WM load, observers were either given a task to maintain spatial WM items concurrently with a visual search task (aiming to unravel both the effects of spatial and executive WM), or a task where WM was performed before or after the visual search task, without a task overlap (aiming to test the effects from executive WM load).The findings revealed reduced contextual cueing under a spatial WM load and this effect was larger for the expression of learned configural associations. No interference was found when the secondary WM task was performed in a non-overlapping manner. It is concluded that the retrieval of context representations from long-term memory is dependent on spatial WM, i.e., divided attention.

Study 3: The possibility remains that contextual cueing is independent from divided attention. This issue was investigated in Study 3. Previously it was shown that visual search improves with task practice and this practice-related gain depends on the characteristics of a given task. Study 3 asked whether automaticity of contextual cueing can be enhanced until a level at which it becomes independent of attentional resources. In order to achieve this, a single (visual search), and a dual (visual search together with a secondary spatial WM) task were presented in close succession in individual blocks of trials. This procedure has been shown to facilitate the development of automaticity in visual search. The results revealed reliable contextual cueing under a demanding spatial WM task. It is concluded that the automaticity of contextual cueing retrieval has a modulatory effect on whether a spatial WM load task exerts a detrimental effect on the memory-guided visual search or not.

Study 4: Memory for contextual cueing was considered to be implicit. However, recent studies questioned the notion of implicit contextual memory both on theoretical and methodological grounds. It was claimed that contextual cueing may rely on either a single (incidentally acquired memory but can be accessible via explicit recognition tasks), or a two-memory (incidentally acquired but cannot be accessible in conscious reports) system. Study 4 investigated the idea that contextual cueing is initially unconscious but can become conscious later on through the help of focal attention (i.e., fixational eye movements). After the learning of contextual cues, observers' eye movements were measured in an explicit recognition test, in which they had to judge the quadrant of the target. The results revealed higher fixation dwell times in the target quadrant of the invariant over random displays. Furthermore, manipulations of observers' gaze in the recognition task showed that fixation dwell times also serve a purposeful role for the conscious retrieval from context memory. At the same time, fixation of the target quadrant was not a requirement of context-based search facilitation. Contextual cueing seems to receive support from at least two independent (automatic and controlled) retrieval processes, and focal attention seems to be the mechanism that links the retrieved information across the two processes.

Chapter 1:

General Introduction

"…After many thousands of experiments, we know only marginally more about attention than about the interior of a black hole."

(Stuart Sutherland, Nature, 1998)

1.1 Visual attention

In the 1890s, William James stated, "*Everyone knows what attention is*" (James, 1890; p. 404). Yet even after 100 years, studies have shown no clear consensus on what determines what we attend to or how attention is represented in the brain. The forms of attention have been widely studied in the last 50 years because the mystery of how visual attention operates has attracted many cognitive-behavioral scientists. Indeed, attention, learning, and memory are remarkable cognitive processes. *Attention* can be defined as a cognitive-behavioral state of focused awareness that enables us to select a subset of relevant input while ignoring the irrelevant ones. In short, what you see in the environment is regulated by where or what you attend to. As our visual world is often complex and involves a numerous amount of unnecessary information for our behavioral purposes, the nervous system has evolved to cope with environmental input that is flowing through our system via different attentional mechanisms. For instance, scanning a visual scene consciously or unconsciously to locate an object is not a random process. During this visual search, attention is guided to the most relevant element via several visual processing aspects. The first well-known aspect is *Bottom-up*, stimulus-driven (exogenous) processing (Gibson, 1966) which is dependent on stimulus properties, but not observers' subjective judgment. These stimulus properties consist of, e.g., color, orientation or a salient feature that pops out through visual search. The second aspect is *Top-down*, goal-driven (endogenous) processing (Gregory, 1970; also see Neisser, 1967) where perception and attentional allocation are based on observer's expectation (Geyer, Müller, & Krummenacher, 2008), prior knowledge or experience. *Density*, *crowding* and (spatial) *grouping* are also known important factors that modulate visual search. For example, when the display density increases, search becomes easier (Nothdurft, 2000; Sagi, 1990), or the close proximity of items makes them seem crowded or grouped which makes it difficult to find the target in the scene (Levi, 2008). *Priming* and *contextual cueing* are other important aspects for the search guidance. The memory of previously seen items affects search performance in the next trials, which can be defined as priming effect (Kristjánsson & Driver, 2008). Further, the repeated association of a target location among invariant search context improves visual search, the effect known as contextual cueing (Chun & Jiang, 1998; also see section 1.2 for more information). In contextual cueing, previously seen display layouts modulate reaction times (RTs) and speed up the search, this context-based guidance of attention is quite robust. Recently, additional factors were claimed to affect search efficacy (Wolfe & Horowitz, 2017). One of these factors is *guidance by scene properties,* which is the combination of two types of guidance as *syntactic and semantic guidance* (also see Biederman, Mezzanotte & Rabinowitz, 1982). *Syntactic guidance* refers to the physical constraints of the visual object. For example, if the object stands against gravity, thus contradicting physical laws, the visual system is directly guided to the locations where objects can physically stand. A real world application of this would be, when searching for a book in the library, observers' attention will not be directed to the air since the book cannot float, instead it will be directed to the shelves on which they can stand. S*emantic guidance* relies on the meaning of the scene, in which the observer would not look for a science book on the history shelves or on the floor because it is unlikely to be on either, instead attention will be directed to the science shelves which are higher than the floor level. G*uidance based on the perceived value of the objects* refers to the situation when observers are rewarded to search for a certain object, for instance, when they search for a red item that has a high value among different colored items on the screen, their attention will be more likely to be deployed by that particular red object. In the g*uidance based on search history,* prior history of search (e.g., priming) modulates attention. Typically this form of guidance manifests over different time scales, ranging from milliseconds over seconds up to hours or days. It includes phenomena such as within-trial (inhibition of return, IOR) memory and cross-trial priming, in addition to perceptual and statistical learning (see, e.g., Shore & Klein, 2001, for a review). All these attributes are important to understand the degree and the nature of attentional guidance and search efficacy that is modulated. The current dissertation focused on the guidance of visual search by long-term statistical learning, which relies on the ability to rapidly learn environmental regularities (contexts) over time.

Visual search mainly relies on top-down orienting, and in a visual search task observers' goal is to look for the presence of the relevant target that is surrounded by distractors in the visual scene. A real world application of this would be, the expectation of finding a pen on the office desk will orient attention towards the penholder, while ignoring the surrounding items on the desk. The top-down expectations will guide attention towards the expected target location. However, it is still limited to acquire reliable data from real-world context. Therefore, laboratory visual search tasks are designed as similar as possible to the ecological search tasks to investigate and understand real-world search, including long-term learning in ecological settings. In these tasks, observers search for a target object amongst distractors with hundreds of trials. Typically, in half of these trials the target is present and in the other half it is absent. Set size or the number of items in the scene differ from trial to trial or differ for the purpose of the study. After subjects complete all the trials, both accuracy and observers' reaction times (RTs) are recorded to understand the exact time of observers' target detection. The slope of the function relating RTs to set size is the standard calculation to measure search efficacy. RTs are claimed to increase in a (roughly) linear fashion, which led researchers to conclude that the nature of visual search is based on serial processing (see Wolfe, 1998). However, there are alternative views about visual search process such as parallel processing of the search items (Duncan & Humphreys 1989). Related to this, there is the debate as to whether RTs increase with increasing set size in a linear or exponential (logarithmic) fashion, the latter indexing parallel processing (e.g., Buetti, Cronin, Madison, Wang & Lleras., 2016). A third issue concerns the actual measure of visual search; that is, whether RTs increase with decreasing number of items of fixations in a given trial (Hulleman & Olivers, 2017).

In the present dissertation, the contextual cueing paradigm was used as a main experimental approach to assess the interaction between attention and long-term memory (or statistical learning). In the following, we first introduce the context-guided visual search (i.e., contextual cueing paradigm) and review the important literature concerning the effects of learned spatial configurations on visual search. The second part of the introduction describes and summarizes the relevant studies for the first empirical report examining the interaction of bottom-up guidance factors (i.e., visual grouping) and statistical context learning in visual search. The third part presents core studies that have investigated the relationship between statistical learning and divided, i.e., resource-limited, attention. Part four introduces the notion of automatic and controlled processes and its application to the context-based guidance of visual search. The specific idea tested in this study was the development of automaticity. That is that, with sufficient training, the acquisition of, and retrieval from, context memory can survive a demanding secondary spatial working memory task. Part five introduces the implicit-explicit debate in context learning, and presents an alternative context-memory model. This model is based on different retrieval modes rather than consciousness, which inspired the fourth empirical investigation employing a manipulation of gaze direction to facilitate conscious retrieval from context memory. The final part is the general discussion.

1.2 Context-based guidance of visual search: contextual cueing paradigm

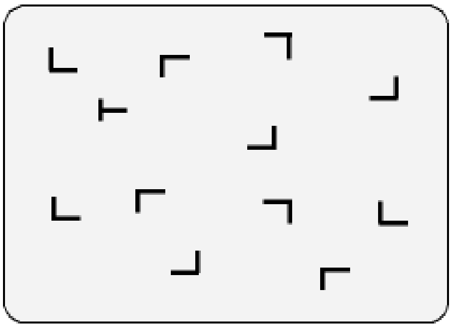
In the real world, objects do not appear in isolation but in meaningful contexts. As the visual system utilizes repetitions in the environment, locating an object in a complex but repeated setting becomes easier. Early studies of contextual learning have shown that context influences our perception of objects in space (Palmer, 1975, Biederman 1972). Searching for an object in a repeated context cues the object location and search becomes faster than in a novel context. This search facilitation provides adaptive benefits in daily life. Examples of this would be, finding your car in the car park, or finding a book on the bookshelf. Every time you attempt to find ‘your target item’ the cognitive system lets contextual cues guide your search.

In order to investigate contextual learning, previous studies (Biederman 1972, Intraub, 1997, Simons & Levin, 1997, 1998) used contextual displays, which have ecological validity (i.e., real-world scenes), but not much experimental control. Chun and Jiang (1998; also see Chun, 2000) developed a “c*ontextual cueing*” paradigm to overcome confounding factors of real-world images, such as background or semantic features of the scene. In their pioneer study, they suggested that context increases search efficacy by guiding attention towards the target location. Since then, contextual cueing research has been elaborated with a number of studies investigating, for example: the role of selective attention (Jiang & Chun, 2001; Jiang & Leung, 2005), perceptual grouping constraints (Olson & Chun, 2002), top-down strategies (Lleras & Von Mühlenen, 2004), display factors (Jiang & Wagner, 2004), oculomotor correlates (Tseng & Li, 2004), temporal regularities (Wagener & Hoffmann, 2010) on implicit context learning. Subsequent studies investigated several different aspects of context learning, some of the examples would be: the coupling of attention and context memory (Johnson, Woodman, Braun, & Luck, 2007; Schankin & Schubö, 2010), its underlying (hippocampal) brain mechanisms (Geyer, Baumgartner, Müller, & Pollmann, 2012), the issue of local versus global context learning, in detail; the association between the target location and the entire distractor background (Brockmole, Castelhano & Henderson, 2006; also see Jiang &Wagner, 2004), contextual remapping (Shi, Zang, Jia, Geyer & Müller, 2013), gaze-contingent viewing of the spatial context (Zang, Jia, Müller & Shi 2015), or contextual adaptation to multiple target locations (Zellin, Conci, von Mühlenen, & Müller, 2013; Zellin, von Mühlenen, Müller & Conci, 2014). Eye movement studies also demonstrated contextual cueing with the number of eye fixations reduced in repeated context (Tseng & Li, 2004; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Brockmole & Henderson, 2006).

In a typical contextual cueing task, participants encounter arrangements of letter stimuli, with the target being the letter “T” and distractors being the letter “L” (presented in variable orientations of 0°, 90°, 180° and 270°). Observers’ task is to respond to the orientation of the target letter. If the target is tilted to the right or to the left, they press the corresponding directional button on the computer keyboard (see Fig. 1A). Unbeknown to participants, half of the trials contain repeated, and the other half contain non-repeated (i.e., newly generated) configurations.

Typical findings reveal that search becomes more efficient (i.e., faster RTs) in repeated compared to non-repeated displays. This reaction time difference is the ‘*contextual cueing effect*’ (See Fig. 1B). Further, at the end of the experiment, participants are usually given an unexpected memory test, consisting of repeated and non-repeated (foil) displays. Many contextual cueing experiments found that observers are unable to correctly discriminate repeated from non-repeated displays, which has led to the idea that contextual cueing is acquired via implicit learning mechanisms (e.g., Chun & Jiang, 1998; Chun, 2000; Peterson & Kramer, 2001; Chun & Jiang, 2003). This implicit memory is considered as having a high capacity, being resilient against interference, and long lasting (Chun & Jiang, 2003; Jiang, Song, & Rigas, 2005). However, recent research challenged the view that the memory underlying contextual cueing is implicit. Instead, it was suggested that current recognition tests are inappropriate in terms of their statistical power and validity (see section 1.6 for more details on implicit versus explicit context memory debate).

A.



B.

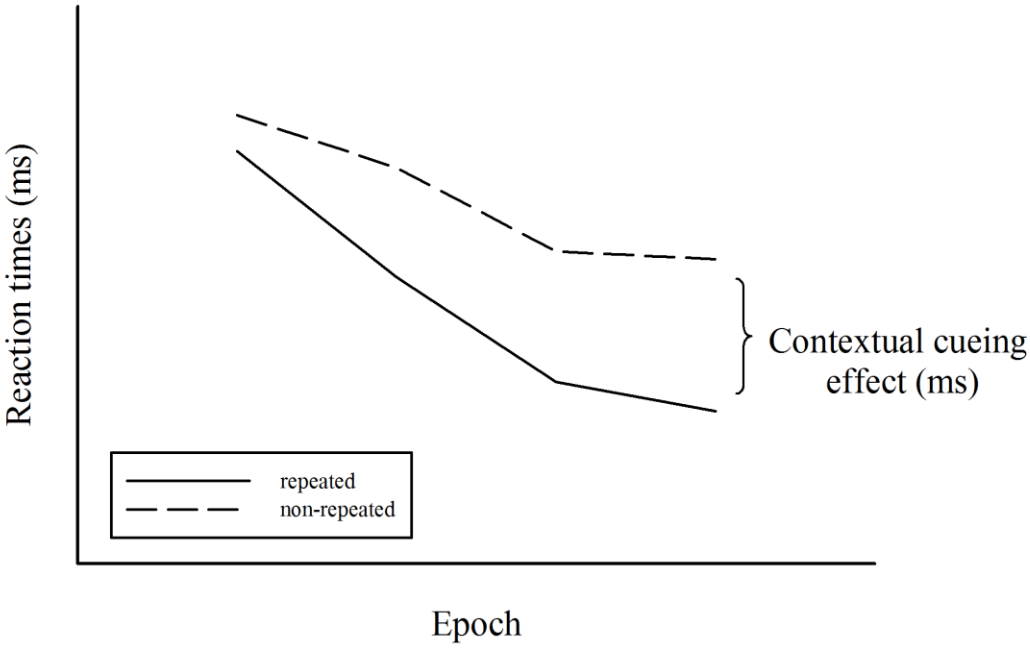


Figure 1: Illustration of the search display (context) and contextual cueing effect. (A) A sample array of contextual cueing experiment where target ‘T’ is presented amongst ‘L’ distractor items. (B) Search performance is shown as a function of practice on the task (epoch). Over the time course of the experiment, RTs become faster for repeated than non-repeated displays and the difference between repeated and non-repeated displays indexes the contextual cueing effect.

In addition to the effects of context memory on attentional guidance, it has been suggested that learnt context can also facilitate ‘late’ processes of the target’s response-critical attributes, in other words response selection. This response selection can be defined as the mapping of the target representation onto the selection of response (after the stimulus and before the response, see e.g., Kunar, Flusberg, Horowitz & Wolfe, 2007). Concerning the latter, it was claimed that there is a *response threshold* component to be able to respond to a target, which is modulated by contextual associations. For example, repeated displays may reduce the threshold, and therefore response to the target would be faster in repeated displays when compared to non-repeated ones, revealing contextual cueing effect. Evidence from event-related brain potentials (ERP) revealed large N2pc component for target locations of repeated displays (Schankin & Schubö, 2009). N2pc results, which are attributed to the attentional guidance, had no correlation with LRP-r onset effect, which is attributed to the late response selection process. Thus, the authors claimed that contextual cueing modulates both attentional guidance and response selection, and these two processes operate independently from each other. In contrast, Geyer, Zehetleitner and Müller (2010) suggested that visual search in ‘pop-out’ scenes enhance the early perceptual process of target selection rather than late response selection.

In summary, context serves to guide visual attention and facilitates search for targets, and the contextual cueing effect is driven by the spatial associations between the target location and its surrounding distractors. This effect leads to the faster detection of the targets that are embedded in repeated arrangements.

1.3 The influence of spatial factors on the adaptation of contextual cueing

Contextual cueing may not be always successful in locating the target in repeated displays, especially when there is a novel, or more than one, target location in the display. Yet, little is known about the adaptive properties of contextual cueing to the multiple target locations. In adaptation studies there are usually two distinct phases in the experiment: the initial phase in which original target locations are associated with invariant context arrangements, and the latter phase in which the target is moved to a novel location on the same invariant displays. The transition of the target from its original location to a new and unpredictable location induces adaptive problems. That is to say, the cueing benefit weakens with a target location that was not associated with the invariant arrangements in long-term memory. Some studies have failed to report adaptation in contextual cueing (Chun & Jiang, 1998; Manginelli & Pollmann, 2009; Makovski & Jiang ,2010; Zellin, Conci,von Mühlenen, & Müller, 2013) while others could reveal adaptation by claiming that learned contextual cueing can adjust itself to more than one location (Conci, Sun, & Müller ,2011; Conci & Müller, 2012; Zellin, von Mühlenen, Müller, & Conci, 2014).

The computational model of contextual cueing assumes that there can be associations in repeated context for multiple target locations (Brady & Chun, 2007). Further, in order to deal with a complex and dynamic environment contextual cueing should be adaptive and flexible for handling new information. For example, when there is a target location change or when there are multiple target locations in the scene, contextual memory should be able to update itself to guide attention to the new target location(s) and facilitate responses. Previous studies investigated this idea by presenting the target at novel locations in repeated search displays (Wolfe, Klempen, & Dahlen, 2000; Manginelli & Pollmann, 2009). Although findings along these lines suggest limitations in contextual cueing, the absence of the cueing effect was not interpreted as a problem of plasticity or adaptivity of context memory. Manginelli and Pollmann (2009) built upon this idea and designed an experiment particularly addressing the issue of adaptation (learning of a new target position in a constant distractor layout) in contextual cueing. They divided the experiment into two parts as training, and test, and allowed participants to learn invariant search displays in the initial phase. In the latter phase, they moved the target (of invariant displays) to a new location. Results revealed reliable contextual cueing in the training phase but not in the test phase, that is, after the target location change search facilitation vanished. Manginelli and Polllmann (2009) claimed that contextual adaptation is inflexible under unpredictable target location change (also see Conci, Sun, & Müller, 2011). Subsequently, Makovski and Jiang (2010) suggested that adaptation occurs only if the new target location is in close proximity with the old target location, and thus, if the target is far away from its original location that leads to *contextual cost*. Therefore, close vicinity between the original and the new target location is an important factor for contextual adaptation.

Conci, Sun, & Müller (2011) investigated more on the adaptive properties of contextual cueing, to understand whether *predictable* target location change increases the flexibility of contextual adaptation (see Manginelli & Pollmann, 2009). They also divided the experiment into two parts as training and test phases. The initial phase was aimed to let contextual cueing manifest without a target location change. In the second phase, target location change was applied either in 'predictable' (i.e., displays that can be learned) or 'unpredictable' locations. Predictable locations were operationalized in such a way that the initial target position and the future target positions matched and allowed the target to be associated with the invariant context. In the unpredictable locations, the initial and future target positions (e.g., when the target was moved to a novel position) did not match and made the target position of the invariant context unpredictable. Results of this study revealed that contextual cueing effect remains reliable when the target location is predictable after the change. They concluded that contextual cueing may be flexible and adaptive to location remapping only if it is in a predictable position. As a comparable article, Conci and Müller (2012) reported that learned contextual cueing is fragile to unpredictable changes, whereas predictable changes can be in favor of adaptation. It is now possible to assume that when there is an unpredictable target location change, then the memory of repeated configurations misguides attention, and therefore RT gains decline. According to Zellin, von Mühlenen, Müller, and Conci (2014) RT decline can recover slowly with extensive training (i.e., 80 repetitions presented over 3 days). In their study, the results showed that after an extensive training with relocated displays, contextual cueing manifests after the 4th day. Additionally, they applied a "return" phase on the 10th day by giving intermixed displays from both initial and return phases and found comparable contextual cueing in both phases, showing that contextual cueing of initial displays does not fade away.

There can be several reasons why adaptation fails in relocated displays. One of the reported reasons is *proactive interference*, in which active learned memories (or experience) interfere with new learning (see review and discussions: Lustig & Hasher, 2001; Zellin et al., 2013; Zellin et al., 2014). An example of such would be, after establishing robust contextual cueing in the initial phase, the memory of learned contexts do not allow acquiring new memories in relocated displays, therefore adaptation fails. However, proactive interference does not explain why negative effects, of RT slowing, occur with relocated targets in constant distractor arrangements. Furthermore, the interference account would predict that there is almost never adaptation of context memory. And yet, a bulk of studies have shown that adaptation can occur when the new target location is predictable or in the close proximity to its original location (Makovski & Jiang, 2010; Conci et al., 2011;Conci & Müller, 2012; Zellin et al., 2013).

An alternative account for the adaptation of context memory to target location changes is bottom-up, *spatial grouping*, process. Previously, it was described that spatial grouping directs attention to the grouped regions, which makes target detection faster (e.g., Humphreys, Quinlan, & Riddoch, 1989; Han, Humphreys, & Chen, 1999; Conci, Müller, & Elliott, 2007). The saliency of such local segments leads to bottom-up processing, resulting in faster RTs and impaired contextual cueing by attention guidance from the grouped regions (Conci & von Mühlenen, 2009). In a sense, grouping cues and learned spatial context would compete for the allocation of attention and because grouping cues would sometimes win this competition, RT gains derived from repeated contexts would effectively be reduced. A related idea is that spatial grouping effectively curtails the time available for context learning (and / or retrieval), and thus effectively hampers the build-up of context memory. These processes may be particularly pronounced in the adaptation of context memory, as the acquisition of a new target-context representation (which would be highly similar to the originally learned target-context representation) may be a difficult, time-consuming, process. To test this hypothesis, Annac, Conci, Müller, and Geyer (2017) conducted a series of experiments to understand how spatial grouping interferes with context learning and the adaptation of this memory. Spatial grouping manipulation was administered by manipulating the display items. In the experiments initial phase displays were presented with targets surrounding two items. In the relocation phase two types of displays were applied as sparse and dense. In the sparse displays the target item was moved from its original location to a locally scarce region where it was always surrounded by 'one' distractor, whereas in dense displays the target was moved to a locally rich region where it was surrounded by 'three' distractors (see chapter 2 and Fig. 1). The results showed that spatial grouping interferes with the adaptation, not learning, of target-distractor associations in visual search (see chapter 2 and Fig. 2). The findings extend existing knowledge on the adaptation of contextual cueing: (1) a new target location can be learned in relation to an existing context representation when target location changes are predicted, or (2) when the new target appears in the close spatial proximity of previously learned target location, or (3) as the findings from Annac et al. (2017) suggests, when bottom-up guidance by spatial grouping is minimal, and thus observers have sufficient time for processing the relocated displays.

1.4 Secondary task effects in contextual cueing of visual search

1.4.1 Selective and divided attention in contextual cueing of visual search: How do we process repeated displays when attentional resources are distributed?

***Selective attention*:** While the studies above undisputedly show that context memory facilitates attention (either in the process of searching for the target or response selection), other studies have investigated the reverse question: whether selective attention is itself required in implicit learning (e.g., Nissen & Bullemer, 1987; Jiang & Chun, 2001, Jiang & Leung, 2005). Further, the question has been asked whether other forms of attention, such as divided or resource-limited attention (Pashler, 1998) affect implicit learning (e.g., Manginelli, Langer, Klose & Pollmann 2013; Annac, Manginelli, Pollmann, Shi, Müller & Geyer, 2013). The effect of selective attention was investigated in a serial search task (SRT task; Nissen & Bullemer, 1987). In these experiments, under single- or dual-task conditions, participants were expected to track the location of a single target item (i.e., asterisk) on the screen, whose location was changed when participants pushed the response key. Unbeknownst to the participants, the sequence in which the target item appeared was sometimes repeated and sometimes random. Results showed that under single task conditions, participants reveal faster RTs for the repeated sequence (i.e., implicit sequence learning). However, when the SRT task was given with secondary tone-counting task, sequence learning did not occur. Nissen and Bullemer (1987) concluded that attention is essential to learn the repeated pattern in SRT task. The role of selective attention in context learning was first studied by Jiang and Chun (2001). In their study, observers were given a visual search task in which half of the display items were in the attended color (e.g., red), while the other half were in the unattended color (e.g., green). Moreover, each the attended and non-attended sets of items were paired with repeated and non-repeated configurations. The results showed a context effect only for attended distractors, appearing in the color with the target item. Jiang and Leung (2005) went on examining this effect of selective, i.e., color-based, attention on context learning. In more detail, Jiang and Leung (2005) had observers detect, and subsequently discriminate, the orientation of a black “T”, presented amongst black and white “L’s”. In Jiang and Leung’s terms, the black L’s were the attended, or target-set distractors, and the white L’s were the ignored, or non-target set distractors. The experiment was divided into a training phase and a test phase. At the intersection of the two phases, the colors of the distractors were swapped:

the black L's became white, and the white L's became black. There were three repetition conditions (with "repetition" referring to the spatial arrangement of the items): repetitions of both target- and non-target set distractors ("both-old" condition), repetitions of only target-set distractors ("attended-old" condition), or repetitions of only non-target set distractors ("ignored-old" condition). Contextual cueing effects were assessed by comparing RTs in these three repetition conditions to RTs in a non-repeated ("both-new") condition. In the learning phase, contextual cueing was found to occur in the both-old and the attended-old, but not the ignored-old, conditions, replicating Jiang and Chun's (2001) findings. Interestingly, the magnitude of contextual cueing was comparable between the both-old and the attended-old conditions, suggesting that the cueing effect (in the both-old condition) was due to the repetition of the attended context alone (see also Geyer et al., 2010, for similar results and conclusions). In the test phase however (i.e., after the swapping of the distractor colors), contextual cueing was observed only in the ignored, but not both-old and attended-old, conditions. Jiang and Leung (2005) concluded from this pattern that the formation of contextual memory is independent of attention. This was evidenced by reliable contextual cueing in the ignored-old condition already at the start of the test phase (indicating that the locations of the to-be-ignored distractors had been successfully learnt in the training phase). In contrast, the expression of learned target-distractor configurations is under the control of selective attention, as evidenced by significant cueing effects in the both-old and attended-old condition in the learning phase and contextual cueing in the ignored-old condition in the test phase.

1.4.2 The interference of spatial working memory (sWM) load on contextual cueing

Divided attention: The cognitive system is required to buffer environmental input for daily activities, and working memory (WM) is an important device that helps to manipulate, or maintain, environmental input for a short time. Working memory interacts with attention by maintaining the information that is necessary for the relevant behavior (Cowan, 2005).

Vickery, Sussman, & Jiang (2010) investigated implicit contextual cueing under dual-task conditions by using secondary WM tasks. The reasoning behind this was to understand whether there is a link between working memory resources and implicit context learning. The assumption was based on whether both visual search and WM tasks are supported by a single attention resource (Kahneman, 1973; Navon & Gopher, 1979), or multiple resource pools (Wickens, 2002). The single-resource-pool account assumes that there is a single pool of attentional resources that can be used to carry out multiple tasks, and the amount of attention varies according to the task, or to the state of arousal of the performer. Dividing attention across tasks would of course come with the disadvantage of performance loss in the individual tasks (relative to the tasks being performed in isolation). Conversely, the multiple-resource-pool account claims that there are several attentional resources (e.g., for the ‘simple’ encoding versus maintenance) of visual material, and that multiple task performance can be high, and comparable to single task performance, as long as multiple tasks do not overlap in terms of their required processing resources.

Vickery et al. (2010) used two distinct phases as training and test. In training phase, WM load was applied as a secondary task in which observers’ WM was occupied for example by: color, dot patterns, dot locations, or multiple targets, together with the visual search (i.e., contextual cueing) task. In the test session, visual search was performed without a concurrent WM task. Under these conditions, Vickery et al. (2010) observed a reliable cueing effect in the test session, suggesting that context cueing does not rely on central WM or divided attention resource, thus supporting the multiple-resource-pool hypotheses. However, later studies challenged these results, claiming that WM load actually impairs contextual cueing (Manginelli, Geringswald, & Pollmann, 2011; Travis, Mattingley, & Dux, 2013). Manginelli et al. (2011) combined the visual search task with either a visuospatial or a non-spatial (i.e., color) WM task and found that WM for spatial locations, but not for color, interfered with the cueing effect. Travis et al., (2013) manipulated the number of items to be held in WM during the search task and found a parametric modulation of the cueing effect, that is to say that the effect decreased as WM load increased. The studies by Manginelli et al. (2011) and Travis et al. (2013) suggest that spatial contextual cueing and WM might be driven by a common resource (single-resource-pool hypotheses). In a sense, WM may be considered as the area that links contents from long-term context memory with the current search display input.

The difference between the outcomes of the studies mentioned above is interesting in another aspect, namely the processes of context learning that are affected by a concurrent spatial WM task. Nissen and Bullemer (1987; see also Jiang & Leung, 2005), made a distinction between the acquisition and expression of implicit memory, corresponding to the processes of learning and retrieval of context memory. In their study, Vickery et al. (2010) examined contextual cueing under dual-task conditions only in the learning, but not in the test phase, with these phases intended for the investigation of the processes of learning and retrieval, respectively. Their results are therefore only valid with regard to the independence of WM and the learning of repeated visual search displays. In contrast, Manginelli et al. (2011) and Travis et al. (2013) addressed the contribution of spatial WM to contextual cueing only during the retrieval of contextual cues. Thus, the question of whether spatial WM influences the expression or retrieval of learned contexts has not yet been investigated in a fully orthogonal design. The critical studies examined the contribution of different forms of WM (i.e., color, spatial) to context-based search guidance, but they did not investigate other forms of WM load. One such load is executive load, resulting from the requirement to schedule the WM and visual search tasks under dual-task conditions. These issues were brought to research by subsequent studies (Manginelli et al, 2013; Annac et al, 2013).

Manginelli et al. (2013) applied spatial WM load together with the visual search task either in the learning or in the test phase. They found that cueing-related RT gains were reduced under spatial WM load in the test phase, supporting Travis et al.'s (2013) findings. In the learning phase, however, spatial WM load did not influence contextual cueing (a finding in line with Vickery et al., 2010). They concluded that not learning, but the expression of learned configurations, is affected by the spatial WM load. Annac et al. (2013) went on to examine the contribution of a common executive resource pool (Baddeley, 1986) to the visual search and WM tasks. They reasoned that performing a secondary task in addition to the search task would increase the executive demands, and thus eventually impair contextual cueing. Annac et al. (2013) considered this possibility, and added a new factor relating to the distinction between spatial WM and executive WM, in order to clarify whether the expression of contextual cueing is hampered by spatial and / or executive WM. In their experiments, the secondary spatial WM task was applied before, after, or concurrently, with the contextual cueing task (measuring the effects of executive and spatial WM, respectively). The results suggested that spatial WM load hampers contextual cueing in the expression of learned contexts, and this effect is independent of executive WM demands (see chapter 3 for more details). Just like the effects of selective attention, the findings above favor the modulatory role of divided attention in contextual cueing that is pronounced on the expression of learned spatial configurations.

1.5 Automatic and controlled processing in contextual cueing: Extended training under a demanding secondary task

There is the possibility that a secondary WM task may not always impair visual search / contextual cueing. Schneider and Shiffrin (1977) claimed that attentional performance improves with extended task practice, and this practice-dependent improvement in search performance relies on the characteristics of the current task. Concerning this, Schneider and Shiffrin (1977) made a distinction between automatic and controlled processes, with only the former benefitting from task practice. Schneider and Shiffrin (1977, pp. 2–3) defined the automatic attention response as a special type of process that directs attention automatically to the target stimulus. In contrast, a controlled process is a process wherein “a temporary sequence of nodes activated under the control of, and through attention by, the subject.”

Moreover, it was suggested that controlled processes are “tightly capacity limited”. The differences between automatic and controlled attention processes were initially studied in two search conditions: consistent and variable mapping. In the consistent search condition, the set of target stimuli was constant throughout the experiment. It was surmised that under consistent mapping, automatic attention processes can develop, which previously differed in the degree of automaticity (here the claim was made that the development of full automaticity typically requires hundreds of trials). In the variable mapping condition, a stimulus that was a target, and thus required a response in one trial, was a distractor in another trial, and thus required a different (withholding) response in the next trial. Under this variable mapping condition, the coupling of a certain stimulus onto a certain response is impossible, as a result observers cannot form a consistent mapping between a stimulus and its associated response. According to Shiffrin and Schneider (1977), this prevents the development of automatic attention processes.

Schneider and Shiffrin’s (1977) work has received a great deal of interest as it shows that attention performance improves with increased practice on the task, given consistency of the mapping between a target template and its response requirements. In subsequent work, Schneider and collaborators (e.g., Schneider & Fisk, 1982) further addressed the issue of automatic versus controlled processing by combining consistent and variable mapping in a single task. In more detail, Schneider and Fisk (1982) examined the development of automaticity in single- and dual-task conditions, which was measured by the slope of the function relating behavioral performance (i.e., signal detection accuracy) with time (i.e., number of trials), in the experimental task. In single-task conditions, observers were required to perform either the consistent or the variable mapping task across an entire block of (48) trials. In essence, they had to report the display, or frame, when a predefined target was present in streams of rapidly presented displays (a kind of rapid serial visual presentation task). Observers were informed about the respective target at the beginning of each trial. In the dual task condition, half of the trials were consistent-mapping, and the other half were variable-mapping trials, with the order of (single vs. dual condition) blocks being a random variable. There were two important findings: (1) observers improved their search detection in the consistent-mapping, but not in the variable-mapping condition (replicating Shiffrin & Schneider's 1977 results), which was independent of whether they performed the consistent-mapping or variable-mapping conditions in an isolated or combined manner (corresponding to single-blocks or dual-blocks, respectively). (2) For the consistent-mapping condition, the practice-dependent gain in performance was even higher under dual-task conditions. Schneider and Fisk (1982, p.277) argued that controlled processes (in variable-mapping blocks) can act as a "…training wheel…" (p.277) for automatic performance (in consistent-mapping blocks). In a sense, performance on a controlled task would leave no processing resources left for the automatic task and thus, maximize the development of automaticity.

Re-evaluating the above findings on the dependency of contextual cueing from spatial working memory in light of the dichotomy between automatic and controlled processes, would give new impetus for the development, and testing of, the relation between contextual cueing and working memory. If one considers contextual cueing as a form of skill, or procedural learning (see, e.g., Chun & Phelps, 1999 for the development of this idea), that is basically as a form of automatic processing (Schneider & Shiffrin, 1977), then this would lead to the somewhat paradoxical prediction that context effects come to the forefront, specifically under conditions of a demanding (and controlled) secondary task, such as a spatial WM task. In Annac et al. (in preparation; see chapter 4) we investigated this hypothesis. We combined the visual search (contextual cueing) task with a secondary spatial WM task. In contrast to previous investigations (on the coupling between contextual cueing and WM; refs see above), we adopted a paradigm similar to that of Schneider and Fisk (1982), in which we presented repeated displays interchangeably in a single (search-only) versus dual (search-and-WM) blocks of trials. Under these conditions, it was surmised that the spatial WM task should soak up attentional resources, leaving no room for controlled processing to spill over to the search task / contextual cueing. This should then foster the development of automatic processing (i.e., retrieval from context memory), manifesting a contextual cueing effect even in the presence of a demanding spatial WM task. The results supported our hypothesis in that we found a reliable context-based guidance of visual search when the search task was performed together with a concurrent spatial WM task. Findings along these lines would suggest contextual cueing as a form of memory-based automaticity (see, e.g., Chun & Jiang, 1998, for this view).

1.6 Explicit recognition of contextual cueing measured by eye movements

1.6.1 The debate on implicit and explicit context memory

In many studies, contextual memory was considered as an implicit mechanism (Chun & Jiang, 1998; Jiang, Song, & Rigas, 2005; see review Goujon, Didierjean & Thorpe, 2015). However, recent theoretical and methodological reports challenged this account, and started a discussion on the nature of contextual memory by claiming that awareness in contextual cueing is not always absent (Smyth & Shanks, 2008; Schlagbauer, Müller, Zehetleitner & Geyer, 2012; Vadillo, Konstantinidis, & Shanks, 2016; but see Colagiuri & Livesey, 2016 for recent evidence of implicit context). The issue about the memory system underlying contextual cueing has led to a thorough debate on single- (implicit and explicit) or two-memory (implicit vs. explicit) systems. Single memory system claims that although contextual memory is acquired incidentally (automatically) in the course of the visual search task, it is still consciously / strategically accessible when queried later, by means of an explicit recognition test. Two-memory system predicts the opposite, namely that (implicit) context memory established through the visual search task is inaccessible for conscious reports.

Standard recognition tests of contextual cueing consist of 24 trials (i.e., 12 repeated 12 non-repeated displays), which compares to some 400 trials (200 repeated, 200 non-repeated) in the visual search task. An explicit cueing effect would have to be massive in order to be statistically detected. This methodological weakness of the current recognition tests was made ‘explicit’ recently. For example, Smyth and Shanks (2008; see also Vadillo et al., 2016) claimed that evidence for explicit contextual cueing may be revealed when larger numbers of recognition trials are used. In their experiments, they implemented 4 blocks of 24 recognition trials (i.e., overall 96 trials with 48 repeated displays, in which each repeated configuration was presented twice) rather than presenting the typical 24 trials to measure awareness about repeated visual search displays. Using this extended, and statistically more powerful, recognition test they found evidence for explicit contextual cueing. This they attributed to the operation of a single memory system in the context-based guidance of visual search. Similarly, Vadillo, Konstantinidis, and Shanks (2016) performed a meta-analysis of 73 studies of contextual cueing that includes statistics from 181 awareness tests. While the majority of individual studies found no evidence of explicit learning in contextual cueing, Vadillo et al.’s (2016), meta-analytic estimate of awareness (i.e., mean Cohen’s d_z) was 0.31 [with a 95 % CI ranging from 0.24–0.37]) and thus indexing awareness in contextual cueing. The claim was that, null-findings in many previous studies reflect false negatives that were likely due to insufficient statistical power.

Other researchers approached the issue of the implicit versus explicit nature of context learning from a different angle, using alternative measures of explicit context learning in repeated visual search. For instance, Schlagbauer, Müller, Zehetleitner, and Geyer (2012) used brief display presentations and asked observers about their visual experience, and their confidence of seeing the target stimulus after each trial. The results showed a reliable contextual cueing effect and higher clarity in both consciousness measures for repeated compared to non-repeated displays. It was concluded that, contextual cueing is associated with increased visual experience (and confidence) about the target stimulus. Although Schlagbauer et al. (2012) could not distinguish between sensitivity and response bias in their clarity ratings, in their subsequent work they could distinguish between these two (Schlagbauer, Rausch, Zehetleitner, Müller, & Geyer, in revision). The important findings of this study were that context memory improved visual search, and at the same time increased observers' insight or metacognition about the processing of the search displays. The finding about increased metacognition of display parameters in repeated displays would complement findings from, e.g., Smyth and Shanks (2008), and align well with recent findings suggesting that context memory receives support from brain structures that are usually associated with explicit (i.e., declarative) forms of learning (see Chun & Phelps, 1999; Geyer, Baumgartner, Pollmann, & Müller, 2012). Spatial context memory may therefore be conceived as a device that stores relational information independent of how this information is encountered or learned (i.e., incidentally or strategically). Context memory also differs largely from other forms of explicit memory. For instance, it is robust against interference in that it can last up to several weeks (e.g., van Asselen & Castelo-Branco, 2009). It also shows great capacity (i.e., observers are able to form contextual memory for as many as 60 repeated displays; cf. Jiang, Song, & Rigas, 2005). However, context memory lacks flexibility, in that, changes of the target location in a constant distractor arrangement are not incorporated in the existing memory representation (Zellin, von Mühlenen, Müller, & Conci, 2014; see chapter 2 of this thesis). Furthermore, repeated search displays are represented in context memory with regard to a highly specific (viewer-centered) reference frame. That is to say, contextual facilitation of RT performance is strongest if the orientation of the test display is identical to that of the learning display (Chua & Chun, 2003). In a very recent investigation, Colagiuri and Livesey (2016) found no correlation between explicit recognition and contextual cueing when using very large samples; of N > 600 observers (such a correlation would be expected by a single memory system especially with large samples, cf. Vadillo et al., 2016). The authors concluded that contextual cueing of visual search is supported by an implicit memory system.

In summary, the memory underlying visual context learning is accessible for conscious reports and receives support from brain structures that are typically concerned with explicit (i.e., relational) learning. In contrary, context representations are relatively inflexible in that the search items are bound in an inseparable representation, without access to the individual elements (e.g., Zellin et al., 2014). This raises the question of whether spatial context learning is really an explicit effect.

1.6.2 The role of eye movements in context memory

Although explicit measurements provide information about conscious awareness in contextual cueing, eye movement data may further provide insights into understanding conscious accessibility and inaccessibility of context memory. This is because eye movements have been suggested as a very sensitive measurement of learning and memory (see, e.g., Hannula et al., 2010). Moreover, previous studies investigating contextual cueing found that the number of eye fixations together with reaction times decrease in repeated displays (Peterson & Kramer, 2001; Tseng & Li, 2004; Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Schlagbauer, Mink, Müller, & Geyer, 2017). As a novel approach, recent studies recorded eye movements during explicit recognition of learned displays, to understand whether memory about these displays can modulate memory-sensitive eye fixations. The studies suggested that learned and non-learned displays can be distinguished even though participants are unaware of the learned content (Ryan, Althoff, Whitlow, & Cohen, 2000; Hannula & Ranganath, 2009; Hannula, Baym, Warren, & Cohen, 2012). Eye movements occurred very rapidly after stimulus onset, which also suggests that they reflect memory effect (rather than strategic decision variables, e.g., Hannula, Ryan, Tranel & Cohen, 2007). Findings along these lines gave rise to the hypothesis that conscious reports involve two separate processing stages (see, e.g., Moscovitch, 2008; Sheldon & Moscovitch, 2010). During stage one, learned content is retrieved automatically and without concomitant awareness, and the retrieved memory contents may be revealed by ‘indirect’ measurement (e.g., Merikle & Reingold, 1991), such as reaction times or oculomotor measurements (e.g., Hannula & Greene, 2012). During the second, slower stage of processing, retrieved contents may become consciously accessible and can influence ‘direct’ measurements (of explicit recognition task performance).

In the fourth empirical study (see chapter 5 for the details), we investigated such a process-based account of memory in relation to contextual cueing. We recorded eye movements during an explicit recognition task and compared observers’ fixational dwell times between correct and incorrect trials. Note that we also used a novel (generation) recognition task, in which the target was substituted by an additional distractor element. Observers’ task was to judge the location of the substituted target, which required spatial memory. Fixational dwell times were recorded in the target’s substituted quadrant. Interestingly, dwell times were higher for correct responses relative to incorrect responses (hit versus false alarms, respectively), suggesting that eye movements can distinguish correct from false context memory. However, the relationship between eye movements and context memory does not necessarily prove a causal relationship between gaze or overt attention, and retrieval from context memory. For this reason, we conducted a second experiment, in which we manipulated the generation task. Participants were again encouraged to make a decision about the quadrant of the substituted target. However, this time they were additionally required to hold their gaze at a certain location (quadrant) of the recognition displays, which was either consistent (spatially overlapping) or inconsistent (spatially disparate) with the quadrant of (substituted) target stimulus (cf. Johansson & Johansson, 2014). With this procedure, we were able to determine whether covert attention is a requirement for conscious retrieval from context memory. The results showed higher memory accuracy for consistent relative to inconsistent trials. In a follow-up experiment, we applied a related procedure to the visual search task. In a gaze-contingent eye-tracking experiment, the quadrant that contained the target was blurred upon observers’ fixation of this quadrant. This was done in an attempt to further clarify the role of attention (fixations) in contextual cueing, and explicate a two-stage retrieval model of the context effect. The idea is that the information learned in contextual cueing is: (a) initially unconscious, but (b) can possibly become conscious with the intervention of visual attention. While (b) is perfectly in line with the results, (a) would have required further testing. For this reason, we implemented gaze-contingent eye tracking in a contextual cueing experiment to blur (mask) the target quadrant upon its fixation. Observers could therefore solve this task only with peripheral vision. The results showed a reliable contextual cueing effect, even when overt attention is unavailable for retrieval from context memory during the search task. This is an important pattern of findings suggesting: (1) a two-stage model of retrieval may be a proper account of contextual cueing, and (2) selective, focal, attention can bring the output of the first, unconscious stage to a conscious stage. In other words, focal attention is a prerequisite for conscious retrieval from context memory but not necessarily for the context-based guidance of visual search.

1.7 Thesis overview

The present thesis assumes a bi-directional relationship between attention and context memory, a form of search guidance acquired through repeated encounters of identical arrangements of visual search displays. On one hand, selective attention and visual search receive support from context memory, which is the issue that has been investigated in many cognitive-neuroscientific studies (cf. chapter 1.2). On the other hand, spatial context memory is itself dependent on attention, which is the focus of the current thesis. These dependencies apply to both aspects of attention: selectivity, and processing resources deployed.

Study 1 investigated the role of bottom-up attention, i.e., spatial grouping, on context memory and found a gradual influence of attention on the initial learning and later adaptation of context memory (attention effects were larger in the adaptation of contextual cues). Study 2 examined secondary task effects on contextual cueing of visual search, and showed that resource-limited attention is necessary to retrieve learned display arrangements from memory, where contextual cueing diminished (or recovered) in the presence (or absence) of an attention-demanding secondary WM task. These influences were due to spatial, not executive, load coming from the secondary WM task. Study 3 further investigated the effect of spatial WM on the retrieval of learned display arrangements. Particular emphasis was given to the practice regime. In study 3, which was in contrast to study 2, we introduced single-blocks and dual-blocks, the latter containing trials with both search and WM task. These dual-blocks should facilitate the development of automaticity, i.e., the independence of context memory from limited-resource attention. The results showed reliable contextual cueing under a concurrent spatial WM task. This may suggest that the requirement of context memory from divided attention depends on the strength of automaticity (of retrieval from context memory). Study 4 studied the impact of selective attention on context learning during an explicit recognition task. The major finding was that attention is a necessity for the conscious retrieval from contextual memory.

Chapter 2:

Local item density modulates adaptation of learned contextual cues (2017)

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Annac, E., Conci, M, Müller, H. J., & Geyer, T. (2017). Local item density modulates adaptation of learned contextual cues, *Journal of Visual Cognition* : 1-16. https://doi.org/10.1080/13506285.2017.1339158

This article is published at tandfonline.com

2.1 Abstract

In everyday scenes, searched-for targets do not appear in isolation, but are embedded within configurations of non-target or distractor items. If the position of the target relative to the distractors is invariant, such spatial contingencies are implicitly learned and come to guide visual scanning (“contextual cueing”). However, the effectiveness of contextual cueing depends heavily on the consistency between bottom-up perceptual input and context memory: following configural learning, re-locating targets to an unexpected location within an unchanged distractor context completely abolishes contextual cueing, and gains deriving from the invariant context recover only very slowly with increasing exposure to the changed displays. The current study induces variations of the local target context, i.e., item density, to investigate the relation between this factor and contextual adaptation. The results showed that learned contextual cues can be adapted quickly if the target is re-positioned to a sparse local distractor context (consisting of 1 neighboring non-target item), as compared to no adaptation with a dense context (with 3 surrounding non-targets). This suggests that contextual adaptation is modulated by spatial factors and is not per se limited by order effects in the learning process.

Keywords: contextual cueing, visual search, implicit memory, spatial grouping, multiple target location learning

2.2 Introduction

Scanning a complex environment is a highly demanding process. Given this, having consistent context information can help to guide visual search and object recognition. One approach to studying memory-based visual search is provided by the contextual cueing paradigm (Chun & Jiang, 1998). In the standard paradigm, observers perform a relatively difficult search for a target letter T amongst letter L distractors. Unbeknown to them, half of the trials contain stable, i.e., repeated target-distractor (spatial) arrangements. The key finding is that reaction times (RTs) are faster to repeated than non-repeated displays, indicating that contextual regularities are learned and come to guide, or “cue” visual search. While the importance of contextual memory to perception and attention is now widely acknowledged (see, e.g., Cheung & Bar, 2012), recent work has shown that context memory is also severely limited. For example, Conci and collaborators reported that once observers have acquired a memory representation for a given target-distractor context, changes of the target location – within a repeated, i.e., unchanged, distractor layout – are difficult to incorporate in the existing configural memory representation (e.g., Zellin, von Mühlenen, Müller, & Conci, 2014, see Fig. 1). The present study induces target position changes in learned distractor contexts under conditions that carefully control local item density, in order to examine how this factor affects the adaptation of contextual cueing.

2.2.1 Lack-of-adaption of contextual cueing

In their seminal study, Chun and Jiang (1998; see also Jiang, Song, & Rigas, 2005) proposed that the memory underlying contextual cueing is of high capacity. However, while learning of contextual information is efficient to acquire spatial regularities, it has nevertheless turned out to be remarkably inflexible to adapt learned regularities subsequent to environmental changes. For example, a number of experiments suggest that contextual cueing does not recover easily after target location changes within a learned display (Conci, Sun, & Müller, 2011; Zellin, Conci, von Mühlenen, & Müller, 2013; Makovski & Jiang, 2010;

Manginelli & Pollmann, 2009). These studies typically consisted of two phases: learning and test. The key manipulation was a change of the target location at the transition from the learning to the test phases while keeping the distractor locations unchanged (see Fig. 1 for an illustration of the basic procedure). The main findings were that (i) contextual cueing was substantially reduced immediately after the target location change; and (ii) the effect recovered only with massive amounts of training on the changed displays (see Zellin et al., 2014, who had their observers perform 3.600 trials on the changed displays across several days, with contextual cueing recovering only after some 1500 trials following the presentation of the "relocated" displays). – It should be noted that the problem to re-instantiate contextual cueing after a change of the target location is unlikely to result from limitations in memory capacity. For instance, Jiang et al. (2005) reported reliable contextual cueing across five days of training, where observers were presented with variable sets of repeated displays on each day. Thus, while the capacity of the memory underlying contextual cueing is quite large, the adaptation of the cueing effect subsequent to a change of the target location (in an otherwise invariant layout) appears to be much less efficient.

The lack of adaption may at least in part suggest a primacy effect in contextual cueing (see Junge, Scholl, & Chun, 2007), with learning being largely confined to early phases of the experiment. However, such a "turn-off" of learning would be highly maladaptive in the real world since statistical structure – which is usually present in the environment – would go undetected.

Arguably, though, temporal constraints on learning may not be the only conceivable reason for the failure to adapt contextual cues. One other, as yet unexplored cause may relate to bottom-up, spatial grouping processes. For instance, it has been shown that visual search is aided by perceptual, i.e., spatial, grouping, effectively making it easier to detect and / or recognize a target within grouped regions compared to the processing of individual items (e.g., Conci, Müller, & Elliott, 2007; see also Han, Humphreys, & Chen, 1999, for a comparison of the effectiveness of different grouping mechanisms in vision). Such grouping and segmentation processes may reveal a crucial influence on paradigms that examine the adaptability of contextual cueing. For instance, it is possible that in changed displays, the target and the distractors may be grouped together, thus forming a segmentable region (Conci & von Mühlenen, 2009) or a 'salient' cluster of items that is prioritized for the assignment of bottom-up attention. Thus, because the search display is removed upon the response, insufficient time may be available for the system to encode, i.e., (re-)learn, the spatial target-distractor relations (e.g., Ogawa & Kumada, 2008) or there may be no incentive for (re-) learning as the target is found efficiently. Note that these accounts are neutral as to whether bottom-up attention affects the processes of the build-up, i.e., acquisition of a new association between the changed target position and the old distractor context or the expression, i.e., retrieval of this (adapted) representation from context memory.

Alternatively, the rich local context provided by (attended) grouped regions might facilitate the acquisition of the new target-distractor associations – thus promoting the adaptation of contextual cueing. It has, in fact, been shown that contextual cueing is particularly effective within segmented regions of an invariant display (Conci, Müller, & von Mühlenen, 2013; Hodsoll & Humphreys, 2005; Geyer, Shi, & Müller, 2010). In this view, presenting a changed target in a dense cluster of distractors may, in fact, facilitate the adaptation of contextual cueing because the dense local context surrounding the relocated target would allow a learned context to be effectively associated with the novel target location.

On this background, the present study was designed to test the effects of spatial grouping on contextual adaptation by systematically varying the number of distractors in the (relocated) target's immediate context. This manipulation is based on findings showing that contextual cueing is almost entirely supported by memory of individual target-distractor associations formed in the local vicinity, i.e., quadrant, of the target (Brady & Chun, 2007). Applied to the adaptation of contextual cueing, a manipulation of local target density should facilitate shifts of attention towards the grouped region either curtailing the time available for encoding individual distractor locations and thus updating the contextual memory representation (*local-grouping hypothesis*), or, alternatively, promoting the acquisition of new local target-distractor associations in the grouped – contextually-rich – region, engendering the rapid adaptation of contextual cueing (*local-learning hypothesis*). On both accounts, fast (bottom-up) stimulus- and comparatively slower (top-down) memory-based processes would provide separable sources of information for search guidance, where contextual cueing acts in the way of memory-based automaticity (e.g., Logan, 1988; Chun & Jiang, 1998). Thus, although cueing operates automatically, it requires the activation of memory representations by the search array, which provides the guidance signals.

2.2.2 Rationale of the present study

In a departure from previous adaptation studies, which did not control for local density effects, the present study was designed to examine for the effects of local item density on contextual cueing by contrasting dense versus sparse distractor contexts. The study consisted of four experiments. Experiment 1 was a baseline experiment that investigated the 'default' processes of contextual learning and adaptation using arrangements of letter stimuli with the aim to replicate the basic pattern revealed in previous experiments. This experiment was divided into a learning and test phase, measuring contextual learning and adaptation, respectively. The critical manipulation was a change of the target position at the transition from the learning to the test phase (while keeping distractor locations unchanged). In Experiment 2, the placement of the target in the learning and test sessions was carefully controlled (unlike in Experiment 1 and in previous studies, where item locations were selected randomly), allowing the effects of spatial grouping on contextual cueing adaptation to be investigated. Specifically, in the initial learning phase, the target was positioned in such a way that it was always surrounded by two distractor items (see Fig. 1). In the subsequent test phase, distractor-dense and distractor-sparse contexts were introduced, consisting of three and, respectively, one distractor in the vicinity of the re-positioned target. In Experiment 3, distractor-dense and distractor-sparse contexts were introduced already in the initial learning phase in order to investigate how this factor affects the initial build-up of contextual cues (over and above the effects of density on the adaptation of learned contextual cues). Finally, Experiment 4 investigated the effects of spatial grouping on learning of a new set of repeated displays subsequent to initial learning of a different set of displays. In this experiment, distractor-dense and distractor-sparse contexts were novel in a sense that the respective arrangements were not shown in the previous learning phase.

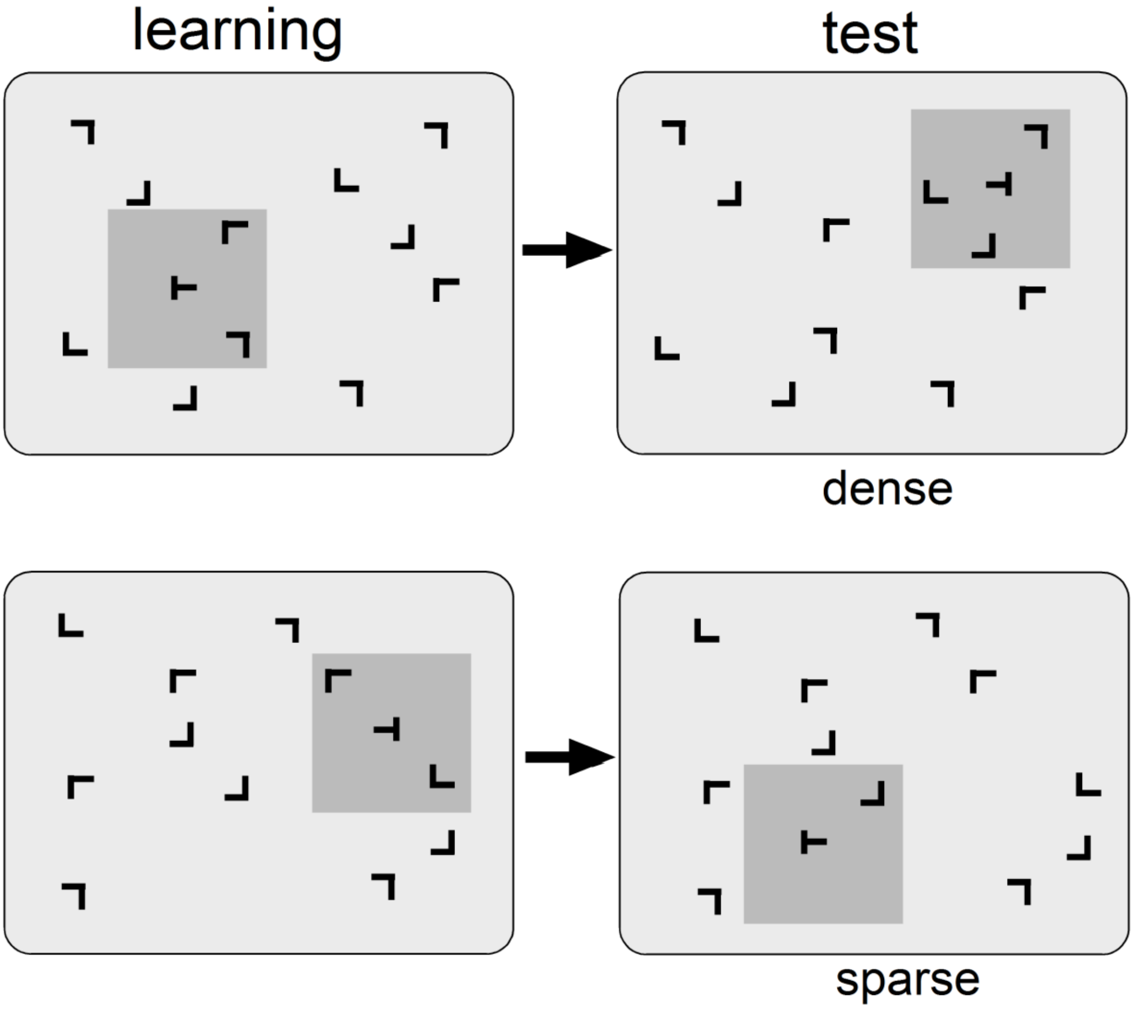

Fig. 1. Examples of repeated search displays used in the present experiments. During learning, observers are presented with invariant target-distractor layouts to promote contextual learning of the repeated displays. In the subsequent test phase, the location of the target is changed whereas the context of distractors remains as before. Experiment 1 was a baseline, introducing a change of the target location at the transition from the learning to the test phase while keeping the distractor arrangement constant. In Experiment 2, in addition to the changes of the target location, displays in the learning phase (left panel) always contained two distractors in the immediate surround of the target location. In the subsequent test phase (right panel), targets were presented in local contexts of one or three distractors (sparse or dense display conditions), respectively. Experiment 3 consisted of only a learning phase to examine the impact of sparse and dense display conditions on the initial learning of context cues. Experiment 4 tested the effect of density on new learning using the same procedure as Experiment 2, except that a novel set of distractor-dense and distractor-sparse displays was shown in the test phase. The grey squares, of approximately 7.5° x 7.5°, mark the target's local context and are provided here for the purpose of illustration only.

2.3 Experiment 1 (baseline)

The purpose of Experiment 1 was to show, in the first instance, that with our stimuli we can actually replicate previous findings showing a general lack of adaptation in contextual cueing to relocated targets (e.g., Zellin et al., 2014).

2.3.1 Method

Participants and Setup

For Experiment 1, we tested a sample of N=20 observers (Experiments 2 and 3: N=14 observers each; Experiment 4: N=13 observers). But following previous investigations of contextual cueing (e.g., Conci & Müller, 2012; Kunar & Wolfe, 2011; Olson, Chun, & Allison, 2001; Zellin, Conci, von Mühlenen, & Müller, 2013), of these 20 participants we took into account only those who displayed an above-zero contextual cueing effect (RT [non-repeated display] minus RT [repeated display] > 0) in the learning phase. The rationale of this was that observers who fail to display contextual cueing in the learning phase are likely to acquire memory of the target in relation to the stable distractor configuration only later on, that is, they only show successful learning of relocated targets in the test phase (see, e.g., Zellin et al., 2013, who, in an analysis of N=38 excluded observers, showed this effect of late contextual learning). Conceivably, such (late) contextual learning of relocated targets may be preceded by some (target-independent) configural learning initially, with the target-context association being formed only later, during the test phase (cf. Beesley, Vadillo, Pearson, & Shanks, 2016). Thus, in order to examine true adaptation of previously learned target-distractor associations, rather than late learning, observers with negative contextual cueing scores in the learning session were excluded from the study (N=7 observers in Experiment 1, N=1 observer each in Experiments 2 and 3, and N=0 observers in Experiment 4). These 9 excluded observers showed a mean negative contextual cueing effect of 24 ms in the learning phase and a mean positive effect of 84 ms in the test phase (see Appendix).

Amongst the 13 participants in Experiment 1 with positive contextual cueing effects in the initial learning phase (6 female; mean age: 27.1 years, sd: 3.83), all reported normal or corrected-to-normal vision and were naïve as to the purpose of the study. Prior to the experiment, participants provided written informed consent and were compensated with either course credit or monetary payment (8 Euro, i.e., ~9 USD). – Note that the sample sizes of our remaining, selected group of observers (N=13 observers in each experiment) are comparable to the sample sizes in previous studies that investigated multiple target location learning in contextual cueing, including the pioneering study of Chun and Jiang (1998).

Stimuli and Design

The experiment was programmed in Matlab (version 7.5.0.342 R2007b), in combination with the OpenGL-Psychtoolbox extension (Brainard, 1997), and run on an Intel computer. Search displays used in both the learning and test phases contained one target and 11 distractor stimuli. The target was a T-shape, rotated by either 90° or 270°, distractors were L-shaped and were rotated by either 0°, 90°, 180° or 270°. All stimuli subtended 0.7° x 0.7° of visual angle and were presented in white color (67.0 cd/m^2) on a grey background (33.1 cd/m^2). The items of a search display were presented in the cells of an invisible 6×8 matrix. Cell size was 2.5º×2.5º. The items were slightly jittered (0.1º×0.1°) to prevent collinearities in the display.

Learning (phase 1)

The learning phase consisted of 384 trials divided into 24 blocks of 16 trials. Each block contained two different types of search displays: 8 repeated and 8 non-repeated displays. In repeated displays, the location of the target and the location and identities of distractors were held constant across trials. Non-repeated displays were generated anew on each trial. In order to equate target location repetition effects across the two conditions, the target was presented equally often at a fixed set of 16 locations across learning: 8 locations were used for repeated 8 (different) locations for non-repeated displays.

Test (phase 2)

The test phase was almost identical to the learning phase. There were 384 trials divided into 24 blocks of 16 trials. The major change consisted of the placement of the target at a novel location, while keeping the distractor locations unchanged (in the repeated condition). 16 new target locations were selected at the beginning of the test phase. 8 locations were used in repeated and 8 (different) locations in non-repeated displays. These new target locations were chosen in a way to equate the distances between old and new locations across the two types of displays (6.9° and 7.0° in repeated and non-repeated displays, respectively).

Procedure

Observers received written instructions at the beginning of the experiment. The experiment started with a practice session (16 trials) to familiarize observers with the task. The practice session was immediately followed by the learning and test sessions. Each search trial started with the presentation of a black fixation cross at the center of the screen for 500 ms. The search array was presented subsequently and remained until a response was issued. Participants were to respond as fast and as accurate as possible to the orientation of the target stimulus. If the target was tilted to the left (right) they pressed the left (right) key of the computer mouse with their left (right) index finger. After an erroneous response, a red horizontal line was presented for 1000 ms. The inter-trial interval was 500 ms.

At the end of the search experiment, observers performed a yes-no recognition test, intended for the assessment of explicit memory of the repeated configurations (cf. Chun & Jiang, 1998). To this end, 8 repeated displays from the initial learning session and 8 newly composed displays were shown and observers were asked to indicate whether or not they have seen a given display previously (by pressing the left and right mouse keys; unspeeded responses).

2.3.2 Results and Discussion

Data analysis was performed using R (R Core Team, 2014). Both frequentist and Bayes analyses were performed. Bayes Factors were calculated using the package BayesFactor (Morey & Rouder, 2015). The natural logarithm of a Bayes factor (BF_{10}) is reported, with values greater than 1 [= log(3)] providing substantial, and values greater than 2.3 [= log(10)] strong evidence for the alternative hypothesis (Wetzels et al., 2011). Error trials and trials with extreme RTs (outside 2.5 SDs from the individual mean) were discarded.

Accuracy

Overall response accuracy was 98.8%. A repeated-measures analysis of variance (ANOVA) on the error rates with the factors phase (learning vs. test) and display type (repeated vs. non-repeated displays) revealed neither of the main effects nor their interaction to be significant (all F's<1). If anything, error rates were slightly lower in the learning than in the test session (1.2% vs 1.3%).

RT performance

RTs in the learning phase were collapsed into four epochs, with each epoch representing an average of six consecutive blocks, so as to obtain reasonably stable RT estimates over time. For the learning phase, a 2 (display type: repeated, non-repeated) x 4 (epoch: 1-4) repeated-measures ANOVA revealed main effects of display type, $F(1,12) = 15.38$, $p<.01$, $BF_{10}=12.87$, and epoch, $F(3,36) = 16.16$, $p<.001$, $BF_{10}=5.48$. For the test phase, by contrast, a 2 x 4 repeated-measures ANOVA failed to yield a significant main effect for either display type, $F(1,12)=0.11$, $p=.73$, $BF_{10}=0.15$, or epoch, $F(3,36)=2.80$, $p>.05$, $BF_{10}=0.02$. As shown in Fig. 2 (panels A1 and A2), the contextual cueing effect (i.e., RTs for non-repeated minus repeated displays) dropped substantially between the learning and test phases (71 vs. 6 ms) and did not recover even with extended practice on the changed displays. This pattern clearly replicates previous (own) results relating to the lack of adaptation in contextual cueing (see Fig. 3). Specifically, in our previous work, we conducted six other experiments on the adaptation of contextual cueing. All experiments revealed reliable differences in contextual cueing obtained between the learning and test sessions (all p’s <.01). An overview across all (85) observers in the present Experiment 1 and the previous experiments revealed a mean contextual cueing effect of 131 ms in the learning phase, which compares to a contextual cueing effect of only 4 ms in the test phase (reduction: 97%). This pattern of results suggests that, while contextual cueing can provide a (potentially) powerful mechanism of search guidance, this mechanism is severely limited in its ability to adapt to target location changes.

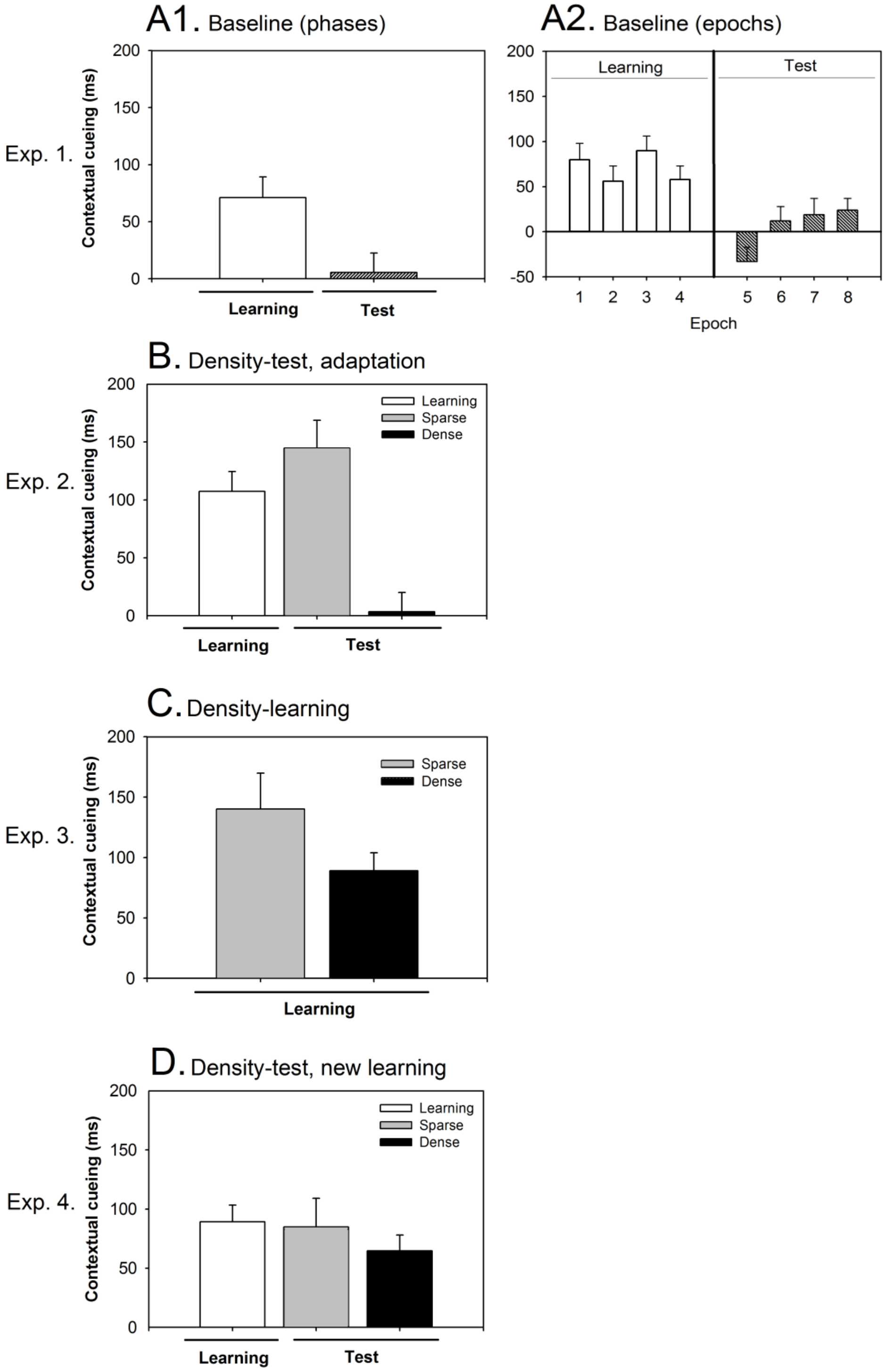

Fig. 2. Results of Experiments 1-4. Panels A1 and A2: Contextual cueing as a function of phase (panel A1) and epoch (panel A2) in the baseline Experiment 1. Panel B: Experiment 2. Contextual cueing in learning and test, where the test phase presented a target location change in otherwise unchanged distractor-sparse and distractor-dense displays. Panel C: Experiment 3. Contextual cueing arising from dense and sparse displays in the initial learning session. Panel D: Experiment 4. Contextual cueing in learning and test, where the learning phase was identical to Experiment 1 and the test used a novel set of previously unseen distractor-dense and distractor-sparse displays. Contextual cueing is computed by subtracting reaction times to repeated displays from reaction times to non-repeated displays. Error bars represent the standard error of the mean.

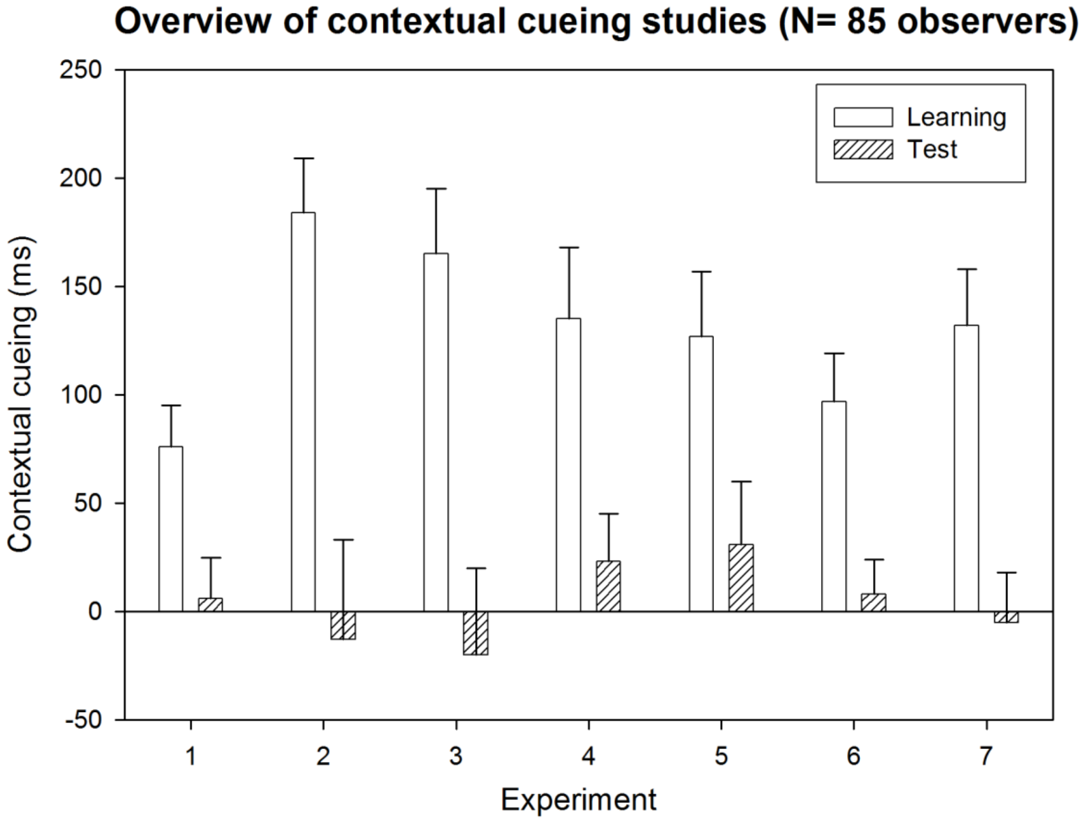

Fig. 3: Overview of seven experiments (with N=85 observers) showing that contextual cueing drops massively after target location changes at the transition from a learning to a test phase (white and dashed bars, respectively). Note that the distractor layout remained unchanged throughout the entire experiments. Experiments: (1) Experiment 1 of the current study; (2) Conci et al. (2011), Experiment 1; (3) Conci & Müller (2012), Experiment 2; (4) Zellin et al. (2013), Experiment 1A; (5) Zellin et al. (2013), Experiment 1B; (6) Zellin et al. (2013), Experiment 3; (7) Zellin et al. (2014), Experiment 1 (mean contextual cueing for test summarizes performance on day 1).

Recognition Test

Observer's ability to recognize repeated displays was estimated by using the signal detection measure *d* prime [d' = Z (hit rate) − Z (false-alarm rate); Green & Swets, 1966]. A hit means that observers correctly classified a repeated display as having seen this layout in the previous search task, while a false alarm means that they incorrectly judged a non-repeated layout as a repeated display. Mean d-prime score was .11, which was not significantly different from zero, *t*(12) =0.49, p=.63, BF_{10}=0.46. In fact, the low BF_{10} value supports the null hypothesis of no positive relationship between cueing and recognition. Thus, there was little evidence that observers had explicit knowledge of the repeated displays. One caveat here is, of course, the low power of the current recognition test (with only 8 trials with repeated and 8 with non-repeated displays), which limits any conclusions as regards the involvement of explicit knowledge in contextual cueing (see Vadillo, Konstantinidis, & Shanks, 2016).

2.4 Experiment 2 (density at test, adaptation)

Experiment 2 went on to re-examine the lack of contextual cueing found in Experiment 1 (and prior studies). In a departure from Experiment 1 (and previous adaptation studies), which did not control for local density effects, Experiment 2 introduced a grouping manipulation, examining the effects of local item density on contextual adaptation. During initial learning, search layouts were presented with an "intermediate", i.e., baseline level of density, where two distractor items always surrounded the target. In the subsequent test phase, and following the target position changes, distractor-dense and distractor-sparse contexts were introduced, consisting of three and, respectively, one distractor in the vicinity of the target (Fig. 1). In total, participants were to learn 8 repeated displays during the initial learning phase. During test, half of them became distractor-dense and the other half distractor-sparse displays.

Assuming that contextual cueing is supported by memory for local, i.e., individual, target-distractor pairs (Conci et al., 2013; Hodsoll & Humphreys, 2005; Geyer, Shi, & Müller, 2010), re-positioning the target to a ‘rich’ learning region – of many local distractor items – should facilitate the re-learning of target-distractor associations. The hypothesis of *local-learning* thus predicts rapid recovery of contextual cueing in the distractor-dense condition, which provides a contextually rich region for the re-learning of target-distractor relations. For the same reason, adaptation of contextual cueing should be less strong in the distractor-sparse condition. By contrast, the *local-grouping* hypothesis predicts no advantage of contextual cueing in the distractor-dense condition, but an advantage in the distractor-sparse condition. This is because with dense (but not sparse) displays, attention is guided efficiently in a bottom-up manner to the target region, thus decreasing the incentive for encoding the local target-distractor relations, i.e., for relying on top-down contextual cues.

2.4.1 Method

The method of Experiment 2 was essentially similar to Experiment 1, except for the details as provided in the following.

Participants and Setup

A total of 13 new participants took part in the experiment (8 female; mean age: 24.0 years, sd: 2.79 years).

Stimuli and Design

The learning and test phases consisted of 384 trials each, divided into 24 blocks of 16 trials. Each block contained two different types of search displays: 8 repeated and 8 non-repeated displays. Repeated displays were generated prior to the experiment in order to implement different target densities across learning and test. This involved the creation of a set of 8 search displays with manually chosen target and distractor locations. Note that the same repeated displays were shown to individual observers. For the learning phase, items were positioned so as to have exactly 2 distractors in the 8 cells in the immediate surround of the target location (Fig. 1). For the test phase, item locations were chosen to have 3 or 1 distractors in the target's neighboring cells, corresponding to the dense and sparse conditions, respectively. From the 8 repeated displays in learning, 4 became dense and the other 4 sparse displays in the test phase. There were three further restrictions in determining target locations: (i) The target was never presented in the four central locations or in the corners of the display matrix. (ii) Targets were presented equally often in each of the four display quadrants in each experimental phase (learning, test) and display condition (repeated, non-repeated display). (iii) The average distance of targets from the display center was held constant at 3.5° across the four display type (repeated, non-repeated displays) x session (learning, test) conditions.

2.4.2 Results and Discussion

Accuracy

Overall response accuracy was 98.2%. A repeated-measures ANOVA on the error rates with the factors phase (learning vs. test) and display type (repeated vs. non-repeated displays) revealed the main effect of phase to be significant, $F(1,12)=4.89$, $p<.05$, $BF_{10=}0.19$: error rates were slightly lower in the learning than in the test phase (1.6% vs 2.0%).

RT performance

RTs in the learning phase were again collapsed into four epochs, with each epoch representing an average of six consecutive blocks, so as to obtain reasonably stable RT estimates. For the test phase, contextual cueing was assessed by comparing RTs in dense and, respectively, sparse repeated displays against RTs from (in terms of density) comparable non-repeated displays, that is: for the non-repeated condition, only a subset of RTs was included in the analysis dependent on whether the target was embedded in a dense or a sparse local context (3 vs. 1 distractors). RTs were thus collapsed across all blocks of the test phase.

For the learning phase, a 2 x 4 repeated-measures ANOVA with the factors display type (repeated, non-repeated) and epoch (1-4) revealed the main effects of display type, $F(1,12) =49.34$, $p<. 01$, $BF_{10}=3.93$, and epoch, $F(3,36)=19.66$, $p<.01$, $BF_{10} =2.44$, to be significant. The interaction was borderline-significant, $F(3,36)=2.77$, $p=. 05$, $BF_{10} =0.80$, indicative of an increase in the gain from contextual cueing over the course of the learning phase (from epoch 1: 73 ms to epoch 4: 128 ms). The mean cueing effect was 107 ms, demonstrating that participants formed robust contextual memories in the first phase of the experiment (Fig. 2C).

For the test phase, a 2 x 2 repeated-measures ANOVA with the factors local context (dense, sparse) and display type (repeated, non-repeated) revealed the main effect of local context to be significant: $F(1,12) = 47.92$, $p<.01$, $BF_{10}=3.18$: RTs were overall faster for dense than for sparse displays: 812 vs. 946 ms. Furthermore, and most importantly, the display type x local context interaction was significant, $F(1,12) = 34.03$, $p<.01$, $BF_{10}=3.40$, with contextual cueing being stronger for sparse than for dense displays (145 vs. 4 ms; see Fig. 2C).

This result clearly supports the *local-grouping hypothesis*, assuming a competitive relationship of attention guidance from contextual cueing and spatial grouping. In the presence of local grouping cues (distractor-dense condition), visual search is relatively effectively guided towards the target location (region) by these cues, leaving relatively little time for the in-depth processing of and adaptation to relocated displays. By contrast, in the absence of local grouping cues (distractor-sparse condition), visual search is to a large extent driven by long-term memory of repeated search arrangements, importantly, also including guidance from adapted context representations.

However, the above analysis also showed that RTs were significantly faster in the dense condition, which may be taken to suggest that mere response speed, rather than spatial inter-element grouping, modulates contextual cueing adaptation. For instance, it is possible that RTs in the distractor-dense condition leave no room for the modification of context memory.

This idea presupposes that context-based guidance of visual search will never manifest in the presence of local grouping cues at fast RTs. To test this, in Experiment 3, we examined contextual cueing in two new conditions. Here, distractor-dense and distractor-sparse contexts were introduced already in the initial learning phase. Under these conditions, it was possible to examine the impact of response speed particularly on the initial acquisition of context memory. If contextual cues can be established only with relatively slow RTs, then we expected a reliable cueing effect only in the distractor-sparse condition. If, however the build-up of cueing is relatively independent of response speed, and thus the time available for processing the repeated displays is critical only in the adaption of context cues, then RT advantages due to contextual cueing should be observed in both the distractor-dense and the distractor-sparse condition.

Recognition Test

Mean d prime was .13, which was not significantly different from zero, $t(12) =0.81$, $p=.43$, $BF_{10}<0$, suggesting that observers were unable to explicitly recognize repeated displays.

2.5 Experiment 3 (density at learning)

Experiment 3 was carried out to examine the alternative explanation that the original build-up of context memory, rather than the adaptation of an existing context representation, may occur only when there is enough time for the visual search, and contextual cueing, to evolve. If this alternative hypothesis is correct, then distractor-dense displays should produce hardly any contextual cueing effect during the initial learning of target-distractor arrangements.

2.5.1 Method

The method of Experiment 3 was essentially similar to Experiment 2, except for the following differences.

Participants and Setup

A total of 13 new observers took part in this experiment (7 female; mean age: 26.6 years, sd: 4.02 years).

Stimuli and Design

Participants performed a single ‘learning’ session of 24 blocks of 16 trials each, yielding a total of 384 trials. A given block contained 8 repeated and 8 non-repeated trials. Among the repeated trials, half were distractor-dense and half distractor-sparse displays. The learning session was followed by a recognition test of 1 block of 16 trials.

2.5.2 Results and Discussion

Accuracy

Overall response accuracy was 98.7%. A repeated-measures ANOVA on the error rates with the factors epoch (1-4) and display type (repeated, non-repeated displays) revealed no effects, all *F’s <.1,* $BF_{10} < 1$.

RT performance

A 2 x 2 repeated-measures ANOVA with the factors local context (dense, sparse) and display type (repeated, non-repeated display) revealed the main effect of local context to be significant, *F*(1,12) =85.14, p<.001, BF_{10}=17.20: RTs were again faster for dense than for sparse displays: 969 vs. 1219 ms. Furthermore, the main effect of display type was significant, F(1,12)=36.30, p<.001, BF_{10}=2.38, with repeated displays giving rise to faster responses than non-repeated displays (1034 ms and 1149 ms). The display type x local context interaction was only borderline-significant *F*(1,12) =3.28, p=.09, BF_{10}=25.25, though the large BF_{10} value provides support for the hypothesis that contextual cueing has a lesser effect in dense than in sparse displays: 90 vs. 140 ms, respectively. This result pattern indicates that contextual cueing is not per se limited by the presence of local grouping cues: the cueing effect of 90 ms with relatively fast RTs was reliably larger than zero, *t*(12)=6.01, p < .01, BF_{10}=8.29. On the other hand, the cueing effect was reduced to some extent with faster as compared to slower search performance (i.e., for the distractor-dense vs. the distractor-sparse condition). Overall, this pattern of effects may be taken to suggest that spatial grouping is detrimental to contextual cueing, with the effect being most marked in the adaptation of (already) learned contextual cues.

Recognition Test

Mean d prime was .23, which was not significantly different from zero, t(12) =0.88, p=.39, BF_{10}=.38, suggesting that observers could not reliably tell apart repeated from non-repeated layouts.

2.6 Experiment 4 (density at test, new learning)

Experiment 3 showed reaction time facilitation for distractor-dense displays suggesting that processing time per se is not the limiting factor in context learning, but may be of particular importance for successful adaptation of previously learned contextual cueing displays. The requirement to spend a sufficient amount of time with the changed display may arise because of the high similarity between the original and relocated displays (see General Discussion for a more in-depth discussion of this idea). A prediction that follows from this proposal is that dense displays should generate a reliable contextual cueing effect even if these displays are shown only later in the experiment. To this end, Experiment 4 implemented a variant of the contextual cueing task which presented two entirely different sets of repeated displays during the learning and test phase (see, e.g., Jiang et al. 2005; Zellin et al., 2013). Under these conditions, no interference should arise between the original and the novel set of displays because these displays would differ in terms of their underlying memory representations. As a result, a reliable cueing effect should again emerge even for the distractor-dense displays in the test session. This hypothesis was tested in Experiment 4.

2.6.1 Method

The method of Experiment 4 was essentially similar to Experiment 2, except for the following differences.

Participants and Setup

A total of 13 new observers took part in this experiment (8 female; mean age: 27.1 years, sd: 4.25 years).

Stimuli and Design

Participants performed ‘learning’ and ‘test’ sessions of 24 blocks of 16 trials each, with a total of 768 trials. In the learning session (which was identical to Experiment 2), in each block, participants encountered 8 repeated and 8 non-repeated displays with the target item always being surrounded by 2 distractor items. Target positions were different for repeated and non-repeated displays. During test, again 8 repeated and 8 non-repeated displays were shown in a given block of trials. Half of these displays were distractor-dense and the other half distractor-sparse displays, with the target surrounded by either 3 or 1 distractors, respectively. Unlike Experiment 2, observers were presented with different sets of repeated displays (and target positions) in each phase. Participants received one set of repeated contexts in the training phase (density level: 2) and another set in the test phase (density levels: 3, 1). At the end of the experiment, participants performed a recognition test of one block of 16 trials, which presented the 8 repeated displays from the test session and 8 newly generated random layouts.

2.6.2 Results and Discussion

Accuracy

Overall response accuracy was 98.6%. A repeated-measures ANOVA on the error rates with the factors phase (learning vs. test) and display type (repeated, non-repeated displays) revealed no effects, all $F's <1, BF_{10} < 1$.

RT performance

For the learning phase, a 2 x 4 repeated-measures ANOVA with the factors context (repeated, non-repeated displays) an epoch (1-4) revealed main effects of display type, $F(1,12)=42.97$, $p<.001$, $BF_{10}=10.85$ and epoch, $F(3,36)=7.36$, $p<.001$, $BF_{10}=0.10$, suggesting an emerging contextual cueing effect in the learning phase. The display type main effect shows a reliable contextual cueing effect of 89 ms.

In the test phase, RT performance was analysed my means of a 2 x 2 repeated-measures ANOVA with the factors local context (dense, sparse) and display type (repeated, non-repeated display). This ANOVA revealed the main effects of local context, $F(1,12)=80.01$, $p<.001$, $BF_{10}=2.80$, and display type, $F(1,12)=28.92$, $p<.001$, $BF_{10}=0.67$, to be significant. Further, the local context x display type interaction was borderline significant: $F(1,12) =3.75$, $p=.07$, $BF_{10}=0.71$. Concerning the main effect of local context, RTs were faster for distractor-dense than distractor-sparse displays: 912 vs. 1030 ms. The main effect of display type indicated that there was a reliable cueing effect of 75 ms overall in the test session. The (borderline significant) interaction was due to the fact that contextual cueing scores were reduced in distractor-dense compared to distractor-sparse displays: 64 ms and 85 ms, respectively. However, and as confirmed by direct t-tests, the RT difference between repeated and non-repeated contexts was highly reliable for both types of display (p's $< .01$). The results of Experiment 4 thus further confirm Experiment 3 in showing that distractor-dense displays do not per se hinder that contextual cueing emerges, even if these displays are shown only during later phases of the search experiment.

Recognition Test

Mean d prime was in Experiment 4 was .13, which was not significantly different from zero, $t(12) =0.47$, $p=.64$, $BF_{10}=.30$, suggesting that observers could not reliably tell apart repeated from non-repeated arrangements.

2.7 General Discussion

The present experiments investigated the adaptation of long-term memory for target-distractor associations (Chun & Jiang, 1998). Previous research showed that while contextual cueing is of high capacity (Jiang et al., 2005) and is considered a genuine form of effortless, nonconscious, learning (Colagiuri & Livesey, 2016), the memory underlying the cueing effect is quite resistant to forming an association between a new target location and an existing distractor representation. This ‘lack of adaptation’ was replicated in Experiment 1 and in various other experiments conducted in the course of our research (see Fig. 3). In Experiment 2, variations of local contexts were induced by carefully controlling the placement of the target before and after target location changes (see Fig. 1). We observed that distractor-sparse contexts gave rise to robust adaptation of contextual cueing, while distractor-dense contexts did not. Further, mean RTs were faster overall for dense displays, suggesting that bottom-up search towards a dense target region conflicts with adaptation of learned contextual cues in these regions. Experiments 3 and 4 revealed that the lack of adaptation with dense displays was not due to a floor effect, that is, the overall faster RTs to displays with distractor-dense contexts. Moreover, across all three experiments, explicit recognition of repeated displays was not different from chance level, suggesting that observers had little explicit knowledge of the repeated displays.

2.7.1 Lack of adaptation of contextual cueing revisited

These findings provide evidence for the view that contextual cueing is an adaptive mechanism that is not per se restricted by order effects in context learning (with an overall advantage of early relative to late trials; see Junge et al., 2007). Further, they appear to be at odds with Zellin et al. (2014), who found adaptation of contextual cueing only after massive amounts of training with the ‘relocated’ displays. However, Zellin et al. did not control for local item density – a manipulation that was central to the current experiments. It is thus possible that (fast) adaptation did take place in prior studies but was statistically reduced by local distractor density effects.

In the present study, local item density interacted with contextual cueing in two ways: First, sparse contexts produced a reliable contextual adaptation; second, dense contexts interfered with the adaptation of contextual cues. The fact that RTs were overall faster for dense displays demonstrates that the interference is likely due to attention capture by dense regions, facilitating the detection of the target when it is present in such a region, as was the case in the present experiment. Cueing then is effectively bypassed by stimulus-based, bottom-up factors. By contrast, memory-based cueing can come into play when search is more effortful and time-consuming, that is, when search is not immediately summoned to the target region based on display density factors. In this case, associations may be retrieved from memory and come to guide search. But again, for adaptation of a relocated target, this is only effective when the repositioned target is not located within a dense region.

Evidence for this proposal is provided by the findings that contextual cueing was smaller with dense than with sparse displays (though still reliable for the former) when these displays were presented in the initial learning phase or when a new set of repeated displays was shown in the test phase (after initial learning; Experiments 3 and 4, respectively). In addition, contextual cueing was absent in dense displays during test, when context memory about these displays had already been established during the learning phase (Experiment 2). Given these findings, it appears that the differences in contextual cueing with dense displays across learning and test are quantitative, rather than qualitative, in nature. In both phases, dense regions attract attention and thus shorten the time for in-depth processing of the display arrangements, including the detection and subsequent learning of target-distractor relations in these displays. Such temporal restrictions may be particularly harmful for the adaptation of contextual cueing, given that the re-learning of a changed, but relative to the original display highly similar, display would require extended processing time to encode the new target-distractor relations (recall that only the target position differs between the original and the changed displays). However, since processing times are relatively short for dense displays, due to the effective capture of attention by the dense region, this counteracts the build-up of a new memory representation of the changed target position in relation to the previous (and unchanged) distractor positions.

Overall, this pattern resembles relatively recent work on contextual cueing in feature-singleton search (e.g., Ogawa & Kumada, 2008; Geyer, Zehetleitner, & Müller, 2010), showing that contextual cueing can also be observed for these relatively fast ('pop-out') searches, but requires time to become effective. In these studies, the feature-singleton displays were preceded by placeholder displays (presented for some 700 ms), with the placeholders marking the locations of the subsequent search items, without providing information as to their identities (as distractors or target). The cueing effect was observed only under these 'pre-view' conditions.

2.7.2 Adaptation, recognition, and crowding

Although it is theoretically appealing to argue that spatial grouping plays a significant role in contextual cueing adaptation, there are other possible accounts that need to be considered: pattern recognition and crowding.

Concerning the former, it is possible that re-positioning the target across learning and test may have differentially changed the appearance of the display, making the original context either more or less recognizable. Given that the context-based guidance of visual search requires the activation of corresponding memory representations, it is conceivable that a small change in the position of one item may impact the display appearance and thus the recognition of changed displays. Assuming that dense contexts provide stronger cues for retrieving the originally learned configuration (e.g., because attending to a dense region, of three distractors, may more robustly trigger an originally learned spatial memory representations than attending to a sparse context, of only one distractor), this could explain why adaptation of contextual cueing failed with dense displays. – However, this idea is from our point of view potentially unlikely because it is not clear whether targets surrounded by 2 distractors in the originally learned configurations are actually better recognizable targets in dense displays (with 3 surrounding distractors). Instead, re-locating the target to a dense region may make the changed display actually less similar to the original display, than when relocating the target to a sparse region. This may occur because the target location change modifies the display summary statistics such as the display items' center of mass (e.g., Alvarez & Oliva, 2008) towards the dense region. The latter would actually predict the opposite outcome, namely, that contextual cueing should recover for dense displays after the target location changes. Of interest in this regard, Manginelli and Pollmann (2009) found that, following target location changes in a contextual cueing adaptation task, RTs can actually be even slower to repeated than to non-repeated displays – which they attributed to a 'misguidance' of attention towards the originally learned target location. If a dense context was more 'reminiscent' of the original configuration, this would imply that focal attention tends to be misguided to the 'wrong' – that is: the originally learned – target location, where this misguidance would require a corrective, time-consuming shift of attention to the changed target position and thus increase RTs. But this is not what we observed: in fact, mean RTs were overall faster for dense than for sparse displays, suggesting that attention was effectively captured by the dense region. For this reason, we argue that our findings are better explained by a spatial grouping account

A second alternative account of the present findings may be in terms of 'crowding', that is, a deterioration of performance for targets that appear in a dense (i.e., cluttered or 'crowded') display region (e.g., Whitney & Levi, 2011) due to a loss of visual resolution in peripheral vision for such items. Applied to contextual cueing, for dense local contexts, crowding may impede target detection, which in turn could interfere with the adaptation of contextual cues. For instance, crowding may require search to operate with a narrow, item-based focus of attention, impeding the encoding and thus the re-learning of local target-distractor relations (cf. Lleras & von Mühlenen, 2004). However, this account too encounters a difficulty: crowding should not only reduce contextual cueing but also slow search, that is, result in longer RTs overall. However, RTs were actually faster, rather than slower, for dense displays in Experiments 2 to 4 of the present study.

2.7.3 Grouping and contextual cueing

We propose that the absence of contextual cueing in combination with fast RTs for dense displays is better explained by spatial grouping and its role in the guidance of attention, importantly also including perceptual long-term learning. This view complements previous ideas that propose a central role for grouping processes in visual search. For instance, Duncan and Humphreys (1989, 1992; see also Humphreys & Müller, 1993), in their attentional engagement theory, propose that the output representations of an early, preattentive coding stage (so-called ‘structural units’) are formed through the operation of basic grouping processes (notably grouping based on similarity, but also proximity, etc.). Structural units then compete for access to visual short-term memory, which is thought to be equivalent to the deployment of attention. Attentional engagement theory thus equates the efficiency of visual search with the efficiency of visual grouping (and segmentation) processes: the better the inter-element grouping – of the target and the distractors into separable target and non-target groups – the faster the selection of the target group. Besides bottom-up grouping processes, Duncan and Humphreys (1989, 1992) allowed for top-down – ‘template’-based – influences on visual selection, i.e., a top-down enhancement of items sharing features specified in the target template. The present study investigated one variant of such a top-down effect: long-term memory of (consistently encountered) target-distractor spatial relations, which may act as a specific form of ‘search template’, guiding attention more effectively to the target location. Our results show that both stimulus- (grouping) and memory-based (contextual cues) factors are available to guide visual search, where the contribution of context memory however is dependent on the efficiency of spatial grouping processes (see Feldmann-Wüstefeld & Schubö, 2014; and Conci & von Mühlenen, 2011, for a related proposal, albeit investigating feature-based grouping in contextual cueing).

This relationship is best explained by theories assuming a reciprocal relationship between bottom-up attention and memory (e.g., Logan’s, 1988, instance theory of automaticity; see also Jiang & Leung, 2005, or Annac et al., 2013, for evidence of the effects of attention – both in terms of selectivity and processing resources deployed – on contextual cueing). At the heart of these proposals is the idea that repeated encounters of visual search displays lead to the build-up of memory about these displays, with the memory representation, in turn, facilitating detection performance. However, the present results qualify this relationship in that the effects of bottom-up attention on memory formation turned out to be highly specific, with a crucial difference depending on whether memory is established initially or whether an existing memory representation is updated to incorporate a changed target position into it. Only in the latter case did fast, bottom-up search processes interfere substantially with contextual cueing.

Note that our suggestion that context memory requires time to be adapted is essentially consistent with other studies on the effects of grouping on contextual cueing. For example, Feldmann-Wüstefeld and Schubö (2014) manipulated the featural (color, orientation) identity of the background distractors and found that an increase in similarity (or in their terms homogeneity) of the distractors can enhance contextual cueing (see also Conci & von Mühlenen, 2011). While this facilitatory effect of grouping on contextual cueing may in the first instance be difficult to reconcile with the current findings, a striking difference between Feldmann-Wüstefeld and Schubö (2014) and the present investigation is that of the time, or experimental phase, when the grouping manipulation was applied. While Feldmann-Wüstefeld and Schubö (2014) investigated grouping effects in the (initial) learning of context cues, here we addressed the issue of grouping effects in the adaptation of contextual cueing. In fact, spatial grouping during initial learning (Experiment 3) did not interfere with contextual cueing (though it was smaller with dense compared to sparse displays). Furthermore, it is possible that different forms of grouping vary in their effects upon contextual cueing (Conci & von Mühlenen, 2011). Assuming that grouping expedites visual search (Duncan and Humphreys 1989), for grouping by proximity this may come along with the disadvantage of observers having less time to encode and subsequently learn target-distractor associations. This could have reduced the contextual cueing effect with dense displays in learning and effectively interfered (abolished) the adaptation of the cueing effect in the test phase. By contrast, feature-based grouping (investigated by Feldmann-Wüstefeld & Schubö, 2014), though effectively boosting visual search, may reinforce the impression of a coherent ensemble of distractor items and thus effectively enhance target-distractor learning in repeated displays. Whatever the explanation, together, these studies suggest a role of grouping in contextual cueing. However, whether grouping facilitates or interferes with contextual cueing may be dependent on the type of grouping (spatial proximity versus featural grouping) and / or the experimental phase when grouping is administered (learning versus adaptation of contextual cueing). This might be an avenue for future research.

2.8 Conclusion

In conclusion, the present results show that contextual adaptation occurs more readily when the number of distractors surrounding the target is low. This rules out factors such as order effects in perceptual learning or a temporally sluggish re-learning process in the adaptation of learned target-distractor arrangements. Instead, the results suggest that one important factor for the lack of adaptation found in previous contextual cueing studies is spatial grouping, effectively guiding attention towards grouped regions, and thus limiting the time for processing the changed displays in order to bring into play existing target-distractor representations. The more general implication is that ‘Gestalt’ factors relating to display design are crucial in investigations of contextual cueing in visual search. Future work should take this into consideration when interpreting context-based learning in visual search.

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2.10 Acknowledgements

This research was supported by Deutsche Forschungsgemeinschaft (DFG) Research Grants (GE 1889/3-1 and CO 1002/1-1). Correspondence concerning this article should be addressed to: Efsun Annac, Ludwig-Maximilians-Universität München, Department of Psychology, Leopoldstraße 13, 80802 München, Germany (email: Efsun.Annac@psy.lmu.de).

2.11 Appendix

Additional analyses were performed to investigate the development of contextual cueing in the learning and test phase while also taking into account observers who displayed a negative contextual cueing effect initially and effective learning of re-located target in the later test session. To this end, our complete samples of N=20, 14, and 14 observers in Experiments 1, 2, and 3, respectively were included in the subsequent analysis (Note that in Experiment 4, no observers were excluded and hence, no additional analyses are reported).

For experiment 1 (with 7 'late' learners), a 2 (display type: repeated, non-repeated) x 8 (epoch: 1-4 in learning; 5-8 in test) x 2 (phase: learning, test) repeated-measures ANOVA revealed main effects of display type, $F(1,19) = 12.28$, $p<.01$, $BF_{10}=0.23$, and epoch, $F(3,57) = 32.58$, $p<.01$, $BF_{10}=0.36$, in addition to a significant epoch x phase interaction, $F(3,57)=5.90$, $p<.01$, $BF_{10}=0.08$. The context x epoch x phase interaction did not reach significance, $F(3,57)=1.71$, $p=.17$, $BF_{10}=0.00$. Separate 2 x 4 repeated-measures for the learning and test phase revealed a borderline-significant effect of display type, $F(1,19) = 3.79$, $p=.06$, $BF_{10}=0.18$ and a significant main effect of epoch, $F(3,57) = 22.53$, $p<.001$, $BF_{10}=0.15$. The epoch and context interaction was not significant, $F(3,57) = 0.25$, $p=.85$, $BF_{10}=0.02$. For the test phase, the 2 x 4 repeated-measures ANOVA yielded a significant main effect of display type, $F(1,19)=5.26$, $p=.03$, $BF_{10}=0.02$ and epoch, $F(3,57)=7.04$, $p<.001$, $BF_{10}=0.22$. Interestingly, the epoch and context interaction was also significant, $F(3,57) = 2.79$, $p<.05$, $BF_{10}=0.00$, suggesting that the N=7 observers with initial negative cueing effects display very high learning of re-located targets, leading to a reliable contextual cueing effect in the test session at the level of the entire sample.

In an attempt to further examine the hypothesis that observers who lack a contextual cueing effect initially develop a reliable effect later on, we performed a correlation analysis, comparing individual contextual cueing scores in the learning and test session (across the 20 observers in Experiment 1, given that this experiment contained the largest number of observers with initial negative cueing). Specifically, we predicted a significant negative correlation between contextual cueing values for two reasons: 1) contextual cueing, established during learning, should lead to relearning deficits at test (i.e., lack of adaptation effect; N=13 observers in Experiment 1); 2), a failure to develop a contextual cueing effect during learning should be followed by a solid cueing effect in the subsequent test session (i.e., a late learning effect; N=7 observers in Experiment 1). The results confirmed this prediction. Quantifying the relationship between contextual cueing scores across the training and test phases of Experiment 1 revealed a significant negative correlation: *r*(20) = -.44, p=.05, confidence interval: -.74 to .01.

For Experiment 2, a 2 x 4 repeated-measures ANOVA performed on the entire sample of N=14 observers with the factors display type (repeated, non-repeated) and epoch (1-4) revealed a reliable contextual cueing effect in the training phase (74 ms-effect; main effects of display type, F(1,13) =33.76, p<. 001, BF_{10}=15.39), in addition to a reliable main effect of epoch, F(3,39)=19.98, p<.001, BF_{10} =0.16. Further, the interaction was significant, F(3,39)=4.19, p<. 05, BF10 =3.07. For the test phase, contextual cueing was reliable only for sparse, but not dense, displays (153 ms- and minus 16 ms-effects, respectively), as indicated by a 2 x 2 repeated-measures ANOVA with the factors local context (dense, sparse) and display type (repeated, non-repeated), which revealed the display type x local context interaction significant, F(1,13) =22.64, p<.01, BF10=18.66. Further, RTs were faster for dense than for sparse displays: 829 vs. 954 ms (main effect of local context: F(1,13) =17.27, p<.01, BF10=0.62.).

For Experiment 3, the 2 (local context) x 2 (display type) repeated-measures ANOVA performed in the learning phase revealed a main effect of display type, F(1,13)=31.23, p<.001, BF10=0.56, indicating that mean RTs were on average faster for repeated than non-repeated displays (1067 ms vs 1146 ms) when analysing the entire sample of N=14 observers. Further, RTs were faster for dense than for sparse displays: 998 vs. 1215 ms and the display type x local context interaction was significant F(1,13) =47.39, p<.001, BF10=7.03, illustrating that contextual cueing was less pronounced in dense than in sparse displays: 88 vs. 141 ms, respectively.

In a final analysis, we analysed only the ‘excluded’ observers and compared their mean RTs for repeated and non-repeated contexts by means of paired-sample *t*-tests for each experimental phase (learning, test). This analysis was limited to Experiment 1, as this was the experiment with the largest number of (N=7) observers with negative contextual cueing scores in the learning session (and associated with this: differences in the results when either the data of a subset of observers or the entire sample was analysed; cf. above). For the N=7 ‘excluded’ observers in Experiment 1, RTs were slower, by 57 ms, for repeated compared to non-repeated contexts in the initial learning phases, $t(6) = 4.04$, $p < .01$, $BF_{10}=2.20$. Subsequently, however, significant contextual cueing, of 88 ms, was observed for relocated targets in the test phase, $t(6) = 5.00$, $p < .01$, $BF_{10}=3.00$. This pattern shows that contextual cueing can develop rather late and thus massively confound data regarding the adaptation of initially acquired target-distractor associations. Thus, in order to examine the ‘true’ adaptation of contextual cues, it is important to exclude observers with negative contextual cueing scores in the learning session.

Chapter 3:

Memory under pressure: secondary-task effects on contextual cueing of visual search (2013)

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3.1 Abstract

Repeated display configurations improve visual search. Recently, the question has arisen whether this contextual cueing effect (Chun & Jiang, 1998) is itself mediated by attention, both in terms of selectivity and processing resources deployed. While it is accepted that selective attention modulates contextual cueing (Jiang & Leung, 2005), there is an ongoing debate whether the cueing effect is affected by a secondary working memory (WM) task, specifically: at which stage WM influences the cueing effect: the acquisition of configural associations (e.g., Travis et al., 2013) vs. the expression of learned associations (e.g., Manginelli et al., 2013). The present study re-investigated this issue. Observers performed a visual search in combination with a spatial WM task. The latter was applied on either early or late search trials – so as to examine whether WM load hampers the acquisition of or retrieval from contextual memory. Additionally, the WM and search tasks were performed either temporally in parallel or in succession – so as to permit the effects of spatial WM load to be dissociated from those of executive load. The secondary WM task was found to affect cueing in late, but not early, experimental trials – though only when the search and WM tasks were performed in parallel. This pattern suggests that contextual cueing involves a spatial WM resource, with spatial WM providing a workspace linking the current search array with configural long-term memory; as a result, occupying this workspace by a secondary WM task hampers the expression of learned configural associations.

3.2 Introduction

Attention and memory interact in many ways. In recent years, the contextual cueing paradigm (Chun, 2000) has become a promising approach in cognitive psychology for studying the interactions between the two functions. Contextual cueing refers to the observation of faster reaction times (RTs) to targets presented in repeatedly encountered, relative to non-repeated, visual search displays. In a typical contextual cueing experiment, participants are presented with an array of items, one of which is the target and the others are distractors. Unbeknown to the observers, half of the displays contain repeated and the other half non-repeated item arrangements. Participants’ task is to detect and subsequently discriminate the orientation of the target letter, a left- or right-oriented “T”; the distractors are letters “L” in various orthogonal orientations. RTs are analysed as a function of display repetition and experimental “epoch”. The standard finding is that RTs become generally faster over the course (epochs) of the experiment – an effect reflecting non-configural, procedural learning. Importantly, this speeding up of RTs is more pronounced for repeated compared to non-repeated displays – an effect reflecting configural learning. Interestingly, when observers are asked to discern repeated from non-repeated displays in a recognition test performed at the end of the search experiment, they typically perform at chance level. This dissociation between RT and recognition measures has been taken to indicate that contextual cueing is supported by an implicit memory system (Chun & Jiang, 1998; see also Chun & Phelps, 1999, for evidence pertaining to this claim using amnesic patients, or Greene et al., 2007, using functional imaging). However, more recent investigations of the cueing effect using larger numbers of recognition trials, in addition to obtaining different recognition measures, have found that observers do actually have some explicit knowledge of repeated displays (Smyth & Shanks, 2008; Schlagbauer et al., 2012). Smyth and Shanks (2008) took this to suggest that contextual cueing is supported by a general memory system that is mediated by conscious processes.

Other research has shown that the configural memory underlying contextual cueing involves associations between the target location and the configuration formed by the distractors (Jiang & Wagner, 2004) – in particular, though not exclusively, associations of the target to individual distractors in its narrower vicinity (Olson & Chun, 2002; Brady & Chun, 2007). Another set of studies has shown that contextual cueing acts mainly by facilitating focal-attentional selection of the target item (Chun & Jiang, 1998; Johnson et al., 2007; Geyer et al., 2010a), though contextual cueing appears to also influence response selection (Kunar et al., 2007).

3.2.1 Selective and divided attention in contextual cueing

Many studies have argued for a gateway role of attention in conscious perception (Mack & Rock, 1998), explicit learning (Voss et al., 2008), and implicit memory (Jiang & Leung, 2005). Concerning the latter, studies of implicit learning that used the serial reaction time task (e.g., Nissen & Bullemer, 1987) have suggested a distinction between the learning of repeated information (i.e., acquisition of memory traces) and the expression of learned information (i.e., retrieval of memory traces; see also Frensch et al., 1998). More recently, Jiang and Leung (2005; see also Jiang & Chun, 2001) demonstrated the distinction between learning and the expression of learning also for contextual cueing. In more detail, Jiang and Leung (2005) had observers detect and subsequently discriminate the orientation of a black "T", presented amongst black and white "L's". In Jiang and Leung's terms, the black L's were the attended or target set distractors and the white L's the ignored or non-target set distractors. The experiment was divided into training and a test phase. At the intersection of the two phases, the colors of the distractors were swapped: the black L's became white and the white L's black. There were three repetition conditions (with "repetition" referring to the spatial arrangement of the items): repetition of both target and non-target set distractors ("both-old" condition), of only target set distractors ("attended-old" condition), or of only non-target set distractors (“ignored-old” condition). Contextual cueing effects were assessed by comparing RTs in these three (repetition) conditions to RTs in a non-repeated (“both-new”) condition. In the learning phase, contextual cueing was found to manifest in the both-old and attended-old, but not the ignored-old, conditions. Interestingly, the magnitude of contextual cueing was comparable between the both-old and attended-old conditions, suggesting that the cueing effect (in the both-old condition) was due to repetition of the attended context alone (see also Geyer et al., 2010b, for an influence of color-based grouping on contextual cueing). However, in the test phase (i.e., after the swapping of the distractor colors), contextual cueing was observed only in the ignored, but not the both-old and attended-old, conditions. Jiang and Leung (2005) concluded from this pattern that contextual memory is formed independently of (feature-based) attention – as evidenced by reliable contextual cueing in the ignored-old condition, importantly, already at the start of the test phase (this fact indicates that the locations of the to-be-ignored distractors had been successfully learnt in the training phase); by contrast, the expression of learnt target-distractor configurations is under the control of selective attention – as evidenced by significant cueing effects in the both-old and attended-old condition in the learning phase and contextual cueing in the ignored-old condition in the test phase.

The notion of attention-independent configural learning was examined further by Vickery et al. (2010), who tested whether contextual cueing is affected by a secondary working memory (WM) task – based on the idea that if contextual cueing and the secondary WM task share common processes, or draw on common resources (Kahneman, 1973), they would interfere with each other when performed in combination. A related idea is to conceive of WM as an integral part of long-term memory (Cowan, 1999). Applied to contextual cueing, there would also be a functional overlap between the long-term memory underlying contextual cueing and WM – as evidenced by recent neuroscientific studies that revealed the two forms of memory to be linked within a common neural structure: the medial temporal lobes (e.g., Chun & Phelps, 1999; Geyer et al., 2012; Axmacher et al., 2007). On this background, Vickery et al. surmised that if contextual cueing is dependent on (e.g., spatial) WM – for example, because WM is necessary for strengthening associations between the target and nearby distractors (Brady & Chun, 2007) – then a secondary WM task should attenuate contextual cueing. Alternatively, or in addition, it is possible that dividing attention between two similar tasks may introduce difficulties in representing – that is, in the color-based selection of – the target set of items (Jiang & Leung, 2005), which may attenuate the cueing effect. Finally, it is possible that the secondary WM task depletes central resources for search task execution, attenuating contextual cueing. To decide between these alternatives (in particular, spatial vs. color-based WM load effects), Vickery et al. (2010) examined whether WM for spatial arrays, colors, item sequences, etc. would interfere with contextual cueing. However, they actually found contextual cueing to be unaffected by any of the additional WM tasks – which led them to conclude that the cueing effect is not impacted by divided attention.

3.2.2 Spatial, not featural, WM affects the retrieval of contextual cueing

Following Vickery et al. (2010), a number of studies re-investigated the relation between contextual cueing and the performance of a secondary WM task. One limitation of Vickery et al. was that they tested contextual cueing only under single-task conditions, that is, after observers had learned the repeated displays in a dual-task phase. Thus, they could only examine whether the learning of contextual cues is affected by secondary WM load – their results suggest that it is not – but not whether the retrieval of learned information is dependent on WM. For example, as elaborated above, Jiang and Leung (2005) have shown that selective, feature-based attention modulates the retrieval of (previously acquired) configural associations; that is, only the selected items are represented in WM (e.g., Bundesen, 1990) and thus provide effective retrieval cues for stored associations. Given this, it is possible that the addition of some specific type of secondary WM task in a ‘late’, test phase of a contextual cueing experiment would interfere with the retrieval from long-term, configural memory.

This hypothesis was tested in a series of follow-up studies (Manginelli et al., 2013; Travis et al., 2013). The general approach taken in these studies was to divide the experiment into a learning phase (e.g., trials 1-360 in Manginelli et al.) and a test phase (trials 361-480). Importantly, in Manginelli et al. (2013), the search task was combined with a secondary WM task that was applied in either the training or the test phase. The results revealed reliable contextual cueing when the WM task was administered in the learning phase – a result compatible with Vickery et al. (2010), but not when administered in the test phase. Interestingly, Manginelli et al. (2013; see also Manginelli et al., 2011) investigated the effects of both featural (i.e., color-related) and spatial WM tasks (between-subject manipulation), but found only the latter task to interfere with contextual cueing. Manginelli et al. took this to mean that the expression of learned target-distractor associations is mediated by spatial WM. However, the results of Manginelli et al. (2011, 2013) were only partially supported by Travis et al (2013), who found that a spatial WM task can also interfere with the acquisition of contextual associations in the learning phase (we will return to this study in the General Discussion). At the first glance, these results seem to conflict with those of Manginelli et al. However, there are also some critical differences between the studies, such as the type of spatial WM task employed or observers experience with visual search in general, which complicate any comparisons and conclusions derived from these. Given this, it remains an open issue whether WM influences the learning of configural information or whether a secondary WM task interferes with the retrieval of learned target-distractor associations from long-term memory.

3.2.3 The present study: interference from spatial and executive WM

The above-reviewed evidence of secondary WM tasks attenuating contextual cueing raises the question as to where the WM interference effects actually arise. In the present study, we draw a distinction between the potential role of spatial and executive WM functions in contextual cueing. The results of Manginelli et al. (2013) strongly suggest that the search and WM tasks compete for *spatial* WM functions; for instance, contextual cueing might be contingent upon loading a set of learnt spatial associations from long-term memory into WM in order to guide visual search. On this assumption, WM provides the “workspace” that permits information stored in configural long-term memory to be linked with information contained in the search display. At the same time, however, the secondary task and contextual cueing may also draw on a common pool of *central-executive* WM functions, giving rise to interference because the addition of a secondary task would increase the demands for optimally ‘sharing’ a limited-capacity *spatial* WM resource between the two tasks. This is predicated on the assumption that executive load is a function of the degree to which the dual tasks to be performed draw on a *common*, *specific* WM resource (e.g., Pashler, 1994) [Footnote 1].

Of particular relevance in this context are findings from Lavie et al. (2004), showing separate effects of concurrent WM load and dual task coordination demands in a selective attention – namely, a variant of the ‘Eriksen flanker’ (Eriksen & Eriksen, 1974) – task. In more detail, Lavie et al. combined the attention task with a concurrent verbal WM task. There were two conditions: “high” versus “low” WM load, with observers having to maintain six digits versus only one digit in WM while performing the attention task. In the latter task, observers responded to the identity of a letter at the center of the display (e.g., “x” vs. “z” mapped to the left vs. the right hand), which additionally included a second (flanker) letter in the periphery: a distractor that was either compatible (e.g., a peripheral “X” in the presence of a central “x”), incompatible (e.g., “Z”), or neutral (e.g., “N”) with respect to the target letter.

Typically, RTs to the target are faster with compatible, and slower with incompatible distractors relative to the neutral condition, suggesting that observers cannot effectively ignore the (task-irrelevant) distractor letter. Of note, in their Experiment 1, Lavie et al. (2004) found greater distractor interference (RT incompatible minus RT compatible distractor) in conditions of high versus low working memory load. Interestingly, distractor interference was also greater under dual relative to single task conditions, even when the WM task was performed prior to the flanker task (Experiment 4: “high” WM condition), so that the ‘phonological loop’ component of WM (e.g., Baddeley, 2003) was free at time of the attention task. Moreover, when the WM and attention tasks were temporally segregated, greater distractor interference for dual relative to single task conditions was also found when the demands on WM were minimal (Experiment 5: “low” WM condition). Most importantly, under conditions of temporal segregation, the distractor interference was comparable in magnitude between the “high” and “low” WM demands (comparison between Experiments 4 and 5; Lavie et al., 2004, p. 351). With regard to contextual cueing, this pattern of findings would support the view, outlined above, that (1) secondary WM tasks (non-spatial as well as spatial) do interfere with the attention task and that (2) the requirement for dual task coordination (i.e., executive control) is a chief factor in regulating performance in the attention task [Footnote 2].

Importantly, these considerations concerning the role of spatial versus executive WM functions in contextual cueing go beyond what has been shown previously. A closer look at Manginelli et al. (2013) reveals that contextual cueing was actually reduced in the presence of both a featural and a spatial WM task, although the reduction was reliable only with the spatial task. The (numerical) decrease of contextual cueing under featural WM conditions may be taken to suggest that context effects are generally dependent on executive WM functions, too, although, for the reasons elaborated above, executive resources may be particularly challenged when the two tasks draw on a common, spatial WM resource. On this background, the present study was designed to disentangle the role(s) of spatial versus executive WM functions in the contextual cueing of visual search.

To this end, in the current experiments, we combined a visual search with a concurrent spatial WM (sWM) task. The secondary sWM task was applied either early (early trials) or late (late trials) during search performance, to permit secondary task effects to be re-examined on the acquisition and, respectively, retrieval of search-guiding configural information (Manginelli et al., 2013). However, our main focus was on whether WM interference effects on contextual cueing are solely due to spatial WM load or to executive WM load. To investigate this, one group of observers had to maintain a spatial pattern in WM while performing the visual search task (Experiments 2c, 2d). For another group of observers, the sWM task did not overlap with, but instead was performed immediately after (Experiments 2a, 2b) or before (Experiments 3a, 3b) the search task. Thus, only in the "while" group was the spatial (and executive) short-term memory resource occupied during the search task. In contrast, in the "after" and "before" groups, sWM was not occupied at the time observers performed the search task. Thus, the "after" and "before" conditions imposed only demands on dual-task coordination (Lavie et al., 2004). Based on the findings of Manginelli et al. (2013), we assumed that the sWM task hampers retrieval from configural memory. This would lead to two interesting predictions: (1) contextual cueing should be reduced under dual task conditions in a late test phase, that is, after the effect has been reliably developed under single task conditions in an early training phase. (2) Conversely, contextual cueing should become manifest under single task conditions in the test phase, even when the sWM task was paired with the search task in the training phase. Regarding the effects of spatial versus executive WM load, we hypothesized that if sWM interference effects are due to increased demands for scheduling multiple tasks (executive-load hypothesis), the addition of the secondary sWM task should reduce contextual cueing in all (i.e., the "while", "after", and "before") groups – because in all groups, observers would at least have to coordinate the two tasks. By contrast, if secondary task effects are due to increased sWM demands (spatial-load hypothesis), the cueing effect should be reduced particularly for observers in the “while“ group – because only in this group are the two tasks performed concurrently and the secondary task could take away spare WM capacity required for contextual cueing.

3.3 General Method

The present study comprised of seven experiments (see Table 1 and Figure 1). Each experiment was divided into three epochs of training and one epoch of test. Each epoch included five blocks of 24 search trials each. Experiment 1 served as the “baseline” condition, including only search trials, against which we compared contextual cueing in the other, “dual task” Experiments: 2a, 2b, 2c, 2d, 3a, 3b. In doing so, first we computed mean contextual cueing scores (RT non-repeated minus RT repeated display); second, we entered these values in mixed-design ANOVAs with group (baseline vs. dual-task; between-subject factor) and phase (training vs. test; within-subject factor) as variables. Note that for the training session, only RTs values for epoch 3 were entered in this analysis. We reasoned that any secondary-task effects should be revealed by an interaction between the two variables. In Experiments 2a and 2b (3a, 3b), the sWM task was applied in close succession to the search task. These experiments were intended to examine the effects of executive, i.e., dual-task coordination, load on configural learning (Experiments 2b, 3b) or the expression of configural cues (Experiments 2a, 3a). In Experiments 2c and 2d, observers had to maintain a spatial pattern in WM by the time they performed the search task. These experiments aimed at testing whether concurrent spatial load attenuates configural learning (Experiment 2d) or the expression of learned contextual cues in the visual search task (Experiment 2c). In each experiment (and for each experimental condition), RT± 2.5 standard deviations from the mean were discarded as outliers (overall 2,99% of trials). Further, error response trials were also excluded from analysis (overall, 2,46% of trials; see statistics below).

Participants

A total of 119 volunteers (17 in each experiment) from Ludwig Maximilian University Munich (41 *males 78 females*; *mean age* = 25.6 [*SD*=5.8] years) participated in the experiment. Participants were either paid 8 Euro per hour (approx. 11 USD) or received course credits for their participation. All observers had normal or corrected to normal vision. Six observers were left-handed. Instructions were presented in German language.

Apparatus

Stimuli were presented on a 19-inch CRT-monitor (AOC, Amsterdam, NL), positioned approx. 55 cm away from observers. Participants' head was stabilized by means of a chin rest. The experiments were programmed in Matlab (version 7.3.0.267 R2006b; The MathWorks, Sherborn, MA), in combination with the OpenGL-Psychtoolbox extension (version 3.0.9; Brainard, 1997), and run on a "standard" (Intel) computer controlled by a WinXP Prof. operating system. Participants executed their responses via computer mouse and computer keyboard. Headphones were used to provide auditory feedback in the search and WM tasks, that is, the sWM task plus an articulatory suppression task. The stimuli for the latter task – two digits – were also presented via the headphones: participants had to vocally repeat two digits until (the test at) the end of the trial, so as to occupy the articulatory rehearsal process and thus prevent verbal coding of the to-be-remembered spatial stimuli [Footnote 3].

Stimuli

Spatial working memory task

The sWM task required participants to remember spatial locations (Oh & Kim, 2004; Manginelli et al., 2011; see also Figure 1). On each trial, a memory display of four black squares (size: 0.6° x 0.6°) was presented on a gray background (RGB = 128,128,128). The positions of the four items were randomly chosen among eight equidistant locations on an imaginary circle (radius approx. 3.0°).

Search task

The search stimuli were the target letter “T” (tilted 90° vs. 270° relative to the vertical, upright orientation) and the distractor letters “L” (0°, 90°, 180°, and 270°). The size of each stimulus was 0.6° x 0.6°. The screen background was gray (RGB = 128, 128,128). The color of the items was chosen randomly among red, blue, yellow, green, with the restriction that each color occurred equally frequently (25%) in the display. Each search display consisted of 1 target and 15 distractor items, presented on four imaginary (concentric) circles with different radii of 1.7°, 3.4°, 5.1°, and 6.8° (see Figure 1). Targets appeared only on the second or the third circle. Further, the distribution of the 16 items was balanced across the four quarters, such that there were four items in every quarter.

Procedure

Participants were tested in a dimly lighted room. Each experiment lasted approximately 2 hours (except the “baseline” Experiment 1, which took some 30 minutes to complete) and comprised of four phases: (1) training on the search task (12 trials; data not recorded); (2) learning phase (360 trials, divided into 15 blocks of 24 trials each); (3) test phase (120 trials, divided into 5 blocks of 24 trials); and (4) explicit recognition test (24 trials). Experiments 2-5 included a fifth phase, in which observers were provided with training on the search and sWM task (12 trials; data not recorded). This phase preceded the training on the search task. At the beginning of each phase, participants received instructions displayed on the screen about which task they were going to perform. Between blocks in the learning and test phases, participants were allowed to take a rest, until they pressed a key on the computer keyboard starting the next block. In each block of trials, 12 repeated and 12 non-repeated displays were shown. In repeated displays, the position, orientation, and the colors of distractors were kept constant, in addition to the position and color of the target. In contrast, the orientation of the "T" target letter (left vs. right) varied randomly on each trial in order to avoid response preparation (learning) effects. To equate target location repetition effects between repeated and non-repeated displays, targets in non-repeated displays appeared also in a limited set of 12 locations. However, in these displays, the locations of the distractors, and thus the configuration of the items, were randomly generated on each trial.

“Baseline” condition (Experiment 1).

This experiment comprised of 15 blocks of learning (360 trials) and 5 blocks of test (120 trials). In each trial of the training and test phases, observers performed only the search task. They were encouraged to detect, and subsequently discriminate, the orientation of the “T” target letter (left vs. right) presented amongst differently oriented “L” distractor letters. Response feedback was provided in the form of a brief tone of 2000 Hz (correct answer) or 300 Hz (wrong answer). On a given trial, the order of events was as follows: (A) presentation of fixation cross for 2000 milliseconds (msec). (B) Presentation of search stimuli until response or for a maximum duration of 3500 msec. (C) Auditory response feedback. (D) Intertrial interval of 500 msec. During this time, a white fixation was shown in the display center.

“sWM-after condition” (Experiments 2a and 2b).

In the sWM-after condition (see Figure 1), the search task preceded the sWM task. Each trial started with the presentation of a fixation cross for 2000 milliseconds (msec). Thereafter, the search items were presented until observers’ response or a maximum of 3500 msec. Correctness of response was indicated by auditory feedback (correct answer: 2000 Hz tone; incorrect answer: 300 Hz tone). Next, two random auditory digits, ranging from 1-9, were presented for 2000 msec. Observers were instructed to rehearse the two digits until the end of the trial. The auditory stimuli were followed by the sWM items, plus a white fixation cross, presented for 500 msec. After a retention period of 4000 msec (only fixation cross shown), a memory test display was presented consisting of one black square presented at one out of eight possible locations on the virtual memory circle. Observers' task was to indicate, by button press, whether or not the "test" square was at the location of a previous "memory" square. Following their response or a maximum of 3000 msec, they received auditory feedback regarding the correctness of their sWM response. The same tones were used as in the search task. Next, a fixation cross was shown for 1000 msec. Following this event, participants performed a memory test on the articulatory suppression task. In doing so, two white digits were displayed in the center of the screen on a gray background for a maximum of 3000 ms and subjects had to indicate whether or not they matched the two digits they had been rehearsing during the trial. Again, auditory feedback was provided. During the intertrial interval, of 500 msec, a white fixation cross was shown. Experiment 2a ("sWM-after-test") contained 15 blocks of training (360 trials), in which only the search task was administered. In the subsequent 5 blocks of the test phase (120 trials), observers performed the search in combination with the sWM task. In contrast, in Experiment 2b ("sWM-after-training"), the search and sWM task were combined in training, but the sWM task was removed in test trials (see Figure 1).

"sWM-while"-condition (Experiments 2c & 2d).

In this condition, observers performed the search task while they maintained the four black squares in working memory. On a given trial, the order of events was as follows (see Figure 1): (A) presentation of a white fixation cross for 2000 msec. During this time, participants also heard the two digits for articulatory suppression (i.e., they had to repeat them aloud until the end of the trial). (B) Presentation of the sWM stimuli plus a fixation cross for 500 ms. (C) Appearance of the search display until response or a maximum of 3500 ms. (D) Auditory feedback on the search task. (E) Presentation of a white fixation cross for a variable length between 500 ms and 4000 msec, depending on the observer's RT in the search task, in order to determine a constant retention period of 4000 ms for the sWM items. (F) Application of the sWM memory test. (G) Auditory feedback on the sWM task. (H) Presentation of fixation cross for 1000 msec. (I) Probing memory for the articulatory suppression items by the presentation of two digits. (J) Feedback on articulatory memory task. (H) Intertrial interval of 500 msec plus presentation of white fixation cross. In Experiment 2c (sWM-while-test"), 'early' training trials contained only the search task and 'late' test trials both the search and sWM tasks. In Experiment 2d ("sWM-while-training"), the search and sWM tasks were paired in training trials, but the latter task was removed in test trials (see Figure 1).

"sWM-before condition" (Experiments 3a & 3b).

This condition was near- identical to the "sWM-after-condition" (Experiments 2a and 2b), except, however, that the search task was administered after participants performed the sWM task. In this regard, the sWM-before condition was similar to Lavie et al.'s (2004) Experiments 4 and 5 (2004). Experiments 3a and 3b were motivated by the idea that the presentation of the search task at the beginning (sWM-after condition), as compared to the end (sWM-before condition), of a given trial would impose only minimal requirements for dual task coordination, 'simply' because the search task would always be the first task to be performed (Glyn Humphreys, personal communication, July 2012). That is, the sWM-after condition may provide only a 'weak' condition for tapping executive WM functions, likely underestimating the requirements for dual task coordination. Therefore, in the sWM-before condition, the sWM task was administered prior to the search task in order to increase the demands on dual task coordination. Using such a design, Lavie et al. (2004) showed reliable effects of dual task coordination on performance of the primary task (in their case: the Eriksen flanker task; in the present case: the contextual cueing task). In the sWM-before condition, each trial started with the auditory stimuli: two auditory digits (randomly chosen from the set of 1–9) were presented for 2000 ms, and participants were asked to rehearse the digits until the end of the trial. Next, four black to-be-remembered squares appeared for 500 ms. The retention period was 4000 ms and followed by the sWM and articulatory suppression (digit) tests (response time max. 3000 ms for both tests). This was followed by the search task (max.

display presentation: 3500 ms). In Experiment 3a, the sWM task was administered in the 'late' test phase (trials 361-480; trials 1-360: only search task); in Experiment 3b, the sWM task was performed in combination with the search task in the training phase (trials 1-360; trials 361-480 only search task) (see Figure 1).

Explicit recognition test.

At the end of each experiment, participants performed a recognition test, querying observers' explicit knowledge of repeated displays. The recognition test contained 24 trials, half of which presented a repeated display and the other half a non-repeated display (random order). Observers' task was to indicate whether they believed having seen a given display already in the search task. With this 'old-new' test, the chance rate for recognizing a repeated display is 50%.

To preview the results, the main finding of the present study was that of concurrent spatial – but not executive – WM load interfering with the expression, rather than the acquisition, of contextual associations. In Experiment 2c, contextual cueing was attenuated when a concurrent sWM load (i.e., a secondary sWM task) was introduced in late experimental trials. In Experiment 2d, concurrent sWM load suppressed cueing in training trials; however, when this secondary task was removed in late trials, contextual cueing recovered (see Figure 2).

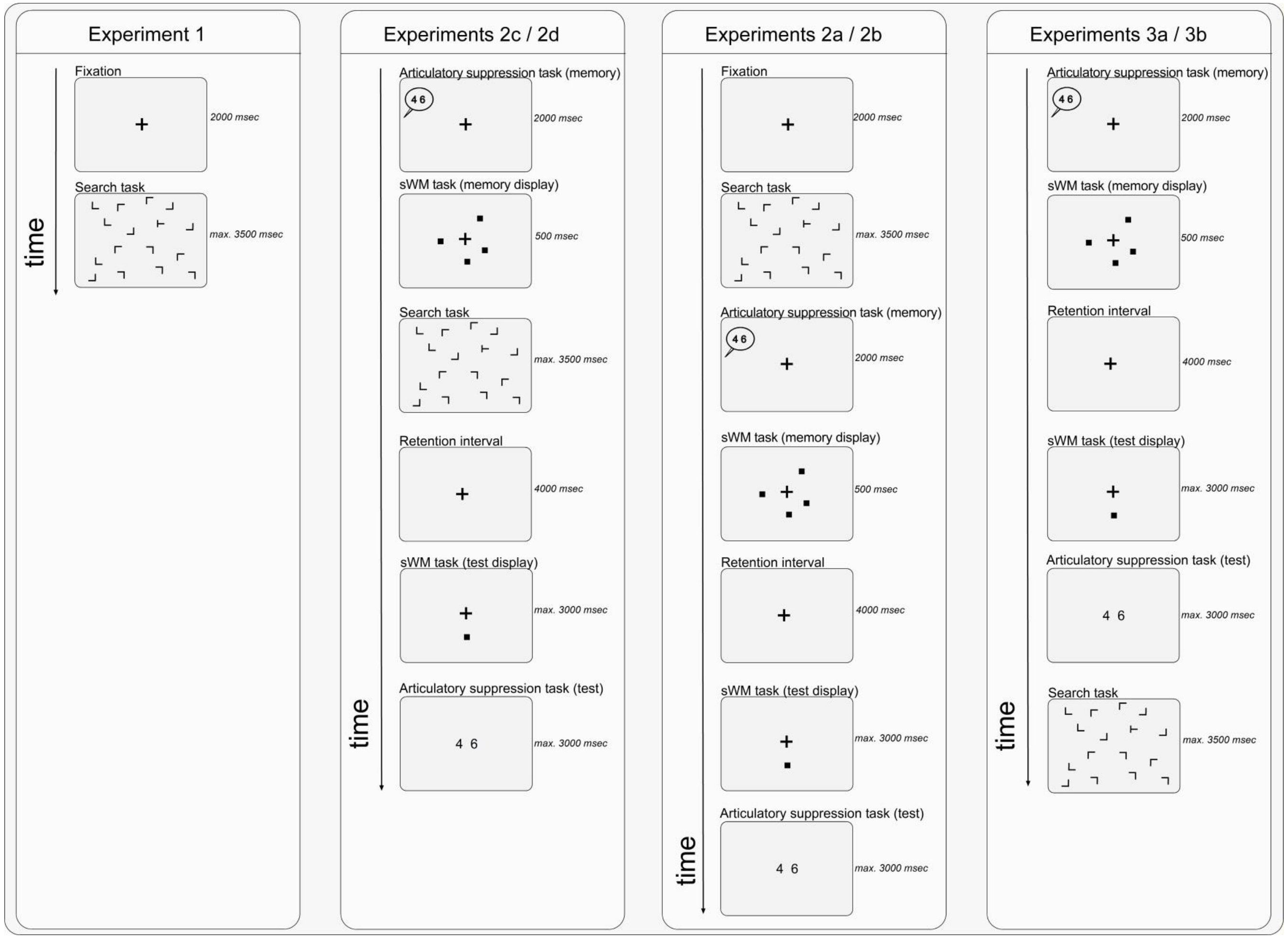

Figure 1. Illustration of the “baseline”, “while”, “after”, and “before” conditions. The single task Experiment 1 was intended to provide a ‘baseline’ measure of contextual cueing, unconfounded by secondary task effects. In the other, dual task experiments, the search task was combined with a secondary spatial working memory (sWM) task performed in early (“training”) or late (“test”) trials either in parallel with (“while” condition; Experiments 2c, 2d) or temporally segregated from the search task (“after” condition: Experiments 2a, 2b; “before” condition: Experiments 3a, 3b; in the “after” condition the sWM task was performed after, and in the “before” condition prior to the search task). In all dual task experiments, the search and sWM tasks were accompanied by a third, articulatory suppression task.

Figure 2

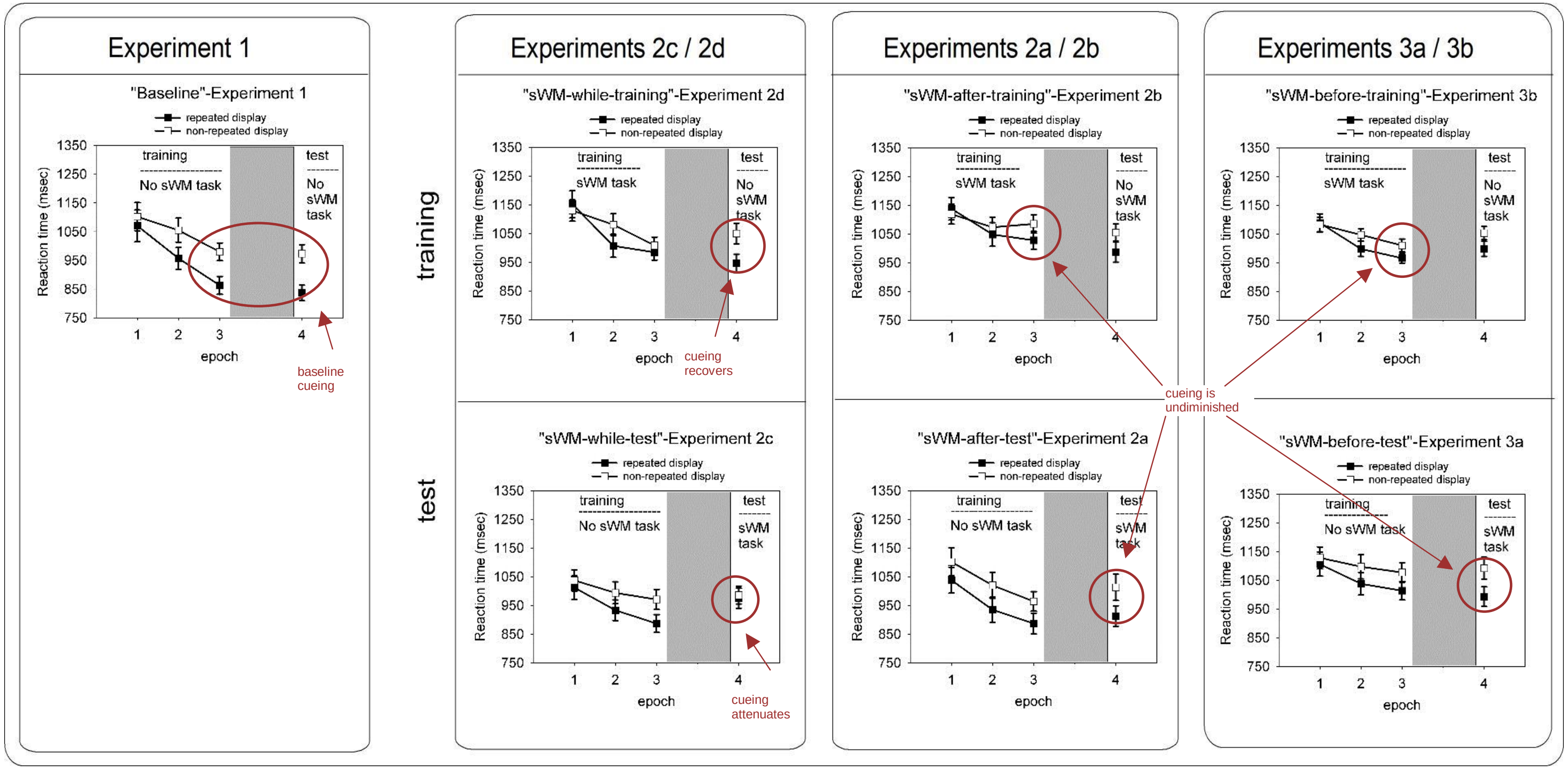

Figure 2. Mean reaction times (RTs) and associated standard errors to repeated and non-repeated displays (black and white symbols, respectively) as a function of experimental epoch (1–4). The upper and lower panels show RTs for the conditions with the sWM task administered in “training and “test” trials, respectively.

3.4 Results

Accuracy performance in the WM tasks

Table 1 shows mean accuracy performance in the two WM tasks, sWM and articulatory suppression, in Experiments 2a through 3b. Overall, accuracy was quite high: 95% in the articulatory suppression task and 83% in the sWM task. Analyses of variance (ANOVAs) revealed no accuracy differences among the experiments [articulatory suppression: F(5,96)=0.96, p=.44; sWM: F(5,96)=1.34, p=.25]. From this, one can conclude that Experiments 2a–3b were comparable in terms of articulatory and WM performance.

Accuracy performance in the search task

Response accuracy in the search task was also overall high: 97.5%. A mixed-design ANOVA on the error rates with the factors display type (repeated vs. non-repeated displays; within subject factor), epoch (1-4; within subject factor), and experiment (1-3b; between subject factor) only revealed the effect of display type to be significant: F(1,112)=8.61, p<.01). This main effect was due to response errors being lower for repeated than for non-repeated displays (2.26% vs. 2.67% respectively).

Contextual cueing in the "baseline" Experiment 1

Experiment 1 was intended to yield a measure of contextual cueing "uncontaminated" by the secondary sWM task. Recall that observers performed the search task (only) in a total of 480 trials (training: 360 trials; test: 120 trials). Figure 2 presents the results. RTs were analysed by means of a repeated- measures ANOVA, with display type (repeated vs. non-repeated) and epoch (1-4) as factors. The main effect of epoch was significant [F(3,48)=25.435, p<.01]: RTs became faster as the experiment progressed (epoch 1: 1086 ms; epoch 4: 905 ms). The general improvement in task performance can be attributed to non-configural, procedural learning, such as the mapping of a particular stimulus onto a response

(Shiffrin & Schneider, 1977). The main effect of the display type was also significant [F(1,16)=20.695, p<.01]: RTs were faster for repeated relative to non-repeated displays (932 vs. 1028 ms). Importantly, the interaction was significant, too [$F(3,48)=6.049, p<.01$]. Paired sample t-test revealed the difference between repeated and non-repeated displays to be significant in epoch 2 and all subsequent epochs (all p's <.001). This indicates that contextual cueing emerges after sufficient training on the task. A further t-test (paired-samples) showed that the cueing effect was comparable between epoch 3 (last epoch of training phase) and epoch 4 (test phase): 118 vs. 137 ms [$t(16)=.670$, $p=.50$] (see also Figure 2 and Table 2).

Tables

Table 1. Mean accuracy performance in the sWM and articulatory suppression tasks in the “dual task” Experiments 2a–3b. The dependent variables were compared by means of two separate ANOVA’s, each with “experiment” as between-subject factor. The ANOVA results are presented in the last table row.

Experiment	**sWM task**	**verbal suppression task**
Experiment 2a “sWM-after-test”	87%	98%
Experiment 2b “sWM-after-training”	82%	90%
Experiment 2c “sWM-while-test”	79%	97%
Experiment 2d “sWM-while-training”	80%	95%
Experiment 3a “sWM- before-test”	84%	96%
Experiment 3b “sWM- before-training”	86%	98%
ANOVA results	***F(5,96)=1.34, p=.25***	***F(5,96)=0.96, p=.44***

Table 2. Mean contextual cueing values (RT non-repeated minus RT repeated display) in the training and test trials of Experiments 1 through 3b. Each “dual task” Experiment 2a–3b was compared against the “single task” (baseline) Experiment 1 in separate group (single vs. dual task) x phase (training vs. test) mixed-design ANOVAs. The column “2 x 2 ANOVA” gives the theoretically important interactions.

Experiment	**Application of sWM task**		**Contextual Cueing**		**2 x 2 ANOVA**	**Experimental objective: result**
	Training	**Test**	**Training (epoch 3)**	**Test (epoch 4)**	**group x phase (F1,32)**	
Experiment 1 “Baseline	No	No	118 ms	137 ms	-	Providing a ‘baseline’ measure of contextual cueing unconfounded by secondary task effects
Experiment 2a “sWM-after-test”	No	Yes	77 ms	101 ms	0.01, p=.91	Assessment of executive WM effects on the retrieval of learned configural associations: contextual cueing is undiminished in the test phase
Experiment 2b “sWM-after-training”	Yes	No	57 ms	68 ms	0.03, p=.86	Assessment of executive WM effects on the acquisition of configural associations: contextual cueing is undiminished in the training phase
Experiment 2c “sWM-while-test”	No	Yes	84 ms	11 ms	5.61, p<.02	Assessment of spatial WM effects on the retrieval of learned configural associations: contextual cueing is reduced in the test phase
Experiment 2d “sWM-while-training”	Yes	No	24 ms	104 ms	3.30, p<.05	Assessment of spatial WM effects on the acquisition of configural associations: contextual cueing is reduced in the training phase, but recovers in the test phase
Experiment 3a “sWM-before-test”	No	Yes	63 ms	100 ms	0.14, p=.70	Further investigation of executive WM effects on the retrieval of learned configural associations: contextual cueing is undiminished in the test phase
Experiment 3b “sWM-before-training”	Yes	No	44 ms	55 ms	0.31, p=.86	Further investigation of executive WM effects on the acquisition of configural associations: contextual cueing is undiminished in training phase

Contextual cueing in dual-task Experiments 2a-3b

Contextual cueing was also explored for the dual task experiments 2a through 3b by a further 6 x 4 x 2 mixed-design ANOVA, with experiment (Experiment 2a-3b; between-subject variable), epoch (1-4; within-subject variable), and display type (repeated, non-repeated; within-subject variable) as factors. This ANOVA revealed a main effect of epoch [F(3,288)=46.51, p<.001], due to RTs becoming overall faster as the experiments progressed (1094 vs. 1005 ms in epoch 1 vs. epoch 4). Further, the display type effect was significant [F(1,96)=46.11, p<.001]: RTs were overall faster for repeated relative to non-repeated displays (1003 vs. 1053 ms). Furthermore, the epoch x display type interaction was significant [F(3,288)=9.20, p<.001]. LSD post-hoc revealed contextual cueing (RT non-repeated minus RT repeated display) to be reliable in epochs 2-4 (all p<.001), but not in epoch 1 (p=.25). This pattern of results indicates that contextual cueing was operating under secondary task conditions. But how did the magnitude of the cueing effect vary across the dual task experiments in relation to the single-task (baseline) Experiment 1?

Contextual cueing in the "baseline" Experiment 1 versus the "dual-task" Experiments 2a-3b

The "baseline" Experiment 1 suggests that learned target-distractor associations can successfully be transferred from the training to the test phase – at least under single task conditions. The "dual task" experiments combined the search with a secondary sWM task to be performed on either the training trials (Experiments 2b, 2d, 3b) or the test trials (Experiments 2a, 2c, 3a). Furthermore, the sWM task could be administered after (Experiments 2a, 2b), before (Experiments 3a, 3b), or simultaneously with the search task (Experiments 2c, 2d). This design allowed us to disentangle WM effects in the learning versus the retrieval of configural information (Experiments 2b, 2d, 3b vs. 2a & 2c, 3a), and importantly, examine whether WM effects are due to spatial or executive load (Experiments 2c, 2d vs. 2a, 2b, 3a, 3b). The "baseline" Experiment was used to assess the "costs" of adding a secondary task on training and, respectively, test trials, separately for conditions in which the sWM task was performed after or at the time of the search task. The dependent variable was contextual cueing, determined by subtracting RTs to repeated from RTs to non-repeated displays. This resulted in six mixed-design ANOVAs, each with phase (learning, test) and experiment (single-task, dual-task) as factors. Note that for computing contextual cueing in the learning phase, only RTs from the last epoch (blocks 11-15) were included.

The results of these ANOVAs are summarized in Table 2 (see also Figure 2). There are three notable findings: First, the secondary task attenuated contextual cueing when administered on test trials [$F(1,32)=5.61$, $p<.05$; interaction Experiment (1–baseline vs. 2c–sWM-while-test) x Phase (training vs. test)]. Second, contextual cueing recovered when the secondary task was removed at the transition from the learning to the test phase [$F(1,32)=3.30$, $p=.05$; interaction Experiment (1–baseline vs. 2d–sWM-while-training) x Phase (learning vs. test)]. Third, while these effects were observed when the sWM task was to be performed simultaneously with the search task, administering the sWM task after the search task had almost no effect on contextual cueing, on either training trials [$F(1,32)=.028$, $p=.86$; interaction Experiment (1–baseline vs. 2b–sWM-after-training) x Phase (learning vs. test)] or test trials [$F(1,32)=.012$, $p=.91$; interaction Experiment (1–baseline vs. 2a–sWM-after-test) x Phase (training vs. test)]. And even the presentation of the sWM task before the search task did not affect contextual cueing, in either the training phase [$F(1,32)=.14$, $p=.70$; interaction Experiment (1–baseline vs. 3b–sWM-after-training) x Phase (learning vs. test)] or the test phase [$F(1,32)=.031$, $p=.86$; interaction Experiment (1–baseline vs. 3a–sWM-after-test) x Phase (training vs. test)]. Note that this pattern of results was confirmed in additional analyses taking into account RT data across two epochs of training (i.e., epochs 2, 3) –rather than only one epoch (i.e., epoch 3) as in the above analysis [Footnote 4]. This is also illustrated in Figure 3, which shows RTs to repeated and non-repeated displays as a function of each block (1–20) for Experiments 1 through 3b.

In summary, the results reveal a specific secondary task effect on contextual cueing performance. The cueing effect was attenuated, particularly when the secondary task was added late, on test trials. Interestingly, the effect recovered when the sWM task was removed on late, test trials. This suggests that the formation of configural long-term memory occurs regardless of a secondary WM task. Instead, the results indicate that the expression of learned information is affected by the WM task. Moreover, given that contextual cueing was almost unaffected by the addition of sWM task when added after or before the search task, the findings demonstrate that it is not the requirement of the observers having to coordinate the two tasks, but rather the fact that the two tasks rely on a common, spatial pool of resources that causes the sWM interference.

Figure 3

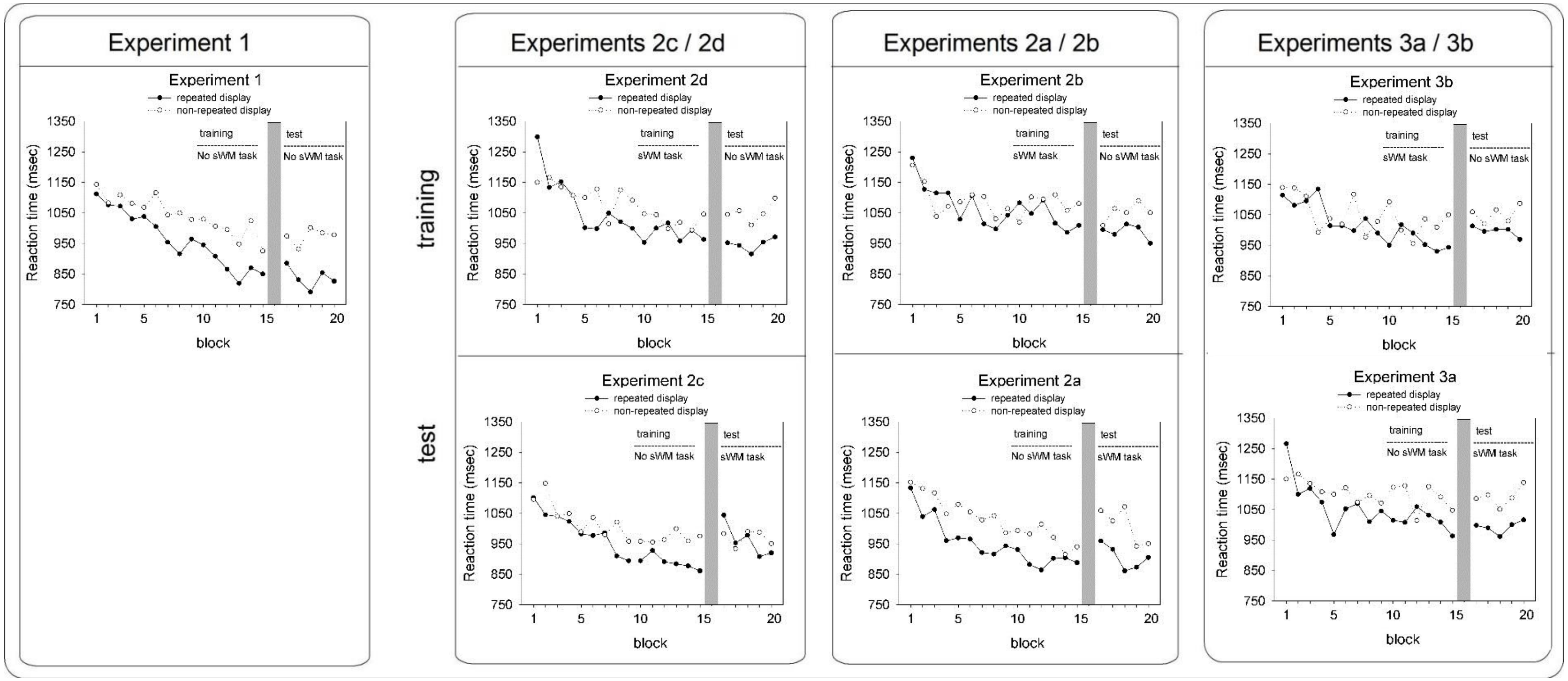

Figure 3. Mean reaction times (RTs) to repeated and non-repeated displays (black and white symbols, respectively) as a function of experimental block (1–20). The upper and lower panels show RTs for the conditions with the sWM task administered in "training" and "test" trials, respectively.

Recognition performance

Observers' ability to explicitly recognize repeated displays was assessed by calculating the hit rates (correct classification of repeated displays as 'repeated', i.e., seen before) and false alarm rates (incorrect classification of non-repeated displays as 'repeated') on recognition trials. More hits than false alarms would indicate that observers could tell apart repeated from non-repeated displays. Interestingly, the mean hit rate was larger than the false alarm rate [.53 vs. .46; $F(1,112)=7.69$, $p<.05$], as confirmed by a mixed-design ANOVA with response type (hit vs. false alarm; within-subject variable) and Experiment (1-7; between-subject variable) as factors. No other effect was significant. Although the difference between hit and false alarm rates was small in magnitude, it suggests that at least some observers have explicit knowledge of repeated displays. Moreover, the use of larger numbers of observers (Experiment 1-7: N=119 participants, compared to typically just 8–16 in standard contextual cueing experiments) could explain this positive finding, as larger sample sizes increase the power of the recognition test.

3.5 General Discussion

The aim of the current study was to investigate whether a secondary spatial WM task would interfere with configural learning or the expression of learned configurations in visual search, and to which mechanism – spatial versus executive WM – interference effects would have to be attributed. The critical findings were: (1) contextual cueing was reliably reduced under dual-task compared to single-task (i.e., baseline) conditions on late trials of the experiments (Experiment 1 vs. Experiment 2c). (2) Contextual cueing, on 'late' trials, was as large as in the baseline condition when the sWM task was administered in early, but removed in late, experimental trials (Experiment 1 vs. Experiment 2d). (3) Contextual cueing was almost unaffected by the addition of a secondary sWM task when the WM task was performed after the search task (Experiments 1 vs. Experiments 2a & 2b). This pattern of results supports the view that a secondary, spatial WM task attenuates the expression of learned configural cues in visual search (Manginelli et al., 2013). Furthermore, they confirm the *sWM-load* hypothesis and rule out the *WM executive-load* hypothesis.

However, one might object that the manipulation of executive load was lacking in power at least in Experiments 2a and 2b, because in the relevant conditions, the search task was always the first one to be performed, followed by the sWM task. As a result, there may have been only few, if any, demands placed on dual task coordination. This issue was addressed in Experiments 3a and 3b, in which the sWM task was performed before, rather than after, the search task (adopting the approach of Lavie et al., 2004). The results were a replication of those in Experiments 2a and 2b: contextual cueing was as large as under single task conditions, indicative of the effect being largely uninfluenced by the increased cognitive load for scheduling multiple (spatial) tasks.

This set of results is novel because the dissociation between the acquisition and retrieval of target-distractor contingencies, most importantly: the effects of spatial versus executive WM load has never been unequivocally demonstrated before. In contrast to previous claims that contextual cueing is unaffected by the requirement to perform a secondary task (Vickery et al, 2010), we found that a secondary sWM task does have a crucial influence on the cueing effect: contextual cueing was affected by the addition of the secondary task, though this effect manifested only when observers performed the search task *while* they maintained an unrelated configural pattern in visuospatial WM. Moreover, secondary task effects were observed only on late experimental trials. Therefore, we take the results to mean that (the availability of) spatial, and not executive, WM resources affect contextual cueing, particularly the retrieval of learned target-distractor contingencies from configural long-term memory (also see Manginelli et al, 2011, 2013).

As mentioned in the introduction, a very recent study by Travis et al. (2013), who also examined the role of WM in contextual cueing, only partially confirms this conclusion. In their Experiment 2, observers were initially trained on the repeated displays under dual task conditions (in the present terms: “sWM-while training”) and then performed the search task under single task conditions. The results showed reliable contextual cueing on late, test trials. However, this result was not replicated in Travis et al.’s Experiment 3, in which the sWM task was paired with the search task on early experimental trials, but removed on late trials. Here, contextual cueing was absent even when tested under single task conditions. One important difference between the two experiments concerns the training trials, which included both repeated and non-repeated displays (Travis et al.’s Experiment 3) or only repeated displays (Experiment 2). On this background, Travis et al. surmised that task difficulty, that is: the presentation of repeated and non-repeated versus the presentation of repeated displays only modulates sWM interference. However, this idea is very difficult to distinguish from the notion that the sWM task modulates the learning, rather than the retrieval, of repeated search arrays. So, how could one explain the inconsistencies between these findings? A closer look at the type of sWM task employed in these studies may help to answer this question. Travis et al. used a task that was qualitatively different from the current sWM task: maintaining the locations of sequentially presented dots (Travis et al.) versus maintaining an array of static dots (current task). This difference is likely to relate to dissociable visuo-spatial WM representations, in terms of a more visual representation, tested by pattern span tasks, versus and a more spatial representation, tested by the Corsi block span task (for a review, see Baddeley, 2003). The Corsi block span task, which involves the tapping of a number of spatially laid-out block objects in the correct (i.e., previously presented) sequence, is similar to the task used by Travis et al. (2013); that is, they are likely to have manipulated the spatial component of visual WM. By contrast, our task (as well as that used by Manginelli and colleagues) is more similar to the pattern span task, and so is likely to have measured visual WM. In other words, it is possible that the application of a secondary ‘spatial’ WM task (Travis et al., 2013) affects configural learning, whereas a ‘visual’ WM task (Manginelli et al., 2011, 2013; present investigation) hampers the retrieval of learned info from configural memory. This hypothesis requires future research.

It is also conceivable that administering a sWM in training trials impedes configural learning, particularly when the sWM is relatively difficult. However, a comparison of sWM task accuracy between Travis et al. (94%) and the current study (83%) suggests that this is not a valid thesis. Assuming that accuracy does reliably index sWM task difficulty, the current task would have been even more difficult than Travis et al.'s approach, which should have further reduced contextual cueing – this was, however, not the case. Given this, it is unlikely that sWM task difficulty as such modulates the acquisition of configural long-term memory (of course, this 'conclusion' remains tentative as we did not manipulate sWM task difficulty here). Rather, sWM for sequentially presented dots may be different from sWM for static visual patterns, and the former might particularly interfere with configural learning (as evidenced by Travis et al.'s, 2013, Experiment 3), whereas memory for visual patterns hampers the expression of learned contextual associations (current investigation). The methodological implication would be that conclusions from investigations of contextual cueing and sWM require a clear definition of the type of sWM task deployed.

In contrast to prior investigations of the contextual cueing effect, analysis of the recognition performance (N=119 participants) revealed that our observers were, to some extent, aware of repeated displays (see also Schlagbauer et al, 2012, for corroborative evidence pertaining to this claim). However, this conclusion would not be warranted when considering each experiment individually (N=17 participants – here the difference between hit and false alarm rates was only non-significant), suggesting that the results – and conclusions – from recognition tests critically depend on the power of the tests (see Smyth & Shanks, 2008, for a similar argument). But note that we neither want to argue for a causal role of awareness in contextual cueing, nor that contextual cueing is supported by a central memory system that is mediated by explicit processes – a thesis advocated by Smyth and Shanks (2008). Instead, the present finding of above-chance recognition may suggest that observers are able to access the memory underlying contextual cueing, but not that the learning of repeated displays requires knowledge of repeated displays. That is, there may be a distinction between the learning and the retrieval of learned configural information, with the latter, but not former, involving explicit processing. Alternatively, retrieval might work automatically (implicitly), but may also, occasionally, generate a sense of explicit awareness in the observer. Further work is necessary to resolve this issue.

In sum, the question of whether WM affects contextual cueing of visual search has received a great deal of interest recently. While some studies found that the effect is independent of a secondary sWM task (Vickery et al., 2010), other investigations found that contextual cuing is affected by sWM load (Manginelli et al., 2011, 2013; Travis et al., 2013). The current study supports the view that in a dual-task situation, the contextual cueing effect, that is, the expression of learned information, is attenuated because the visual search and working memory tasks rely on common spatial WM functions, rather than because observers have an increased need to coordinate the two tasks.

3.6 References

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3.7 Acknowledgements

This research was supported by Deutsche Forschungsgemeinschaft (DFG) Research Projects PO 548/6-2 (grant to Stefan Pollmann) and GE 1889/3-1 (grant to Thomas Geyer), and CoTeSys Excellence Cluster (142) grants. Correspondence concerning this article should be addressed to: Efsun Annac, Ludwig-Maximilians-Universität München, Department of Psychology, Leopoldstraße 13, 80802 München, Germany (email: efsun.annac@psy.lmu.de).

3.8 Footnotes

Note 1. That is, when two tasks draw on separable specific WM resources, such as spatial and, respectively, verbal WM systems, the coordinative demands may be minimal. Accordingly, from the finding that a featural WM task does not, while a spatial WM task does interfere with contextual cueing (e.g., Manginelli et al., 2013), one cannot conclude that all interference arises from the competition for a capacity-limited spatial WM resource.

Note 2. These conclusions receive support from a very recent study (Tsvetanov et al., 2013) which introduced two conditions: working memory (WM) and mere repeat (MR). In the WM condition, observers had to maintain the color and shape of an item in WM (e.g., a red circle) while performing a 'pop-out' search task, namely, to discern the orientation of a line (as left- vs. right-tilted) presented amongst three vertical lines. The search items were presented inside four colored shapes (e.g., red circle, green square, blue triangle, violet hexagon). The crucial manipulation concerned the re-appearance of the WM item in the search display (absent, present) and, if present, the location the target item (inside item matching vs. not matching WM contents). Typically, RTs to discriminate the target are faster when the target appears at the location of the WM item (WM-based RT facilitation) relative to when it appears at a different location (WM-based RT inhibition); note that both effects are assessed relative to a neutral condition, in which the WM item does not reappear in the search display. In the MR condition, in contrast, observers 'only' had to indicate whether two subsequently presented items were the same or different (the identification task was performed prior to the search task). The MR condition was intended to provide a measure of the effects of executive, or general, load on RT performance. Typically, RTs are slower in the WM than in MR condition, indicating that the maintenance of information in WM, rather than merely identifying items, increases general demands on performance (for a review, see, e.g., Soto et al., 2008). Tsvetanov et al. compared content-specific WM effects (RT facilitation, RT inhibition) and content-unspecific WM effects (RT WM condition, RT mere repeat condition) between younger and older participants. They found that content-unspecific WM effects were more pronounced for the older participants (i.e., the slowing of RTs in the WM relative to MR condition was more pronounced for older participants), while content-specific WM effects were larger for younger observers (i.e., RT facilitation and RT inhibition effects were more pronounced for younger observers). This double dissociation led them to surmise that the effects of executive WM load are independent of those of content-based (i.e., featural) WM load in visual pop-out search.

Note 3. Although this introduced another task to be performed concurrently with the search and sWM task, this should not have interfered with these tasks as such, given that articulatory suppression occupies a separable WM sub-system (the phonological loop; e.g., Baddeley, 2003). Also, since the articulatory suppression task was added to all experimental conditions, the extra executive demands imposed by this task were essentially equated across these conditions.

Note 4. In the additional analysis, we did not include RTs from epoch 1, because contextual cueing typically becomes significant only after epoch 1 (see Chun & Jiang, 1998; present investigation).

Chapter 4:

A secondary task is not always costly: Context-based guidance of visual search can benefit from a demanding working-memory task

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Annac, E., Zang, X. Müller, H. J., & Geyer, T. (under review). A secondary task is not always costly: context-based guidance of visual search can benefit from a demanding working-memory task

4.1 Abstract

A concurrent spatial working memory (WM) task can hamper visual search, accompanied by detrimental effects on the learning of statistical regularities in the visual search array. In the present study, we re-investigate the controversial issue of whether long-term spatial learning of repeated target-distractor arrangements in visual search is influenced by a secondary spatial WM task. Here, the spatial WM task was paired with the visual search in each second block of trials. This dual-task training regime has been shown to facilitate the development of automatic processes. The results from two experiments indicated that spatial learning (reaction times non-repeated display arrangement minus reaction times repeated display arrangement) was functional even in the presence of a demanding spatial WM task. Importantly, the advantage for repeated over non-repeated search arrangements remained intact even when different sets of repeated displays were used in visual search under single and dual task conditions. These findings suggest that spatial WM load does not necessarily interfere with the guidance of visual search by long-term spatial memory, given particular training of the visual search task.

4.2 Introduction

Our sensory world typically contains numerous statistical regularities. For example, objects are usually associated with specific environments and are positioned at reoccurring locations such as a mailbox in a front yard (Palmer, 1975). The visual system can pick up these regularities to optimize goal-directed behavior. For instance, it has been demonstrated in visual search that observers become more efficient in detecting a target item when presented with spatially invariant search layouts – an effect called contextual cueing (Chun & Jiang, 1998; Chun, 2000). In a typical contextual cueing task, participants are presented with a number of randomly placed 'L' shaped distractors and a 'T' shaped target item that is either pointing to the left or right. Participants’ task is to detect and subsequently discriminate the orientation of the target ‘T’ as fast as possible. Unbeknownst to them, half of the displays are repeated and the other half non-repeated, random, display arrangements. Over the course of the experiment, participants improve in their reaction time (RT) performance in ‘repeated’ over non-repeated displays (contextual cueing effect). Moreover, participants’ ability for discriminating repeated from non-repeated layouts is typically only at chance level. Together, this pattern of results suggests that target-distractor spatial *context* associations stored in implicit long-term memory can come to guide the search process, *cueing* attention to the target location.

4.2.1 The role of divided attention in contextual cueing of visual search

Previously, it was shown that spatial context memory is itself influenced by attention, both in terms of selectivity and processing resources deployed (see, e.g., Goujon, Didierjean, & Thorpe, 2015 for a review). For instance, Vickery, Sussman, & Jiang (2010) tested whether contextual cueing is affected by a secondary working memory (WM) task, based on the idea that contextual cueing and the secondary WM task share common processes, or draw on a common resource pool (Kahneman, 1973). In doing so, Vickery et al. (2010) examined WM for different perceptual attributes, such as spatial arrays, colors, item sequences, etc., while observers performed a visual search (contextual cueing) task. Their experiments were divided into two distinct phases: training and test. In training, attention load was implemented by a concurrent secondary WM task, intended for ‘sucking up’ participants’ spare WM stores during the search task. In the test session, the visual search task was performed without concurrent WM load. The results showed robust contextual cueing (in the test phase) when the repeated displays were shown initially under a secondary WM task, suggesting that contextual cueing can survive the interference from a concurrent working memory load.

Following Vickery et al.’s (2010) findings, a number of studies re-investigated the relation between contextual cueing and divided attention. One of the most serious criticisms leveled against the study of Vickery et al. (2010) was that they tested contextual cueing only under single-task conditions, that is, after observers had learned the repeated displays in a dual-task phase. Thus, they could only examine whether the learning of contextual cues is affected by secondary WM load, but not whether the retrieval of learned information is dependent on WM. This hypothesis was tested in a series of follow-up studies (Manginelli et al., 2011, 2013; Travis, Mattingley, Dux, 2013; Annac et al., 2013). The general approach taken in these studies was to pair the visual search task selectively with the WM task either in the training or in the test phase. The results revealed reliable contextual cueing when a spatial, not featural (color), WM task was administered in the learning phase (compatible result with Vickery et al., 2010), but not when administered in the test phase. Manginelli and collaborators (Manginelli et al., 2011, 2013; Annac et al., 2013) took this to mean that the expression of learned target-distractor associations is mediated by spatial WM (but also see Travis et al., 2013 for a discrepant view). Annac et al. (2013) went on examining another potential source of WM interference effects in spatial contextual cueing, namely executive WM load. They draw this idea from previous investigations (of different perceptual tasks) that showed that observers’ ability to ignore an additional, task-irrelevant, feature singleton distractor in a visual search display is reduced in the presence of an additional WM task (Lavie, Hirst, de Fockert, & Viding, 2004). To investigate this, Annac et al. (2013) manipulated the order of tasks. One group of observers had to maintain a spatial pattern in WM while performing the visual search task (similar as in Manginelli et al., 2011, 2013). For another group of observers, the spatial WM task did not overlap with, but instead was performed immediately after the search task. Thus, their ‘overlapping’ group had spatial and executive load while observers in the ‘non-overlapping’ group had only executive load. Annac et al. (2013) found that contextual cueing was reduced only in the ‘overlapping’ group. In summary, the findings on the relationship of spatial contextual cueing and WM load suggest that a concurrent spatial WM task interferes with the retrieval from, not the acquisition of, context memory for repeated search configurations (Manginelli et al., 2011, 2013, Annac et al., 2013). Further, neither featural (Manginelli et al., 2013) nor executive (Annac et al., 2013) WM load affect the retrieval of learned context cues.

4.2.2 Contextual cueing as an instance of an automatic process

Schneider and Shiffrin (1977) have shown that visual search improves with increased practice on the task. They further showed that the degree of practice-dependent improvements in search performance are dependent on task characteristics, such as; whether the definition of the target is held constant across trials (their consistent-mapping condition; CM) or whether a given search item can be a target in one trial and a distractor in another trial (their variable-mapping condition; VM). Practice-dependent gains in search performance were manifest almost exclusively in the CM condition. These qualitative differences in the way observers can learn about task parameters led them to propose two qualitatively different processing modes: automatic and controlled processing, supporting performance in the CM and VM conditions, respectively. Automatic processes were claimed as having no capacity limitation, do not require attention, and once observers have learned the critical information, they will unfold automatically using no WM resources. Controlled processes, on the other hand, have a limited capacity and require attention. In subsequent work, Schneider and collaborators (e.g., Schneider & Fisk, 1982) further addressed the issue of automatic versus automatic processing by combining the CM and VM conditions in a single task. In more detail, Schneider and Fisk examined the development of automaticity, measured by the slope of the function relating search performance with trial number, i.e., task practice, in single and dual task conditions. In single conditions, observers had to perform either the CM or VM task across an entire block of (48) trials. In the CM task, a letter from a target set (e.g., A, C, E, M) always appeared as a target and never as distractor item. The search displays were presented in a sequence of 12 brief frames and always contained four items (letters). Observer's task was to indicate whether a predefined target, shown at the beginning of an individual trial, was present on one of the 12 frames. In the VM condition, letters from the target set sometimes appeared as a target, but other times as a distractor item. Note that in the VM condition, a different set of items (relative to the CM condition) served as target and distractor elements. In the dual task condition, half of the trials were CM and VM trials, with the order of blocks being determined randomly. There were two important findings: (1) observers improved with their search performance over time in the CM but not VM condition, independent of whether they performed the CM / VM condition in an isolated or combined manner (single vs. dual-task condition). (2) For the CM condition, the practice-dependent gain in performance was even higher under dual-task conditions. Schneider and Fisk (1982) argued that controlled processes (in the VM condition) can act as a "…training wheel…" (p.277) for automatic performance (in the CM condition), in a sense that performance on a controlled task would leave no processing resources left for the automatic task and thus, maximize the development of automatic retrieval processes.

4.2.3 Rationale of the present study

Re-evaluating the above findings on the dependency of contextual cueing of visual search from spatial WM in light of the automatic vs. controlled processes distinction would give new impetus for the development and test of the relation between contextual cueing and spatial WM load. Specifically, if one considers contextual cueing as a form of skill or procedural learning (see, e.g., Chun & Phelps, 1999 for the development of this idea), in other words, as a form of automatic processing (Schneider & Shiffrin, 1977), this would lead to the somewhat paradoxical prediction that (automatic) context effects could come to the fore specifically under conditions of a demanding, and controlled, secondary spatial WM task. In the present study, we tested this idea by combining the contextual cueing task with a secondary spatial WM task. However, in contrast to previous investigations of attention-dependent contextual cueing, in which the spatial WM task was paired with the visual search task across the entire training session (consisting of hundreds of trials; see, e.g., Annac et al., 2013), we adopted a paradigm that was similar to that of Schneider and Fisk (1982). Specifically, we presented repeated search displays interchangeably in single and dual task blocks. In single-task blocks, observers only performed the visual search task and a given trial in dual-task blocks contained both the visual search and spatial WM tasks. In dual-task blocks the spatial WM task should draw away attentional resources, leaving no room for controlled processes to spill over to the search task, including the retrieval from long-term, context, memory. This should foster the development of automatic processing, manifesting in a contextual cueing effect in the presence of a demanding spatial WM task.

4.2.4 Overview of experiments

In Experiment 1, observers performed a visual search task in which they encountered repeated and non-repeated display arrangements that were presented in random order within a given block of trials. Across blocks, the visual search task was performed either with or without a concurrent spatial WM task ('search-and-WM' and 'search-only' tasks, respectively). This was done in an attempt to remove attention resources in the search task and thus eventually lead to the development of automatic contextual cueing (Schneider & Fisk, 1982). Contextual cueing effects (i.e., RTs [non-repeated display] minus RTs [repeated displays]) were compared between the search-only and search-and-WM conditions, the former serving as a baseline condition. If a concurrent spatial WM task can facilitate the development of automatic cueing, then we should see a cueing effect also in the search-and-WM condition. In Experiment 1, the same repeated display arrangements were shown in search-only and search-and-WM trials. Experiment 2 used different sets of repeated search displays in the search-only and search-and-WM condition to provide a more conservative test for the effects of dual-task training on contextual cueing performance. After each experiment, a recognition test was administered: participants were presented with a certain visual search display and had to indicate whether or not they believed having seen this display in the previous search task (two-alternative forced-choice, 2AFC, task; cf. Chun & Jiang, 1998).

4.3 Experiment 1

Experiment 1 examined the guidance of visual search by learned spatial contexts stored in long-term context memory under default (i.e., no load) and cognitively demanding WM load conditions (search-only and search-and-WM trials, respectively). These conditions were administered in alternating blocks of trials. According to Schneider and Fisk (1982), the existence of search-only and search-and-WM trials (blocks) should facilitate the development of automaticity in the visual search task. Applied to contextual cueing this could mean that the effect survives a concurrent, capacity-dependent WM task. This hypothesis was tested in Experiment 1.

4.3.1 Method

Participants

A total of 17 participants took part in Experiment 1 (10 female; mean age: 23.88 ±1.16 years). All reported normal or corrected-to-normal vision. Participants gave written informed consent and were fully debriefed after the experiment in accordance with the experimental protocol, which was approved by the ethics committee of the Department of Psychology at LMU Munich. They were compensated with either course credit or monetary payment (8 Euro, i.e., ~9 USD). The experiment was conducted in a single session lasting between 2-2.5 hours.

Apparatus

The experiment was programmed in Matlab (version 8.0.0.783 R2012b), in combination with the OpenGL-Psychtoolbox extension (version 3.0.12, Brainard, 1997) and was run on an Intel computer controlled by the Windows 7 operating system. The stimuli were presented on a 22" TFT-monitor (60 Hz refresh rate), at a distance of ~55 cm from the participant. Responses were recorded through the keyboard. Auditory stimuli (i.e., digits) and feedback to the erroneous responses were given through headphones. A high tone was given for correct and a low tone for erroneous responses.

Task and Stimuli

Observers performed two types of experimental tasks: visual search and working memory.

Visual search task

The search stimuli included a T-shape target item, rotated by either 90° or 270° to the left or the right, and 15 L-shaped items as the distractors, rotated by either 0°, 90°, 180° or 270° (see Annac et al., 2013). All items were presented on four concentric circles with radii of 1.7, 3.4, 5.1, and 6.8°. Targets appeared only on the second and the third circles to reduce variability in reaction times (see Annac et al., 2013). There were overall 24 possible target locations, 12 of which (3 in each quadrant) were used for repeated displays, presenting an invariant distractor layout throughout the experiment. The other 12 target locations (again 3 in each quadrant) were used for non-repeated displays with random distractor arrangements. The reason for this was to balance target location repetition effects across repeated and non-repeated displays. – Any performance gains in the repeated condition can thus be only attributed to the learning of the target relation to the constant background of distractor elements rather than the learning of absolute target positions. The color of the items was chosen randomly among red (45.8 cd/m^2), blue (12.5 cd/m^2), yellow (232 cd/m^2), green (183 cd/m^2), with the restriction that each color occurred equally often in the display (25%). The color assignments of both target and distractors were kept constant in repeated displays and the color of the target was constant in non-repeated displays. To avoid learning of a contingency between a given spatial configuration and search task response, the target's orientation (left, right) in both repeated and non-repeated displays changed randomly across. In repeated displays, also the orientation of distractors was held constant across trials. The stimuli were presented on a gray background (RGB = [128, 128, 128], 45.9 cd/m^2).

WM tasks

There were two working memory tasks: an auditory working memory task ('auditory-WM') and a spatial working memory task ('spatial-WM'). In the auditory-WM task, there were two sequential digits (randomly selected between 1-9) that were presented at the beginning of each trial. Participants should memorize these digits and recall them at the end of a given trial. The spatial-WM task consisted of two or four black squares (randomly selected for each trial) with a square size of 0.6 º x 0.6 º. The black squares were presented after stimulus offset in the auditory-WM task. The positions of each square were randomly chosen among eight equidistant locations on an imaginary circle (radius approximately 3.08°;

see Annac et al, 2013). Participants were required to remember the locations of the squares and report them after the visual search display. A trial finished with the presentation of two digits in center of the screen. Participants should indicate whether these digits were same or different relative to those presented at the beginning of the trial (see Design and procedure for details). The stimuli were again presented on gray background (RGB = [128, 128, 128], 45.9 cd/m^2).

Design and procedure

There were two search tasks: search-only and search-and-WM.

Search-only

In search-only trials, participants were required to only search for the target “T” letter presented amongst distractor “L” letters, while being as fast and as accurately as possible. Each trial started with a central fixation cross that was presented for 2000 ms. Following this event, the visual search display was presented, either until a response was given or for a maximum of 3500 ms. If the “T” was oriented to the left (right), participants were required to respond with the left (right) arrow key of the computer keyboard. Participants’ response was followed by a blank inter-stimulus-interval (ISI) of 500 ms duration.

Search-and-WM

In this task, observers were required to perform the visual search task in addition to the auditory-WM and spatial-WM tasks (See Figure 1A). Each trial started with the presentation of the to-be-memorized auditory-WM stimuli (2 digits) via headphones during which a fixation cross was presented on the screen for 2000 ms. This event was followed by the spatial-WM stimuli (either 2 or 4 black squares) around the fixation cross that was presented for 500 ms. Participants were supposed to memorize and retain the auditory- and spatial-WM stimuli. Thereafter, the search items (1 target, 15 distractors) were presented until participants’ button press or for a maximum of 3500 ms. The visual search task was followed by a retention period (blank screen) for 4000 ms. Following the retention period, participants spatial WM was probed by presenting a single black square at a certain position around the fixation cross. This position coincided with a position of one of the previous spatial WM items in 50% of the trials (the square position was randomly selected for one out of the 2 or 4 WM items). Participants should press the 'A' key if they believe that the square location was same as before or the 'D' key if the location was different. At the end of the trial, auditory-WM was tested by means of two new digits presented for maximum 3000 ms at the center of the screen. Participants should indicate whether the two digits were same or different relative to the two digits presented at the beginning of the trial. Again, the pressed the ‘A’ or ‘D’ keys for same or different responses. This procedure was also used by Annac et al. (2013).

Importantly, the search-only and search-and-WM tasks were administered in an alternating fashion across blocks of (24) trials (see Figure 1B). Odd (even) numbers of block contained the search-only (search-and-WM) condition, which was counterbalanced across participants. There were 30 blocks in total (e.g., 15 blocks search-only and 15 blocks search-and-WM; excluding the practice blocks), each consisting of 24 trials, leading to a total of 720 trials (i.e., 360 repeated and 360 non-repeated displays). The same set of (12) repeated configurations were used in the search-only and search-and-WM conditions.

Prior to the experiment, participants practiced the experimental task in a dedicated practice session, consisting of one search-only and one search-and-WM block (data not recorded; the order of conditions was counterbalanced across observers and preserved in the subsequent experimental session). All visual search configurations that were used during the practice session were not used in the following experimental session. At the end of the experiment, a ‘surprise’ recognition test of 24 trials was administered (12 repeated, 12 non-repeated displays). Participants were asked to decide whether or not they had seen a given display during the visual-search task.

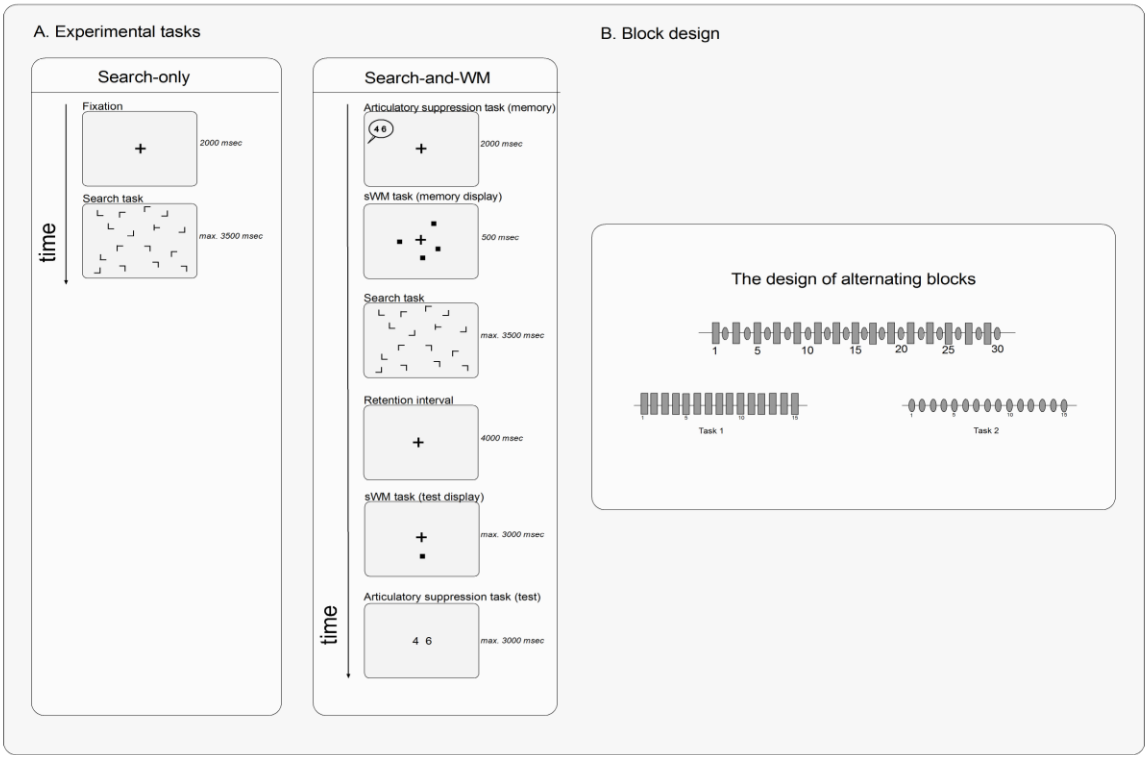


Figure 1: (A) Illustration of the experimental tasks search-only and search-and-WM. In Experiment 1, the search task was given either as a single task or a dual task where a secondary spatial working memory task was combined with the search task. (B) The two tasks were presented in blockwise-alternating order.In Experiment 2, additionally two unique repeated displays were applied in each task, and in the last epoch, the two repeated sets were switched from one condition to the other. In the dual task, the spatial WM task was given with an articulatory suppression task.

4.3.2 Results and discussion

Data analysis was performed using R (R Core Team, 2014). Error trials and trials with extreme RTs (outside 2.5 SDs from the individual mean) were discarded. In order to obtain reasonable estimates of the contextual cueing effect, the data of 6 consecutive blocks of trials were pooled into one ‘epoch’ (see Chun & Jiang, 1998), resulting in 5 experimental epochs.

Response accuracy in search-only and search-and-WM trials

Mean response accuracy in the search-only condition was 90.6%. A 2 (display type: repeated, non-repeated) x 5 (epoch: 1-5) repeated-measures ANOVA revealed main effects of display type, $F(1,16)=7.82$, $p<0.01$ and epoch, $F(4,64)=3.27$, $p<0.01$, indicating that response accuracy was overall higher for repeated displays (main effect of display type) and that accuracy performance improved over the course of the experiment (main effect of epoch). The interaction between epoch and context was also significant, $F(4,64)=3.12$, $p<0.05$, indicating that the beneficial effects of repeated contexts on accuracy performance increased with increased practice on the experimental task. A similar analysis on response accuracy in the search-and-WM condition (mean accuracy was 91.0% in this condition) only revealed the main effect of epoch significant, $F(4,64)=4.25$, $p<0.01$. A final analysis examined observers’ search task accuracy in both search-only and search-and-WM trials by means of repeated-measures ANOVA with the factors display type (repeated, non-repeated), epoch (1-5), and search task (search-only, search-and-WM). This ANOVA revealed the main effects of display type, $F(1,16)=4.51$, $p<0.05$ and epoch, $F(4,64)=5.60$, $p<0.01$ significant.

Memory accuracy in search-and-WM trials

Mean accuracy in the spatial working memory task was 76%, a value that is comparable to previous investigations (e.g., Manginelli et al., 2013). A repeated-measures ANOVA with the factors WM load (2, 4 items), display type (repeated, non-repeated), and epoch (1-5) revealed main effects of epoch, F(4,64)=3.66, p<0.01 (accuracy was higher in late relative to early epochs), and WM load, F(1,16)=54.33, p<0.01 (accuracy was higher with 2 compared to 4 WM items. Accuracy in the auditory working memory task was quite high at 97%. A 2 (load) x 2 (display type) x 5 (epoch) repeated-measures ANOVA revealed no significant effects (all p’s>.05).

RT performance: contextual cueing effects

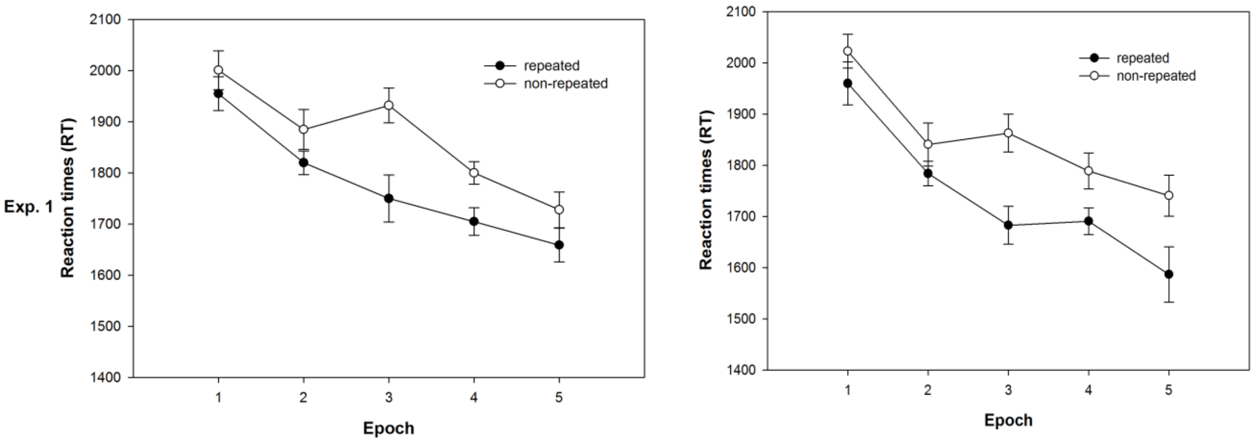
The first set of analyses was carried out independently for the search-only and search-and-WM tasks to better understand the temporal development of the contextual cueing effect in each task. For instance, it is possible that observers, under the present dual task conditions, can learn (i.e., automatize) the use of context cues for their visual search task. However the additional WM task would still be demanding task and exert a suppressive effect on development of the cueing effect. Three scenarios are possible. First, the WM task may decrease the speed with which observers display a contextual cueing effect. If so, contextual cueing would be reliable only in late epochs of search-and-WM trials but comparable in effect magnitude relative to search-only trials. Second, contextual cueing in search-and-WM trials may be developed as early as in search-only trials but the demanding WM task may generally weaken the magnitude of the cueing effect. The third outcome is that contextual cueing, in the search-and-WM task, develops as early, and with similar magnitude, as in the single search task. This would mean that the alternating application of the WM task (in search-only vs. search-and-WM blocks) is a very strong facilitator of the development of automatic contextual cueing.

For the search-only task, a 2 (display type: repeated, non-repeated) x 5 (epoch: 1-5) repeated-measures ANOVA revealed main effects of display type, F(1,16)=7.70, p=0.01; see Fig. A1) and epoch, F(4, 64)=15.63, p<0.001. Further, the cueing effect increased with epochs (see Fig. 2), though this observation was not substantiated statistically F(4, 64)=1.86, p=0.12. FLSD tests showed that contextual was reliable from epoch 3 onwards (mean cueing effect in epochs 3-5: 137 ms; p < 0.01). Crucially, a repeated-measures ANOVA performed on reaction times in the search-and-WM task also revealed main effects of display type, F(1,16)=9.76, p=0.007; see Fig. A2) and epoch, F(4, 64)=17,72, p<0.001. Again, there was a tendency for the reaction time benefit for repeated over non-repeated displays to became more pronounced as Experiment 1 progressed: display type x epoch interaction, F(4, 64)=2.17, p=0.08. As revealed by FLSD tests, repeated contexts facilitated visual search from epoch 3 onwards (mean cueing effects arising from epochs 3-5: 144 ms; all *p*’s < 0.01.

The results from the search-only task are in line with previous investigations of contextual guidance of visual search, which indicates that context information can serve as a strong cue for the detection and subsequent processing of the target in repeated displays (see, e.g., Geyer, Zehetleitner, & Müller, 2010; Kunar, Flusberg, Horowitz, & Wolfe, 2007; Peterson & Kramer, 2001). Most importantly, there was a contextual cueing effect also in the search-and-WM task, which was comparable, in terms of its onset and magnitude, with that in the search-only task. This result was further bolstered by a combined analysis of contextual cueing effects in both the search-only and search-and-WM tasks. A 2 (search task: search-only, search-and-WM) x 2 (display type: repeated, non-repeated) x 5 (epoch:1-5) ANOVA found significant effects of display type F(1,16)=11.02, p<0.005, and epoch F(4,64)=25.79, p<0.001. Further, the display type x epoch interaction was also significant, F(4,64)=3.52, p<0.01). Importantly, there were no effects (main effects and interactions) involving the factor search task (all p’s>.07).

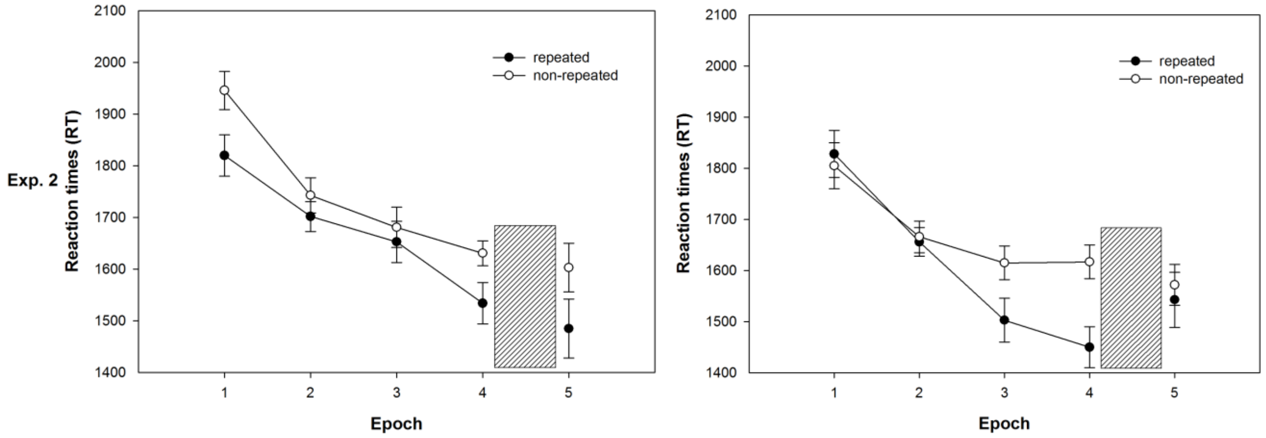
Comparison of contextual cueing effects between low and high WM load

However, caution is indicated in interpreting the above finding in terms of the independence of contextual cueing from a demanding spatial WM task. Recall that the search-and-WM task used variable levels of load (2- vs. 4-WM items). It is thus possible that contextual cueing was particularly reduced under high WM load but functional (and strong) under low WM load. Crucially, high levels of contextual cueing with only two WM items could up-modulate a (small) cueing effect obtained with four WM items, thereby increasing the overall cueing effect when reaction times are averaged across all levels of WM load. However, a comparison of contextual cueing between low and high WM load conditions (2 and 4 WM-items, respectively) did not confirm this hypothesis. Instead, contextual cueing was comparable in the two load conditions. A repeated-measures ANOVA with the factors WM load (2, 4), display type (repeated, non-repeated) and epoch (1-5) only revealed a main effect of display type $F(1,16)=9.77$, $p<0.01$, in addition a main effect of epoch, $F(4,64)=17.70$, $p<0.01$. The mean contextual cueing effect arising in epoch 1-5 from low WM load was 96 ms and that from high WM load 124 ms.



A1. Search-only

A2. Search-and-WM



B1. Search-only

B2. Search-and-WM

Figure 2: Results of Experiment 1 and 2. Mean reaction times and standard errors for repeated and non-repeated displays as a function of epoch. Panels A1 and A2 reveal the results from Experiment 1 where the conditions search-only (A1) and search-and-WM (A2) tasks were applied with experimental epochs 1-6. Panels B1 and B2 reveal the results from Experiment 2 with the conditions search-only (B1) and search-and-WM (B2) with experimental epochs 1-5.

4.4 Experiment 2

Experiment 2 further examined contextual cueing in the presence of a demanding spatial WM task. Experiment 1 revealed robust contextual cueing under WM load, which we attribute to the effects of our alternating dual-task training regime on the development of automatic, WM-independent, contextual cueing. However, there is an alternative proposal to this training view, assuming that contextual cueing is actually developed in the search-only task and transferred to search-and-WM trials. This account is feasible, given that the very same display arrangements were used in the two conditions. To some extent, the alternative proposal is similar to the training view in that successful contextual cueing in a WM task is practice-dependent. However, it is different from the training view in that reliable contextual cueing under WM conditions stems from training in the single task, and the sharing of context memory across the single and dual tasks, rather than practicing automatic context cueing of visual search under WM load conditions. In order to decide between these hypotheses, Experiment 2 used task-specific display arrangements. One set of repeated displays was exclusively shown in the search-only and the other set in the search-and-WM task. This setup prevents any transfer of context memory across the single-search and dual-search tasks. The training hypothesis predicts a reliable contextual cueing effect in the search-only and, importantly, also in the search-and-WM tasks under conditions of separate sets of repeated displays. According to the alternative (transfer) hypothesis, a reliable contextual cueing effect is expected only for the search-only task.

4.4.1 Method

The method of Experiment 2 was essentially similar to Experiment 1, except for the details provided below.

Participants

A total of 17 new participants took part in the experiment (7 female; mean age: 27.76 ±3.63 years).

Design and procedure

In Experiment 2, two different sets of repeated configuration were used for the search-only and search-and-WM tasks. In more detail, there were two unique repeated display sets, each consisting of six repeated displays for the search-only and search-and-WM conditions. Thus, the total number of repeated displays was comparable between Experiment 1 and 2 (N=12 repeated displays). Further, in order to equate Experiments 1 and 2 in terms of the duration of the experimental sessions, in Experiment 2 each repeated display arrangement was shown twice per block, leading to 6 x 2 = 12 presentations of displays per block. These 12 repeated displays were presented together with 12 non-repeated displays at random insertions in a given block of (24) trials. There was again a total number 30 blocks in Experiment 2. Half of them contained search-only and the other half search-and-WM trials. Observers started either with the search-only or search-and-WM task, which was counterbalanced across trials. In epoch 5 (blocks 25-30), the two repeated sets were swapped between the search-only and search-and-WM tasks. This was done as a secondary check to prove the idea that context memory can be shared between search tasks (the hypothesis developed in relation to Experiment 1). If so, we expected a reliable contextual cueing effect for initial search-only (search-and-WM) configurations if they were now presented in search-and-WM (search-only) trials. Statistical analyses were done separately for epochs before and after the swap of two sets of repeated displays.

4.4.2 Results and discussion

Accuracy in Search-only and search-and-WM trials

Mean accuracy in search-only trials was 92.2%. A 2 (display type: repeated, non-repeated) x 4 (epoch: 1-4) repeated-measures ANOVA on the error rates revealed main effects of display type, F(1,16)=6.94, p=0.01 and epoch, F(3,48)=4.05, p=0.005, indicating higher response accuracy for repeated displays (main effect of display type) and an increase in accuracy with epochs (main effect of epoch). Mean accuracy for the search-and-WM task was 92.9%, and a 2 (display type: repeated, non-repeated) x 4 (epoch: 1-4) repeated-measures ANOVA revealed the main effect of epoch significant, (3, 48)=3.79, p<0.01. A comparison of response accuracy after the swap of repeated display sets in epoch 5 of the experiment did not reveal a difference between repeated and non-repeated displays, neither in search-only trials (93.5 and 92.4%, t(16)=.21, p=.84) nor in search-and-WM trials (91.2 and 88.9%, t(16)=-1.23, p=.23). A combined repeated measures ANOVA with the factors display type (repeated, non-repeated), epoch (1-4), and search task (search-only, search-and-WM) revealed main effects of display type, F(1,16)=6.41, p=0.02, epoch, F(3,48)=5.84, p<0.001, and search task, F(1,16)=11.51, p=0.003. The main effect of display type occurred because response accuracy was higher in repeated relative to non-repeated displays (93.0 and 92.0%). The epoch main effect was due to a significant increase of response accuracy with increasing epochs (epoch 1: 91.6%; epoch 4: 93.3%). And, the task main effect indicated that accuracy was slightly lower in search-only relative to search-and-WM trials (92.2 and 92.9%). A 2 (display type) x 2 (task) repeated measures ANOVA performed on response accuracy after the swap of repeated sets showed no significant effects (all p's>.06).

Memory accuracy in WM blocks

The accuracy of spatial working memory task was quite high at 89.2%. A repeated-measures ANOVA with the factors WM load (2, 4 items), display type (repeated, non-repeated) and epoch (1-4) revealed only a main effect of epoch, F(4,64)=3.81, p=0.007. A similar ANOVA performed on response accuracy in the auditory WM task revealed no significant effects (all p's>.05). Mean accuracy in this task was 98.0%. 2 (display type) x 2 (WM load) repeated-measures ANOVA's on performance in the spatial and auditory WM tasks after the swap of repeated displays in epoch 5 revealed no significant effects (all p's>.23).

RT performance: contextual cueing effects

For the search-only condition, a 2 (display type: repeated, non-repeated) x 4 (epoch: 1-4) ANOVA revealed main effects of epoch, F(3,48)=23.14, p<0.001, and display type, F(1,16)=3.99, p<0.05, (see Fig. B1). These results mirror the results from Experiment 1: reaction times became faster with increasing epochs (main effect of epoch). Further, the target was detected faster in repeated compared to non-repeated displays (main effect of display type). Interestingly, this context-based facilitation of search reaction times became measurable already in the first epoch of trials and was not modulated by increased practice on the experimental task (interaction display type x context: F(3,48)=1.25, p=.30). The relatively early onset of contextual cueing is not unusual (see, e.g., Schlagbauer, Mink, Müller, & Geyer, 2017), and may particularly come to the fore when the statistical power for assessing contextual cueing is high (as with Experiment 2, which used two presentations of the very same repeated displays in a given block of trials). A different result pattern was obtained in the search-and-WM task. The 2 (display type) x 4 (epoch) repeated measures ANOVA revealed a main effect of epoch, F(3,48)=28.35, p<.01, but not display type, F(1,16)=1.76, p=.20. However, the epoch x display type interaction was significant, F(3,48)=4.97, p<.01. Inspection of Fig. 2 suggests and FLSD test confirmed a reliable contextual cueing effect in epochs 3 and 4 of the search-and-WM task (both p's < .05). The differences in the early versus late development of the cueing effect in the search-only and search-and-WM tasks was also substantiated by a 2 (task) x 2 (display type) x 4 (epoch) repeated-measures ANOVA, which revealed the three-way interaction significant, F(3,48)=3.32, p<.05 (besides main effects of epoch, F(3,48)=46.83, p<.01, and display type, F(1,16)=6.23, p<.01).

Interestingly, there was an asymmetric transfer of cueing memory from one to the other task (see also Figure 2). Only repeated displays that were learned in search-and-WM trials continued with the search facilitation when later shown in search-only trials in epoch 5 of the experimental session; 1485 vs. 1603 ms, one-tailed t(16)=2.03, p<.05 (repeated vs. non-repeated display respectively). Repeated displays learned initially in the search-only task did not produce a contextual cueing effect when these displays were later shown in the search-and-WM task; 1543 and 1572 ms, one-tailed t(16)=-.64, p=.26 (repeated vs. non-repeated displays, respectively).

Experiment 2 tested whether the cueing effect observed under WM load in Experiment 1 was due to dual-task training or memory transfer. We found a reliable contextual cueing when the visual search task was performed together with a concurrent spatial WM task, replicating the main finding from Experiment 1. However, in contrast to Experiment 1, in Experiment 2 there were two different sets of repeated displays that were presented exclusively in the search-only and search-and-WM tasks. Since this would make any transfer of context memory across tasks (blocks) impossible, the reliable cueing effect in the search-and-WM condition is likely due to practice effects stemming from search-and-WM trials and with it the development of automatic context memory. However, context-based search facilitation developed more slowly in search-and-WM trials, suggesting that (1) the spatial WM task interferes with context learning in the visual search; and (2) this interference can be best described as a gradual rather than constant disadvantageous effect. In this regard note that under WM load context memory became measurable only in later epochs, though it achieved a performance level that was comparable to single task conditions.

A somewhat unexpected finding was that of an asymmetrical transfer of context memory. The cueing effect was functional only in the search-only task after the swapping of repeated search sets. This means that repeated display configurations that yielded a contextual cueing effect initially in the search-and-WM task, continued with their facilitation of search reaction times later on in the single search task. To our surprise, no such effect was observed for repeated displays that were learned in the single search tasks (epochs 1-4) but tested in the search-and-WM task (in epoch 5). But note that these ‘single-search’ configurations yielded a reliable contextual cueing effect in the initial learning phase. Although transfer of context memory across different tasks has been shown previously (e.g., Jiang & Song, 2005, Ogawa & Kumada, 2008), the asymmetric pattern of transfer effects is still surprising. One way how this may work is that both tasks engage different spatial learning processes of configural and non-configural learning (cf. Jiang & Wagner, 2004; Beesley, Vadillo, Pearson, & Shanks, 2016). Configural learning refers to the build-up of an association between the target position and the entire distractor configuration. In non-configural learning, on the contrary, participants form associations between the target location and individual distractor locations. It has been shown that WM load can make visual search less efficient, reflected by a higher number of attentional deployment towards single display items (e.g., Woodman, Luck, & Schall, 2007). This ‘serial’ deployment of attention may lead to some items (distractors) being tightly associated with the target, which would be equivalent to non-configural learning. By contrast, attention may be deployed more strongly to the entire display configuration in search-only trials, which would foster configural learning. Interestingly, Jiang and Song (2005) showed that context memory can transfer from a ‘non-configural’ to a ‘configural’ task (but not the other way around). Given this finding, we speculate that particularly ‘non-configural' context memory formed for the 'search-and-WM' configurations transfers to the single search task.

Comparison of contextual cueing effects between low and high WM load

A further comparison of contextual cueing effects for low and high WM load revealed that contextual cueing in Experiment 2 was not differentially affected by the amount of WM load. A repeated measures ANOVA with the factors WM load (2, 4), display type (repeated, non-repeated) and epoch (1-4) revealed the main effect of epoch, $F(3,48)=8.51$, $p<0.01$ and the epoch x display type interaction to be significant, $F(3,48)=3.22$, $p<0.06$. The interaction was due to an increase in contextual cueing with epochs (epoch 1: 34-ms effect; epoch 4: 190 ms-effect; see Figure 2). Crucially, there was no effect involving the factor search task (neither main effect nor interactions), suggesting that the development of the cueing effect was comparable across the two levels of WM load. A final analysis done on reaction times in epoch 5 after the swapping of repeated displays showed no reliable effect of context memory neither with 2-WM items (RTs for repeated and non-repeated displays: 1485 and 1489 ms; one-tailed $t(16)=-.08$, $p=.46$) nor with 4-WM items (1614 and 1623 ms, one-tailed $t(16)=-.08$, $p=.46$).

Recognition performance

Participants' ability to explicitly recognize repeated displays was tested by means of the signal detection measure *d* prime [$d' = Z$ (hit rate) − Z (false-alarm rate); Green & Swets, 1966]. A hit means that observers correctly identified a given repeated display as being presented during the actual search experiment. A false alarm means that they incorrectly judged a newly composed (non-repeated) display as previous repeated display in the recognition test. In order to increase the statistical power of the recognition test (see, e.g., Vadillo, Konstantinidis, & Shanks, 2016), the analysis of explicit recognition performance was collapsed across the two experiments (N=34 observers). The hit rate was not reliably different from the false alarm rate: 0.52 and 0.49, *t*(33)=0.68, p=0.49. Moreover, mean d prime was .08, which was not significantly different from zero, *t*(33) =0.71, p=.48. These results suggest that observers could not reliably discriminate between repeated and non-repeated displays.

4.5 General Discussion

The results of Experiment 1 and 2 would promote that idea of memory-based automatization of contextual cueing. Previously, it was suggested that concurrent spatial WM load interferes with the context-based guidance of visual search and this effect is larger in the retrieval from context memory (Manginelli et al, 2011; Annac et al., 2013). However, a secondary WM task may not always restrain, but actually, benefit visual search. Schneider and Shiffrin (1977) claimed that visual search performance improves with extended practice, and practice-related benefits depend on the characteristics of a given task. They further differentiated between automatic and controlled processes in order to clarify the effects of training on current task performance. Only tasks with consistent target-response mappings can benefit from training and given sufficient task practice, they are executed with few, if any, demands on spare short-term memory capacity stores (Schneider & Fisk, 1982). The development of automaticity in contextual cueing of visual search was investigated in Experiment 1 using a practice regime that was similar to that of Schneider and Fisk (1982): The memory-based visual search was paired either with or without a demanding secondary spatial WM task in alternating blocks of trials. The idea is that the secondary task gathers attention control processes, such as search of short-term and long-term memory or the transfer of information into and out of working memory, and that these enhanced processing requirements facilitate the development of automaticity, expressed by a reliable contextual cueing effect under dual-task conditions. Experiment 1 confirmed this prediction. However, there remained the alternative possibility that training of the single task helped contextual cueing in the dual task (since the same repeated configurations were used in these tasks). Experiment 2 thus investigated contextual cueing using different sets of repeated displays in search-only and search-and-WM trials. There was again a contextual cueing effect under spatial WM load, demonstrating the need for (the engagement of) control processes for the development of automatization, i.e., the retrieval of learned display arrangements from context memory.

4.5.1 Implications for the relationship between contextual cueing and divided attention

Previous studies are not univocal regarding the contribution of attention to the contextual cueing effect. Repeated displays need to be attended in order to observe a reliable cueing effect (Jiang & Chun, 2001). Further, it has been shown that selective attention is a requirement particularly in the retrieval from context memory (Jiang & Leung, 2005; Geyer, Shi, & Müller, 2010). Similar results, and conclusions, apply to manipulations of divided attention. For instance, the findings of Manginelli et al. (2011, 2013) strongly suggest that concurrent search and WM tasks compete for spatial WM functions; for instance, contextual cueing might be contingent on loading a set of learned spatial associations from long-term memory into WM in order to guide visual search. On this assumption, contextual cueing would be a long-term memory phenomenon that relies on controlled WM processes (Schneider & Shiffrin, 1977): WM may provide the “workspace” that permits information stored in configural long-term memory to be linked with information contained in the search display. At the same time, Schneider and collaborators (Schneider & Fisk, 1982) have shown that retrieval from long-term memory can become an automatic, capacity-free, process, which is depending on the amount of training on the task (given the consistency of target-response mappings as in the present experiments). Specifically, Schneider and Fisk (1982) observed practice-related gains in a consistent-mapping visual search task, which were even higher when the (consistent-mapping) task was performed in combination with a variable-mapping visual search task, the latter requiring controlled processing. Applied to the contextual cueing of visual search, it is possible that the effect is reduced under spatial-working memory load (Manginelli et al., 2011, 2013, Annac et al., 2013). However, with specific training, automatic retrieval from context memory can develop irrespective of the load by a secondary WM task. Note that the term "specific" means that the training is not 'simply' long-lasting, such that observers perform hundreds of trials in sequences of either search-only or search-and-WM trials (as in Annac et al., 2013). Instead, specificity means that the search task is performed in alternating blocks of search-only and search-and-WM trials, as the results of Schneider and Fisk (1982) would suggest and as we have tested in the present investigation. Future work may design other practice regimes and evaluate their impact on the development of automaticity in the memory-based guidance of visual search.

4.5.2 An alternative to the controlled-automatic processing dichotomy in contextual cueing

The above proposal assumes the existence of automatic and controlled processes, with contextual cueing being a form of memory-based automaticity (Chun & Jiang, 1998). Further, it assumes that the effect can be trained up to a level that is almost independent of WM load. However, there is an alternative idea that stands in contrast to the different-processes view, proposing that instead of the development of automatic contextual cueing, participants become better in their representation of individual (search, WM) tasks, and a more efficient use of spare WM capacity stores. This idea borrows from current conceptions of working memory (e.g., Oberauer & Hein, 2012), suggesting that working memory consists of multiple nodes or components distributed across both 'classical' short-term memory (i.e., *broad focus of attention*) and long-term memory (i.e., *activated part of LTM*). Given these components, in search-and-WM trials, a currently non-relevant WM cue (e.g., a working memory display when performing the search task) could be 'outsourced' to LTM, freeing capacity in the limited broad focus of attention. The broad focus would then be available for items in the current search display and the comparison of these items with corresponding context representations in LTM, which would be equivalent to the retrieval of these items from LTM. So, while the alternative account also assumes a role of practice in contextual cueing, the practice would not necessarily lead to automatic retrieval of learned context cues from long-term memory. Instead, the practice would enhance observers’ ability to use individual WM cues (working memory display, current search display) and WM stores (broad focus of attention, activated part of LTM), leading to reliable contextual cueing even in the presence of a secondary spatial WM task.

4.6 Conclusion

The present experiments investigated the relationship between context learning in visual search and divided attention. We present new evidence that spatial WM load does not necessarily interfere with contextual cueing, as it was shown in previous studies (including our own). Presumably, with specific training automatic retrieval from context memory can develop or observers may advance in their use of spare WM stores. This suggests that at least two factors affect the retrieval from context memory: WM load and the type of training on the visual search or contextual cueing task.

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4.8 Acknowledgements

This research was supported by grants from the German Research Council (DFG) to Thomas Geyer (GE 1889/3-1; RTG 2175). Questions concerning study design, data acquisition, and data analysis should be sent to Efsun Annac.

Chapter 5:

Recognition of contextual cueing of visual search is supported by fixational eye movements

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5.1 Abstract

Repeated encounter of target–distractor (spatial) arrangements leads to improved search for such displays. This ‘contextual cueing’ effect is attributed to incidental learning of display configurations. Whether observers can consciously access the memory underlying the cueing effect in a recognition test administered after learning is still a controversial issue. The current study is the first to use eyetracking during the recognition memory test phase, permitting the relation between contextual memory, fixational eye movements, and explicit knowledge of repeated displays to be examined. In Experiment 1, we monitored where observers’ eye fixations would fall while they freely viewed the test display, examining the link between the fixation pattern and explicit recognition judgments. In Experiment 2, we tested whether eye fixations would serve a critical role for explicit retrieval from context memory. Experiment 3 followed on this question and asked whether eye fixations of the target region are critical for the contextual cueing of visual search. The results revealed longer fixational dwell times in the target quadrant for learned relative to previously unseen (foil) displays. Further, explicit recognition was enhanced, and above chance level, when observers were given the opportunity to fixate the target quadrant as compared to when they were prevented from doing so. Critically, observers’ conscious performance was also significantly correlated with their contextual cueing scores. The results argue in favor of contextual cueing of visual search being supported by separable retrieval processes, with fixational eye movements, i.e., the allocation of visual attention, providing an interface between non-/conscious information processing.

Keywords: Visual Search, Contextual Cueing, Memory Systems, Eyetracking

5.2 Introduction

Extracting statistical regularities from a scene is a central capacity of the human visual system (e.g., Chun, 2000; Draschkow, Wolfe, & Võ, 2014; Jiang, Swallow, & Rosenbaum, 2013). For example, if a searched-for target is repeatedly encountered in an invariant (spatial) arrangement of distractor elements, observers can learn these configurations and use them to expedite their search – an effect termed 'contextual cueing' (Chun & Jiang, 1998; Chun, 2000). There is an ongoing controversy whether contextual cueing is supported by a single, explicit, memory system (e.g., Vadillo, Konstantinidis, & Shanks, 2016) or whether it is more appropriate to assume two independent, implicit and explicit, memory systems supporting contextual cueing and recognition of the (target location within) repeated displays, respectively (e.g., Colagiuri & Livesey, 2016). This debate centers mainly around the (null) finding of a lack of explicit memory for repeated displays, while these displays, at the same time, give rise to reliable reaction time (RT) gains in visual search. The present study was designed to investigate whether context cueing would manifest in other, potentially more sensitive, memory measures than explicit recognition responses, in particular: the pattern of eye fixations while deciding where a target was located in the memory test display. If so, a follow-on question was how the processes underlying contextual memory expressed in eye fixation and explicit recognition measures relate to each other: in a causal or merely a correlational way.

5.3.1 Implicit or explicit contextual cueing?

Chun and Jiang (1998), in their seminal study, proposed that contextual cueing is an implicit effect – which has, however, become a controversial issue on both theoretical and methodological grounds (Chun & Jiang, 2003; Colagiuri & Livesey, 2016; Schlagbauer, Müller, Zehetleitner, & Geyer, 2012; Smyth & Shanks, 2008; Vadillo et al., 2016). While standard tests of recognition in contextual cueing studies typically fail to find an explicit effect (for review see, e.g., Goujon, Didierjean, & Thorpe, 2015), increasing the test power has been argued to be sufficient for revealing above-chance recognition (Smyth & Shanks, 2008). This is supported by a recent meta-analysis by Vadillo et al. (2016), which showed that, even though single studies may not ‘detect’ explicit recognition of repeated search displays, the combined evidence indicates above-chance recognition. Both groups concluded that contextual cueing is, in fact, based on a single, explicit memory system (Newell & Shanks, 2014; Vadillo et al., 2016). However, this view has been challenged very recently by an investigation of contextual cueing in very large samples (Colagiuri & Livesey, 2016). Colagiuri and Livesey found no relationship between cueing and awareness, which led them to conclude that contextual cueing is a form of non-conscious perceptual learning and that cueing and recognition are supported by two independent memory systems.

5.3.2 Eye movements index relational memory

While the dissociation between measures of contextual cueing and awareness indeed implies that there exist (at least) two separate sources of processing, on logical grounds, there is no reason to take this as evidence for separable memory systems. Recent accounts of long-term memory conceive of retrieval as a two-stage process, involving a fast, non-conscious process (‘ecphory’) and a second, slower process in which the output of the first stage becomes consciously accessible (e.g., Moscovitch, 2008). As regards contextual cueing, successful retrieval at the first stage may be revealed by *indirect measures*, such as the facilitation of reaction times due to learned target-distractor arrangements in the visual search task or increased fixational dwell times for repeated versus non-repeated displays in an explicit recognition task (the latter is the focus of the current study). Further, the explicit recognition task can itself provide *direct measures* of retrieval at the second stage, such as observers ability to correctly report the display region (quadrant) where the target had previously been presented in a visual search display (Chun & Jiang, 2003). On this view, of distinct processes supporting the retrieval from context memory, it is possible that even though there is only poor recognition at the second stage (a standard finding in contextual cueing experiments; see above), retrieval of contextual cues may nevertheless be revealed (at the first stage) when more sensitive, oculomotor memory measures are employed.

The present study was designed to examine this idea. Specifically, we recorded eye movements during the explicit-recognition memory test of previously, incidentally learned target–distractor arrangements. An increasing number of studies show that eye movements, in particular fixation locations, provide highly sensitive memory measures that can distinguish learned from non-learned materials – importantly, in the absence of participants' awareness (e.g., Ryan, Althoff, Whitlow, & Cohen, 2000; Hannula & Ranganath, 2009; Hannula, Baym, Warren, & Cohen, 2012). On this background, in Experiment 1 we asked whether the idea that retrieval of contextual memory is mediated by different types of (fast and slow) processes would be supported by eye fixation patterns evidencing contextual cueing when explicit recognition of learned contextual cues is only at chance level.

Given that the eye movements indicate successful retrieval of contextual cues, our follow-on question addressed in Experiment 2 concerned the relation between the fixation patterns (reflecting the first, fast stage of retrieval) and explicit memory (reflecting the second, slow stage of conscious recollection). While this two-stage notion is appealing – it could explain a plethora of findings regarding a dissociation between contextual cueing and awareness – it would raise a new question, namely: how does contextual information available to fast, nonconscious retrieval relate to information supporting (slow) conscious recollection? Specifically, are the two stages causally linked, with the information expressed in the eye movement measures determining explicit recognition judgments? It is worth noting that the above-cited studies that support the idea of a relation between eye movements and memory used only faces (and scenes) as stimuli. Thus, it cannot be ruled out that oculomotor measures of memory are highly stimulus-specific, that is, they may obtain only with highly (over-) trained stimulus material. Note in this regard that in the relevant studies, observers typically underwent a dedicated, that is, explicit, phase of learning the face stimuli prior to the explicit recognition task (e.g., 180 learning trials in Exp. 1 of Hannula et al., 2012). Also, of relevance with regard to the relation between fast and slow retrieval processes, in these studies, eye movements were examined only under free-viewing conditions: observers were unrestricted in the way they explored the faces (scenes). Thus, it remains an open issue whether eye movements serve a critical role for explicit reports, rather than there just being some correlational link between the underlying processes. Fixation locations – indicating where (overt) attention is allocated to – may well be a mediating factor for enhanced memory accuracy, just as they enhance perceptual accuracy (e.g., Ferreira, Apel, & Henderson, 2008; Renkewitz & Jahn, 2012). That is, appropriate eye movements may be a necessary condition for the explicit retrieval of learned contextual cues.

A final – and entirely new – issue addressed in Experiment 3 concerned the relationship between fixational eye movements and contextual cueing when fast (unconscious) measures of the cueing effect are investigated. Two-stage models assume that particularly during stage one, studied content is retrieved automatically (obligatorily), which could mean that visual attention, operationalized by eye fixations, is not a necessary requirement for the facilitation of search reaction times (the stage-one measure of the contextual cueing).

In sum, the present work investigates the controversial issue of explicit knowledge of repeated search displays by using the novel approach of examining the relationship between fixations and performance in tests of explicit recognition memory. Furthermore, we do not only study the relation between fixations and explicit recollection (Experiment 1) but also manipulate eye movements experimentally to assess their impact on explicit context memory (Experiment 2). Moreover, we examine the importance of eye movements for the context-based guidance of search reaction times (Experiment 3). In doing so we test two basic ideas from current accounts of episodic memory in relation to contextual cueing: (1) whether learned target-distractor associations are retrieved automatically (unconsciously) from context memory and impact on the facilitation of reaction times in the search task or eye fixation dwell times in the recognition task; and (2), whether context representations can become conscious later on, in an explicit recognition task, with the help of focal attention.

5.3.3 Rationale of the present study

On this background, the present experiments asked three interrelated questions: Is the successful retrieval of contextual cues expressed in the eye fixation patterns while viewing the memory test display (Experiment 1)? If so, do eye movements constitute a critical condition for the conscious recollection of contextual memories (Experiment 2)? And, to what extend are eye movements a requirement for the facilitation of reaction times in the search task? In Experiment 1, observers performed a visual search task in which they were presented, intermixed, with repeated and randomly generated, non-repeated (‘baseline’) display arrangements. Thereafter, a recognition test was administered in which participants’ eye movements were recorded: they were presented with a display arrangement and had to indicate the quadrant in which the search target was located previously, with the target in the test display being replaced by an additional distractor item. This ‘generation’ task directly queries the (implicit) memory that facilitates target detection/localization in the search task (cf. Chun & Jiang, 2003). Further, earlier work had shown that ‘implicit’ cueing is largely supported by memory for individual target-distractor pairs formed in the vicinity of the target (e.g., Brady and Chun, 2007; Kunar, Flusberg, Horowitz, & Wolfe, 2007). Given this, analysing fixational dwell times for the target quadrant may be an apt measure of observers’ ability to consciously access the (substituted) target position within these quadrants. In Experiment 2, following the search task, participants again performed a generation task. This time, however, they had to maintain eye fixation in a display quadrant that was (statistically) either coincident or non-coincident with the to-be-recognized target quadrant (cf. Johansson

& Johansson, 2014) – permitting assessment of a critical role of eye movements for the conscious retrieval from context memory. In Experiment 3 only a single – search – task was administered in which observers' fixations were registered. These measures were used to generate real-time, gaze-contingent search displays that contained visual-field defects. Specifically, when observers fixated one of the four display quadrants, importantly, also including the target quadrant, the information present in this quadrant was suddenly extinguished (masked), making visual search in impossible. Observers could thus solve the experimental task only by not looking at individual (target) quadrants during the ongoing search process and/or at the time of their manual response. However, gaze-contingent masking of the target quadrant would not remove potential context cues for the guidance of the search process, given that observers avoid fixating the target region (otherwise this region is extinguished). Given this, gaze-contingent eye tracking could serve as critical test for the impact of learned display arrangements on the guidance of visual search when observers could not foveally inspect the target item (quadrant).

In each experiment, participants (incidentally) learned a set of 8 repeated displays during visual search. Successful learning would be indicated by repeated displays yielding shorter reaction times to the target compared to a non-repeated display (i.e., a contextual cueing effect). Concerning the recognition test, based on previous investigations (Hannula et al., 2012; Johansson & Johansson, 2014), we expected an effect of context memory on eye movements to manifest in terms of longer fixational dwell times in the quadrant of the (substituted) search target in repeated as compared to non-repeated displays (Experiment 1). Further, if overt eye movements serve a functional role for conscious retrieval from context memory, recognition accuracy was expected to be higher when observers maintain eye fixation in the target quadrant, compared to a non-target quadrant (Experiment 2). Concerning gaze-contingent masking in Experiment 3, if contextual cueing of visual search does not require eye fixations, then we should see reliable contextual cueing effects even when observers are prevented from looking at the target quadrant during the actual search process.

5.4 Methods

5.4.1 Participants and Set-up

A total of 48 participants took part in the experiments (19 male; mean age: 27.67 years; Experiment 1: 17 observers; Experiment 2: 12 observers; Experiment 3: 18 observers). The reasons for these different numbers of observers in Experiments 1-3 were the following: Experiment 1 served as bachelor thesis for one of the co-authors (MP). The data of Experiment 2 were obtained during a BSc course at the Department of Psychology. The observers for Experiment 3 were obtained from the subject panel of the Department of Psychology (unit of General and Experimental Psychology). All observers reported normal or corrected-to-normal vision and were naïve as to the purpose of the study. Participants provided written informed consent prior to the experiment, and received either a course credit or payment of € 10 for their service. Participants were seated in a dimly lit and sound-attenuated experimental booth in front of a computer screen (19-inch CRT monitor [AOC, Amsterdam, The Netherlands]; display resolution: 1024 x 768 pixels; refresh rate: 85).

5.4.2 Stimuli and procedure

Experiments 1 and 2 used a control software purposely written in C++. Experiment 3 used a customized Matlab program in combination with the Psychtoolbox and the Eyelink Toolbox (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002). Visual displays contained one target and 11 distractor stimuli (search task) or 12 distractor items (generation task). The target was a T-shape, rotated by either 90° or 270°; distractors were L-shapes rotated by either 0°, 90°, 180°, or 270°. All stimuli subtended 0.48° 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 stimuli were arranged on four (virtual) concentric circles around the display center (radii: 1.92º, 3.88º, 5.80º, and 7.72º), with three items in each quadrant and the target either on the second or third circle from the center. A black fixation cross was shown at the beginning of a trial (1.00 cd/m^2; size: 0.72 x 0.72°).

5.4.3 Search task in Experiments 1 and 2 (free viewing)

The search task consisted of 384 trials divided into 12 blocks of 32 trials each. Each block contained two different types of search displays: 8 repeated and 8 non-repeated displays (shown twice in each block). The eight repeated displays were randomly generated at the beginning of the experiments and presented in randomly selected trials throughout a given block. Note that in each repeated display, the position and orientation of distractors were kept constant, as well as the position of the target; the orientation of the "T" target letter (left vs. right) was determined randomly on each trial, so as to avoid response preparation (learning) effects. Non-repeated displays were generated anew on each trial. In order to equate target location repetition effects across the two conditions, the target was presented equally often at a fixed set of 16 locations: 8 locations were used for repeated and 8 for non-repeated displays. A search trial started with the presentation of a black fixation cross at the center of the screen for 500 ms. After a blank interval of 250 ms, the search array was presented until a response was given, though 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 tilted to the left (right), they pressed the left (right) arrow key of the computer keyboard with their left- (right-) hand 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.

5.4.4 Search task in Experiment 3 (restricted viewing)

Experiment 3 was identical to almost all aspects of Experiments 1 and 2 in terms of number of trials, search task requirements, and the flow of events in a given search trial. The only difference was the use of real-time, gaze-contingent eye tracking performed by an EyeLink 1000 tower-mount eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada; the sampling frequency was 1000 Hz). Participants were seated 65 cm from the monitor on a chinrest and saw the search displays through the mirror used to reflect the infrared light from the tower-mount EyeLink 1000 system on participants' eyes. Each participant was calibrated at the start of the experiment and after each block (of 32 trials). Calibration was considered accurate when fixation positions fell within ~1.0° for all calibration points. Calibration was further checked at the start of each trial and the search displays were presented only if observers' gaze was within a critical window of ~1.0° centered around a fixation cross presented at the start of each trial (size: 0.5°; luminance: 1.00 cd/m^2). Participants saw the entire search display (1 target, 11 distractors) until they made an eye movement towards a certain display quadrant, in which case this quadrant was suddenly masked with a white screen. The mask was removed when the dominant (right) eye left the fixated quadrant. Note that eye fixation of a given quadrant led to the removal of this quadrant independent of whether this quadrant contained the target or not. This means that gaze-contingent white masks were applied to target and non-target quadrants as well. This was done in an attempt to prevent observers from learning a contingency between the mask and the target quadrant and eventually come to use the mask as effective spatial cue of the target region. The white mask consisted of a white rectangle, of a size of ~4.0 x 4.0°, and was presented with an average delay of some 12 ms, that is, the display was updated almost immediately in the next (85Hz) CRT refresh cycle. When the gaze coordinates were unavailable due to eye blinks or signal losses, the display was kept completely white and no search items were presented. The default psychophysical sample configuration of the Eyelink 1000 (i.e., saccade velocity threshold set as 35°/s, saccade acceleration threshold set as 9500°/s^2) was adopted for the eye data samples. The first saccade was defined as the first eye movement landing outside a diameter of 0.8° of the fixation cross. These settings were also used during the recognition tasks in Experiments 1 and 2.

5.4.5 Recognition task in Experiment 1 (free viewing)

The recognition task was performed shortly after the search task. During this task, participants' eye movements were recorded at a sampling rate of 250 Hz using a remote EyeLink 1000 desktop-mount eye-tracker (SR Research Ltd., Mississauga, Ontario, Canada). The recognition task consisted of 128 trials, divided into 8 blocks of 16 trials each. Each block contained 8 repeated displays from the previous search task and 8 newly generated, non-repeated displays. Note that in the latter, search configurations (i.e., distractor positions) were fully generated anew, that is, not shown in the previous search task. Further, in new displays, the distractors substituting the target (see below) were also shown at a fixed set of 8 locations (previously used in the search task), again in an attempt to equate location repetition effects across the two types of display.

The eye tracker was calibrated at the beginning of each block and calibration accuracy was checked by the experimenter on each trial. Sampling started by the experimenter (by pressing the space key on a standard German keyboard on the control computer) as soon as stable fixation on the fixation marker (defined as the eye resting approximately 1 second within an area of ~1.0° centered on the central fixation cross) was established and ended after a display presentation of 10 sec. The eye movement record was stored and analysed off-line later on with purpose-written C++ software.

In response to the test display, participants' task was to indicate the quadrant in which (in the previous search task) the target "T" had been presented, where the "T" in the test display was replaced by an (oriented) “L” distractor item. For a target located in the top left display quadrant, they pressed the spatially corresponding “7” key on the numeric keypad of the computer keyboard, for the top right quadrant the “9” key, for the bottom left quadrant the “1” key, and for the lower right quadrant the “3” key. Observers could issue their response at any time in the 10-s presentation period and were free to explore the display making eye movements. They were told to place emphasis on response accuracy rather than speed.

5.4.6 Recognition task in Experiment 2 (restricted viewing)

In Experiment 2, the recognition task consisted of 128 trials, divided into 8 blocks of 16 trials each. Only repeated displays from the previous search task were presented. Eye movements were recorded on each trial. The eye tracker was calibrated prior to each block. A trial started with the presentation of nine ‘placeholders’ (size: 0.24° x 0.24; 1.00 cd/m^2; presentation time: 1500 to 2500 ms; distance from center: 8.73°), connected via thin black lines (Fig. 1). This was meant to induce participants to structure the display into four (separable) quadrants. This event was followed by the presentation of single digit – “1”, “2”, “3”, or “4” – in one of the four quadrants (“1” in the top left, “2” in the top right, “3” in the bottom left, and “4” in the bottom right quadrant). The digit, which was presented for a variable interval between 1500 and 2500 ms, marked the quadrant relevant for recognition in a given trial: observers had to indicate whether or not this quadrant had contained a target (in the ‘target-substituted’ display shown subsequently) by pressing the “Y” or “N” key on the computer keyboard with their left- or right-hand index finger, respectively. Prior to the test display and their response, another event occurred: the presentation of a black fixation cross in one of the four quadrants between 1500 and 2500 ms, which participants had to fixate before the 12-item test display was shown. Observers were instructed to maintain eye fixation at the cross or at least at the quadrant of the cross, that is, they were allowed to move their eyes in the current (fixation) quadrant but not in a different quadrant. Eye-movement sampling started with the onset of the search items, which stayed on the screen until observers made their yes-no recognition response. The quadrants for recognition and fixation were pseudo-randomized, implementing the following restrictions: Each quadrant was equally likely to be chosen as the recognition-relevant quadrant, and each recognition-relevant quadrant had (or had not) contained a now substituted target in 50% of the trials, to reinforce unbiased “Yes”/“No” decisions. Further, the quadrants for recognition and fixation coincided in 50% of the trials, so as to equate statistical power between the consistent and inconsistent conditions (spatially coincident and non-coincident quadrants; respectively; cf. Fig. 1).

Prior testing (data not reported) showed that this task was rather hard in terms of maintaining gaze at the fixation quadrant until a response was given. Given this, a trial was considered as correct when the eyes spent at least 80% of the time within the fixation quadrant. Using this liberal criterion, the mean quadrant fixation accuracy was 94.75%.

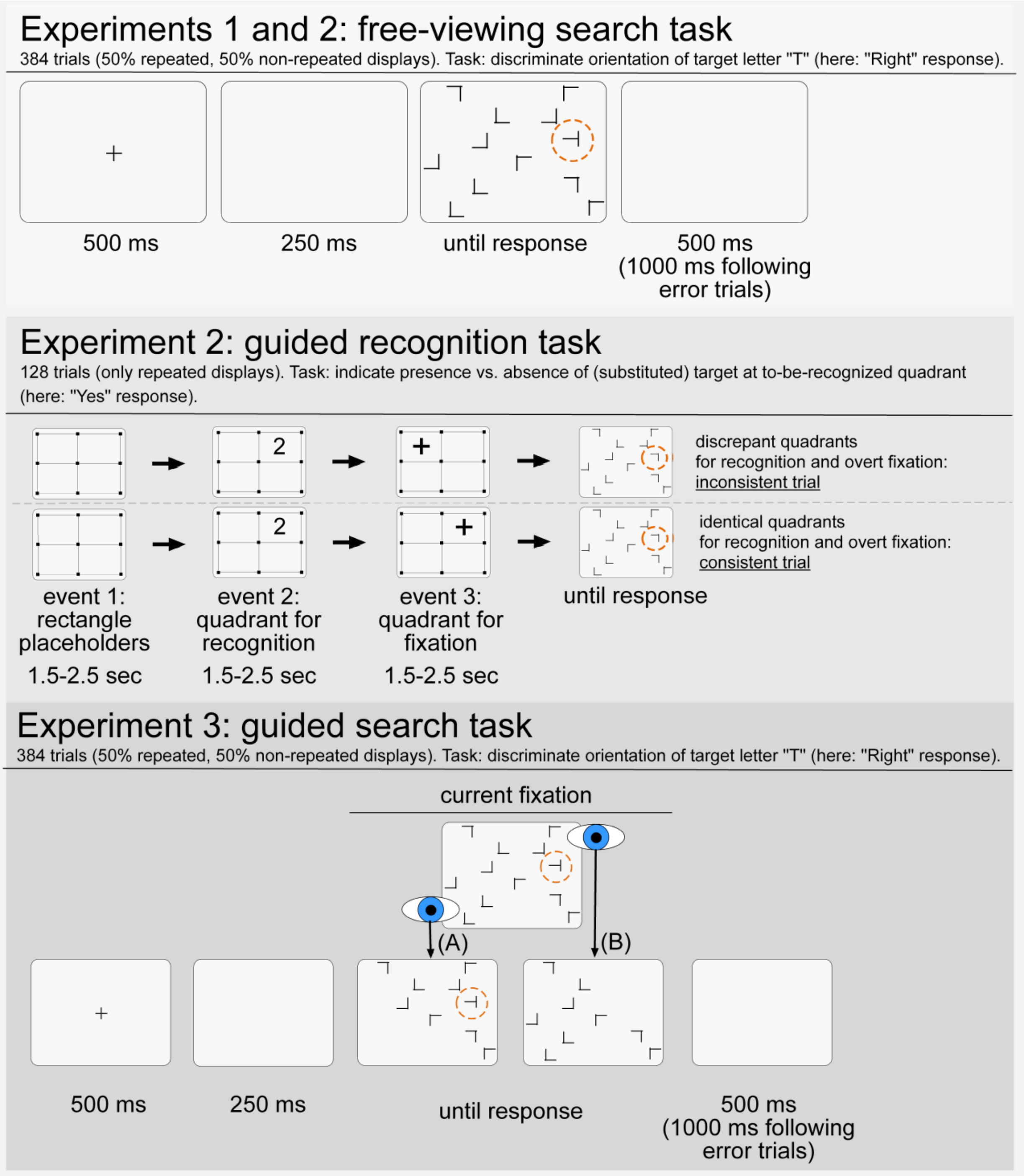

Fig. 1. Illustration of the events on a given trial of the search tasks in Experiments 1 and 2 (top row), recognition task in Experiment 2 (middle row), and search task in Experiment 3 (bottom row). Search tasks in Experiments 1-3. A trial started with a central fixation cross, followed by a brief blank interval and the presentation of the search items. Observers' task was to detect and subsequently discriminate the orientation of the target "T" (left vs. right-tilted relative to the vertical midline). In Experiment 3, display presentations were made contingent on observers' current eye fixations: fixations at, e.g., the bottom-left, non-target, quadrant (A) and importantly also the top-right, target, quadrant (B) led to the presentation of a white mask and thus the removal of the target and nearby distractor items in these quadrants. Recognition task in Experiment 2. A trial started with the presentation of nine rectangle placeholders, followed by a digit (1-4) in one of the four display quadrants. Thereafter, a fixation cross appeared, providing a marker for observers' gaze position during the recognition task. Immediately after this event, incidentally learned displays from the previous visual search task were presented, with the target substituted by an additional distractor. Observers' task was to decide whether the quadrant indicated by the digit had or had not contained the target, while holding their gaze at the fixation cross reference marker. The actual and the substituted target are marked by an orange circle (not shown in the actual experiment).

5.5 Results

Data were analysed using R (R Core Team, 2014). The first 16 trials in each task were treated as practice and excluded from analysis. Furthermore, for the search task, error trials (3.16%) and trials with extreme reaction times (outside 2.5 SDs from the individual mean; 3.38%) were discarded. For RT analysis, two successive blocks of search trials were collapsed into one ‘epoch’ to obtain reasonably stable estimates of the development of contextual cueing over time on the task (cf. Chun & Jiang, 1998).

5.5.1 Contextual cueing performance in Experiments 1 and 2 (free viewing)

The effects of contextual cueing (RT[non-repeated display] – RT[repeated display]) on the search reaction times are depicted in Fig. 2. In Experiments 1 and 2, visual search was unconstrained in that observers could see the whole display through the entire trial. Reaction times were analysed by means of a repeated- measures ANOVA, with display type (repeated, non-repeated) and epoch (1-6) as factors. For Experiment 1, the main effect of the display type was significant (F(1,16)=13.64, p<.01). Reaction times were faster for repeated relative to non-repeated displays (901 vs. 939 ms). Further, the cueing effect increased with increasing epochs (see Fig. 2), though this observation was supported only by a borderline-significant interaction ($F(5,80)=2.03$, $p=.08$). An identical pattern was found for Experiment 2: repeated displays elicited significantly shorter reaction times compared to non-repeated displays (1055 vs. 1104 ms; $F(1,11)=31.78$, $p<.01$). There was also a tendency for the reaction-time benefit for repeated over non-repeated displays to became more pronounced as Experiment 2 progressed (display type x epoch interaction: $F(5,55)=1.57$, $p=.18$; see Fig. 2*)*.

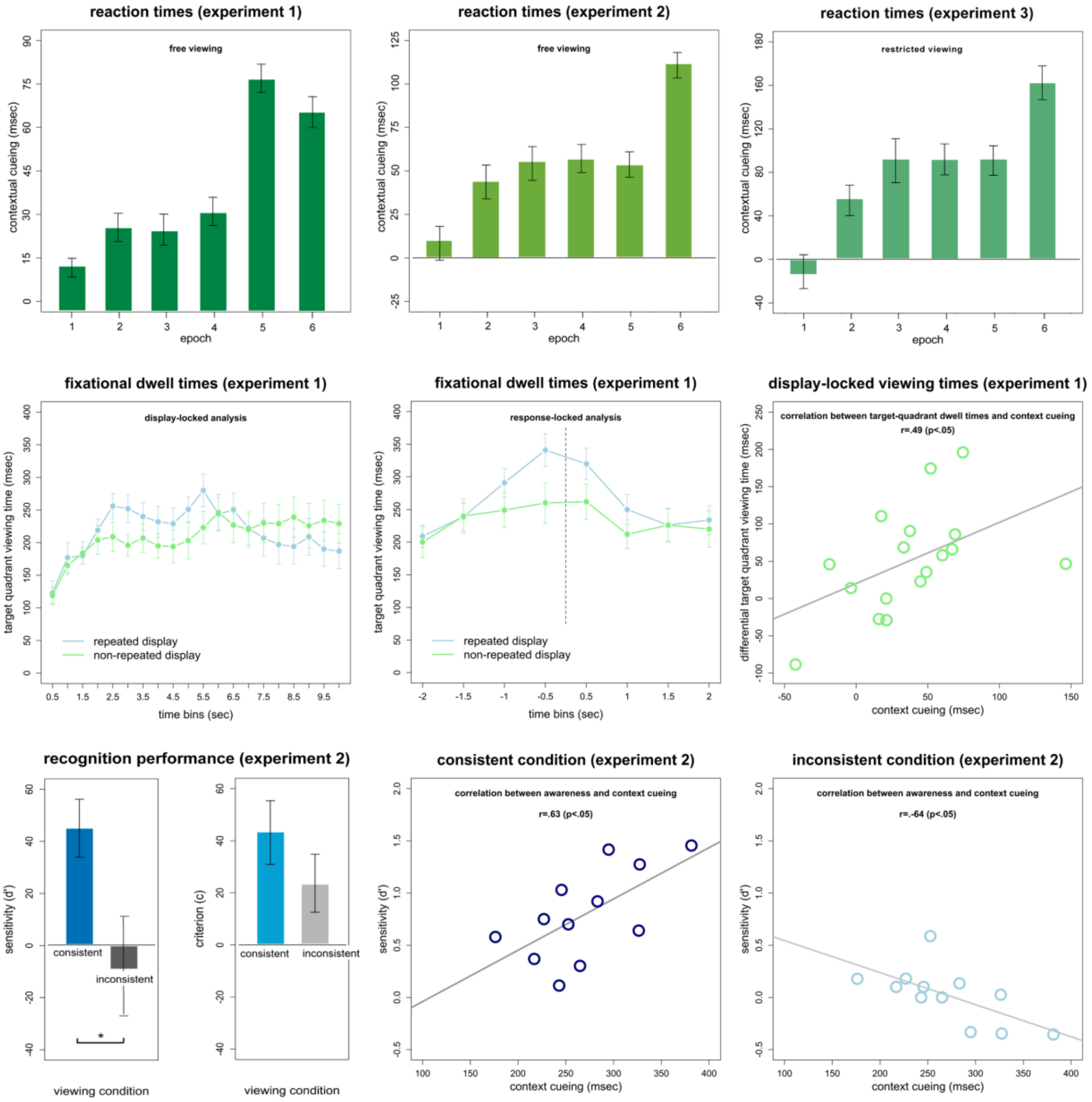

Fig. 2. Results of Experiments 1-3. **Top row**: contextual cueing effects (RT[non-repeated displays] minus RT[repeated displays] as a function of epoch in Experiments 1, 2, and 3 (left, middle, and right panel, respectively). One epoch corresponds to 64 trials. **Middle row**: Fixational dwell times following correct responses ('hits') for repeated and non-repeated displays in the recognition task of Experiment 1 analysed relative to display onset and observers' manual generation response (left and middle panel, respectively). The time point of the response is indicated by the dashed vertical line. Display presentation was always 10 sec. The right panel shows differential fixational dwell times (dwell times[repeated displays] minus dwell times[non-repeated displays] obtained in the 2.5-5.5 sec time window after the presentation of the recognition display plotted by contextual cueing effects. **Bottom row**. The left panel shows signal detection accuracy (sensitivity, d'; criterion, c) in the recognition task of Experiment 2 for consistent and inconsistent conditions (spatially overlapping versus non-overlapping quadrants for fixation and recognition, respectively). The middle and respective right panel show sensitivity (d') in the recognition task of Experiment 2 plotted for contextual cueing scores in the consistent and inconsistent conditions. Sensitivity and contextual cueing scores are taken from subsets of repeated ('learned') displays.

5.5.2 Recognition performance Experiment 1 (free viewing)

Observer’s ability to consciously recollect a repeated display was quantified by a comparison of their hit rates between repeated and non-repeated displays (collapsed across all 128 trials of the generation task). A hit means that observers correctly identified the quadrant of the substituted target. Since observers could solve this task only by chance in non-repeated displays, chance performance is indicated by comparable performance between the repeated and non-repeated conditions. A one-tailed *t* test confirmed the hit rate to be larger for repeated than for non-repeated displays (31.51 vs. 25.39%, $t(16)=2.38$, $p<.01$. Although the difference in conscious performance between repeated and non-repeated displays was small, it was nevertheless statistically reliable. Given that the present recognition task included a relatively large number of (128) trials, the positive finding could mean that the number of trials included in the awareness test makes a substantial difference in the quality of the awareness measure and, consequently, on the ability of the test to detect explicit cueing (the idea advocated by Vadillo et al., 2016).

Fixational dwell times were decomposed into 20 x 500-ms intervals, starting at display onset (display duration was always 10 s, yielding 20 intervals of 500 ms). The dependent measure was the amount of time observers spent in the (substituted) target quadrant in the various intervals. This binning was done separately for hit responses in repeated and non-repeated displays. Given that both conditions involve observers’ selection of the correct target quadrant (with the selection itself leading to shifts of attention and the eyes and thus up-modulations of viewing times), any surplus in viewing times for the target’s substituted location (quadrant) in repeated over non-repeated displays could only be attributed to the effects of context memory on eye fixations.

A repeated-measures ANOVA with bin (1-20) and display type (repeated, non-repeated) yielded a significant interaction, $F(19,304)=2.73$, $p<.01$). Post-hoc (FLSD) tests revealed fixational dwell times to be significantly longer for hit responses in repeated displays compared to non-repeated around 2.5–3 s after test display onset (*p*<.05 in the 2.5 and 3 s bins). A second ‘peak’ in dwell times (following that occurring after 2.5 s) for hits in repeated over non-repeated displays was evident between 5 and 5.5 s post display onset (p<.05 in the 5 and 5.5 s bins). The (group) median RT of observers’ individual mean RTs in the recognition task was 3933 ms, suggesting that the two peaks reflect differences in the speed with which observers responded (with half of them issuing relatively ‘fast’ and half ‘slow’ responses). This was confirmed by a response-locked re-analysis, showing that the differences in target-quadrant fixation times between repeated and non-repeated displays became manifest 1 second prior to observers’ manual recognition response and lasted for one additional second after their responses (*p*<.05 in the -1, -0.5, 0.5, and 1 s intervals; Fig. 2; panel C). – For this analysis, fixational dwell times were re-structured into eight new 500-ms intervals, four before and four after the overt recognition response and examined in an additional repeated-measures 8 (bin) x 2 (display type) ANOVA, which revealed a significant interaction, *F*(7,112)=2.54, *p*<.01.

5.5.3 Recognition performance in Experiment 2 (restricted viewing)

Observers’ ability in maintaining fixation at the critical quadrant was quite high and indistinguishable between the consistent and inconsistent conditions: 94.33 versus 94.94%; t(11)=1.34, p=.20 (recall that a trial was classified as correct if the eyes stayed at least 80% of the time in the to-be-fixated quadrant). Next, we analysed their recognition performance by means of the signal detection measure d prime [$d' = Z(\text{hit rate}) - Z(\text{false-alarm rate})$; Green & Swets, 1966]. A hit means that participants correctly detected a (substituted) target in the quadrant critical (i.e., pre-indicated) for recognition, while a false alarm means that they incorrectly judged the quadrant as containing a target in the previous search display. Mean *d’* was .46 for consistent trials and -.08 (i.e., essentially chance level) for inconsistent trials – a difference that was significant, one-tailed *t*(11)=3.16, *p*<.01. Further, observers response criterion c [*c* = -0.5 * Z(hit rate) +Z (false-alarm rate) was more conservative in consistent over inconsistent trials, though this difference was not significant: .44 vs. .24, one-tailed t(11)=.89, p=.19 (see also Fig. 2).

5.5.4 Contextual cueing in Experiment 3 (restricted viewing)

Experiments 1 and 2 suggest the operation of a reliable contextual cueing effect under ‘default’, free-viewing, search conditions. In Experiment 3, display quadrants were masked dependent on observers current gaze coordinates (i.e., restricted viewing condition). The critical question was whether observers can reinstate memory for learned search displays when they are prevented from eye fixations of individual display quadrants, importantly also including the target quadrant. While a positive result would be an entirely new finding, suggesting that the context-based guidance of visual search is an automatic, fixation-independent process, the results of Experiment 3 would also impact on another issue. Specifically, it is possible that the differences in memory accuracy between consistent and inconsistent trials in Experiment 2 are perhaps due to visual factors pertaining to the decline in visual acuity with increasing distance from fixation (e.g., Straßburger, Rentschler, & Jüttner, 2011). Assuming this, it would be relatively difficult – if at all possible – that observers can perform the search task in Experiment 3, since search-critical – target – information is removed upon fixation in this task. However, if participants can become sensitive to learned spatial patterns even without foveal inspections of individual (target) quadrants, then this could mean that they were also able to perform the recognition task under such conditions. In other words, the finding of a reliable contextual cueing effect under restricted search conditions would make it rather unlikely that the differences in recognition performance between the consistent and inconsistent conditions of Experiment 2 are due to a decline in visual acuity. Instead, any differences are more likely to arise from observers’ inability to fixate the target quadrant (in the inconsistent condition) and thus the inability for conscious retrieval from context memory.

Figure 2 illustrates mean RT differences between repeated (learned) and non-repeated displays. A 2 (display type) x 6 (epoch) repeated-measures ANOVA revealed that reaction times were faster for the former displays, suggesting reliable contextual cueing under restricted viewing conditions (repeated displays: 1004 ms; non-repeated displays: 1084 ms; $F(1,17)=7.58$, $p<.01$). Further, the context-based facilitation of search reaction times increased with increasing epochs, (interaction display type x epoch: $F(5,85)= 3.54$, $p<.01$).

Prior studies showed that contextual cueing of visual search is also reflected in eye movement patterns and that the oculomotor measure the best differentiates repeated from non-repeated displays is the number of fixations in a given search trial (e.g., Peterson & Kramer, 2001; Tseng & Li, 2004; Zang, Jia, Müller, & Shi, 2015). For this reason, we analysed fixation number in the present search task and found that the mean number of fixations to search for the target was smaller for repeated than non-repeated displays (3.89 vs. 4.21, $F(1,17)= 7.79$, $p<.01$). Interestingly, this analysis also showed that observers, in some 7% of all search trials, did not make any eye movements at all, that is: they kept their eyes at the location of the initial central fixation marker during the entire search trial. Further, in another 20% of trials, they made only one fixation after the initial fixation until they pressed the response button. While this suggests that observers were well able to solve the gaze-contingent search task reasonably well without eye movements, importantly: also including the ability to retrieve context cues in the absence of eye fixations, the inclusion of no-eye-movement (0- and 1-fixation) trials may also have confounded the fixation number measure, and eventually also contextual cueing. This idea is based on findings from Lleras and von Mühlenen (2004), who showed that ‘passive’ search can increase the contextual cueing effect. For instance, passive search may lead to the learning of distractor configurations independent of the target position, which later on facilitates the learning of the target in relation to nearby distractor items (Beesley, Vadillo, Pearson, & Shanks, 2016). For this reason, the possibility exists that context cueing in Experiment 3 may have been functional (and reliable) because of observers passively searching for the target in some fraction of trials. However, when we removed no-eye-movement trials, the fixation number and contextual cueing measure were still significant: fixations, 2.64 vs. 2.97, F(1,17)=13.85, p<.01; reaction times: 1126 and 1208 ms, F(1,17)=12.23, p<.01 (repeated and non-repeated displays, respectively). Additional analysis (performed on the data subset) for fixation duration and initial saccade latency (the time it took for the eye to leave the fixation reference marker) showed that these measures were comparable between repeated and non-repeated displays: fixation duration, 221 vs. 224 ms, F(1,17)=1.02, p=.33; saccade latency: 378 vs. 376 ms, F(1,17)=1.18, p=.29.

In sum, the analysis of oculomotor performance showed that observers are able to perform the search task without any eye movement or only a single eye movement in some 25% of all trials. Further, when such trials were removed from analysis, fewer fixations were still required to detect the target in repeated configurations. This suggests that context memory can guide attention towards important regions of the display (that contain the target). Importantly, this guidance can occur without foveal inspection of the critical target region.

5.5.5 Analyses of recognition performance at the level of individual displays

In Experiment 2 (and Experiments 1 and 3), contextual cueing was analysed averaged across eight repeated configurations (with different spatial layouts). It was found that even when observers were made to fixate the likely target quadrant, their d' values were still relatively low – around .50. This raises the question of why the effects of eye movements on explicit recognition of context cues (i.e., the target quadrant) were only modest. One possibility is that the facilitation of visual search due to repeated display arrangements and the explicit recognition of these arrangements are related effects, but that the cueing effect itself manifests for only a limited number of repeated displays. – Indeed, many contextual cueing studies have shown that only very few repeated displays are actually learned (i.e., stored in context memory) during the visual search task; in other words, many repeated displays are searched as “inefficiently” as non-repeated displays (e.g., Colagiuri & Livesey, 2016; Geyer, Müller, Assumpcao, & Gais, 2013; Johnson, Woodman, Braun, & Luck; 2007, Peterson & Kramer, 2001; Schlagbauer et al., 2012; Smyth & Shanks, 2008). Given this, an analysis across all – learned and non-learned – (repeated) displays would substantially underestimate the real influence of fixations on the explicit recognition of repeated displays. Accordingly, if one could identify those repeated displays that were actually learned and came to produce a cueing effect during the search task, one would expect the d’ sensitivity measures for such displays in the recognition test to be markedly elevated in the consistent (vs. the inconsistent) condition.

In the literature, a number of ways have been suggested for ‘determining’ learned displays, which are commonly based on comparisons of reaction times to individual repeated displays with the mean reaction times for non-repeated, baseline displays (e.g., Colagiuri & Livesey, 2016; Smyth & Shanks, 2008; Geyer et al., 2013). However, mean reaction times may only have limited diagnosticity as to whether a given repeated display has actually been learned during the search task. For example, reaction times to a given repeated display may be relatively fast already at the start of the experiment and faster than reaction times to non-repeated displays, for instance, because the target happens to be placed in the central display region, near the fixation cross (which marks the starting point of the search). Given this, it would be more appropriate to use the differential decrease in reaction times over time (epochs) in order to distinguish (repeated) learned from non-repeated displays. Chun and Jiang (2003) have shown that the decrease in reaction times attributable to contextual cueing can be described almost perfectly by an exponential (i.e., power) function, where the critical parameter indicative of learning is provided by the (negative) exponent of this function. To determine learned displays, in the current study, we applied a two-parameter power function of the form RT = $i*x^s$ (cf. Brooks, Rassmussen, & Hollingworth, 2010) to reaction times for each individual repeated display (and non-repeated, baseline displays). Parameter i corresponds to the intercept of the RT x epoch function, and parameter s to the (negative) slope of the function; x represents the epochs (1-6; see Fig. 2). After determining the slopes for each individual display (and observer), we calculated the difference in slopes between a given repeated display and the non-repeated displays – providing a 'pure' measure of context learning (which is possible only with repeated displays) after removing contributions of procedural task learning (which applies to both repeated and non-repeated displays). Negative difference values indicate that the decrease in reaction times across epochs is larger for repeated than for non-repeated displays, indicative of 'true' context learning. Finally, for each observer, we determined the four (out of eight) repeated displays for which the (differential) slope measure was largest (effectively, this involved a median split of the eight differential learning slopes for each observer). The four repeated displays with the highest (negative) slopes were then classified as learned and the sensitivity measurements (in the consistent condition) were calculated for these displays.

Interestingly, taking into account only such 'learned' displays increased explicit recognition (in the consistent condition) considerably : d' = .82, which compares with d' = .46 taking all repeated displays into account. In fact, the d' value of .82 did not differ statistically from that of 1.0, the 75%-correct threshold in a two-alternative forced-choice task (see Klein, 2001, p. 1430). Thus, the analysis at the level of individual (repeated) displays reveals that the effect of eye fixations on the explicit recognition of repeated search displays is actually quite strong, given that the displays generated a reliable contextual cueing effect (i.e., were effectively learned) in the previous search task.

5.5.6 Relations between contextual cueing and recognition performance

The above single-display analysis reveals that awareness is higher when only repeated patterns yielding stronger contextual cueing are considered. This finding is in line with a single memory system of the cueing effect, assuming that both the context-based guidance of visual search and the explicit recognition of repeated displays are supported by a common knowledge base (with nevertheless independent sources of noise, or error, contributing to each performance measure; cf. Vadillo et al., 2016). In the present article we qualify this idea and suggest that (single) context memory expresses its effects at different –automatic and controlled – retrieval stages. However, this raises the problem of how information that is retrieved automatically and quickly from context memory becomes consciousness and eventually serves controlled reasoning processes. As a solution, we suggest that eye fixations are the mechanism by which information that is initially unconscious is aligned with explicit responses. Based on these assumptions, one could make certain hypothesis as regards the relation between measures of contextual cueing within and across different retrieval stages For instance, there should be a positive correlation between awareness and contextual cueing generated by the learned displays (identified with single display analysis), given that observers could fixate the target quadrant during recognition (=consistent condition). Further, the correlation between awareness and cueing should be a negative one when observers could not fixate the target quadrant and thus are hindered from conscious retrieval of context cues (=inconsistent condition). Moreover, a two-stage model of contextual cueing would predict, besides the facilitatory effects of eye fixations for the conscious retrieval from context memory, that measures of the cueing effect obtained at separate (automatic or controlled) stages share a positive correlation. For instance, in Experiment 1 we recorded two ‘automatic’ measures of the cueing effect: facilitation of search reaction times and facilitation of fixational dwell times in the recognition task. According to a two-stage model, the two ‘early’ measures should share a positive correlation.

Concerning first the relationship of measures of contextual cueing obtained at different stages, for the consistent condition of Experiment 2, the d’ sensitivity measure was positively correlated with the context-based guidance of search reaction times across all participants (r=.63, p<.05; see Fig. 2). In the inconsistent condition, by contrast, a significant negative correlation was observed (r=.-64, p<.05). Thus, the explicit detection of the target in a learned spatial pattern was differently affected dependent on whether observers could fixate the substituted target quadrant or not (performance advantages versus disadvantages, respectively). Concerning second the correlation between different measures of context memory obtained at a single (automatic) stage, for Experiment 1 the context-based facilitation of search reaction times and the gains in target-quadrant viewing times for repeated over non-repeated contexts were significantly correlated (r=.49, p<.05; see Fig. 2). – Note that in the latter differential dwell times were estimated in the 2.5-5 sec window after presentation of the recognition displays.

5.6 General Discussion

The present experiments investigated the relationship between context memory, eye fixation patterns, and explicit recognition of learned context cues. Contextual cueing was established by observers' incidental learning of target-distractor arrangements in a visual search task administered prior to the explicit recognition task. For the latter task, we observed that target-quadrant fixational dwell times were increased for repeated relative to non-repeated displays (Experiment 1). There was also a significant positive correlation between eye fixation viewing times and the magnitude of the contextual cueing effect. Moreover, a manipulation of gaze direction showed that explicit recognition of context cues was superior for spatially co-incident compared to non-coincident fixation and recognition quadrants (Experiment 2). This effect became more marked when focusing the analysis on individual displays that produced a contextual cueing effect. Additional analyses performed on these displays showed that the correlation between explicit recollection and contextual cueing of visual search was positive when observers were given the opportunity to fixate the target quadrant. A negative correlation was found when conscious decisions had to be made about a quadrant that was distinct from the current fixation location. Experiment 3 showed that observers were able to use context memory in a visual search task when eye fixations of individual display quadrants were made impossible in this task. The finding of a reliable context effect in Experiment 3 also suggests that observers had the capacity for detecting and subsequently discriminating the target without foveal vision. This makes an account of the data in Experiment 2 in terms of differences in visual acuity between foveal and extrafoveal vision unlikely.

5.6.1 Attention enhances explicit recognition of contextual cueing

These findings demonstrate that eye fixation patterns provide an apt measure for the incidental learning of display arrangements in visual search. Eye fixations did reveal contextual cueing in two ways: First, successful recognition of contextual cues was accompanied by prolonged dwell times in the (substituted) target quadrant; and second, detectability of the target quadrant, that is, retrievability of contextual memory, was improved when observers could direct their gaze to this quadrant. While the first finding may be interpreted in terms of a correlative relationship between eye movements and explicit recognition in contextual cueing, the latter finding suggests that eye movements play a more fundamental, ‘causal’ role in the explicit retrieval of context cues. One idea how this may work is that contextual memory varies continuously in strength along one decision or retrieval axis (e.g., Macmillan & Creelman, 2005) and eye movements shift the target and foil distributions further apart, effectively increasing memory (retrieval) strength and thus recognition accuracy. Alternatively, as outlined in the Introduction, retrieval of contextual cues might be conceived as a two-stage process. On this view, fixation patterns are not simply indicative of successful retrieval at the first stage. Rather, eye fixations (which reveal where attention is allocated) would also provide a mechanism for further elaborating the quickly retrieved information, making it available for conscious report. But we would like to stress that eye fixations are not an ultimate requirement for successful retrieval from context memory. Instead, there are conditions in which context memory can exert its effects in an automatic and obligatory fashion, expressed, e.g., by the facilitation of visual search and overt eye movements in this task (as in the current Experiment 3). However, when it comes to conscious decisions, attention is an ultimate requirement to collect evidence to support eventual conscious judgements of display regions as learned target quadrants.

The relationship between attention and memory was probably most clearly spelled out by Cabeza and co-workers (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008). In their AtoM (Attention to Memory) model, they distinguish between brain structures involved in the long-term storage of (episodic) information and structures that contribute to the retrieval of information from (episodic) memory. As memory structures they consider the medial temporal cortex (MTL), including the hippocampus; and as retrieval structures they propose areas that are concerned with the control of attention, that is, ventral and dorsal parietal cortex (see, e.g., Corbetta & Shulman, 2002). A further assumption of AtoM is that attention is recruited not only by external stimuli, but also by internal memory signals. More precisely, similar to the processing of sensory stimuli, AtoM postulates two attention mechanisms in the retrieval from episodic memory: bottom-up and top-down. Bottom-up attention tracks the (automatic) retrieval of task-related memory contents in MTL and makes them available to ongoing processes of task performance. As regards the current experiments, it is possible that indirect measures of the cueing effect (i.e., expedition of visual search reaction times, eye guidance to the target quadrant), in particular, were supported by bottom-up retrieval processes. Top-down attention comes into play when the memory decision is more laborious, as in the present, explicit generation task, and/or the ‘default’ MTL activations associated with repeated search displays are below some threshold for conscious report. Under these circumstances, a strategic search is induced in MTL, and in case of a match (between the current sensory input and memory representations), information from long-term memory is made available to cognitive processes, including visual consciousness. – The current findings qualify the AtoM model in two ways: First, the postulated relationship between attention and memory does not only hold for classically conceived episodic – that is, self-related, ‘autonoetic’ (Tulving, 1985) – memory. Rather, it appears that the model also provides an apt account for other forms of – sensory-perceptual – episodes, such as the scanpath the eyes traversed during a visual search task. This presupposes that contextual cueing, too, is supported by MTL memory. That this is indeed the case has demonstrated in a number of neuropsychological (Chun & Phelps, 1999, Manns & Squire, 2001) and functional imaging studies (Greene, Gross, Elsinger, & Rao, 2007; Geyer, Baumgartner, Müller, & Pollmann, 2012).

Second, the postulated relation between attention and memory seems to be limited not only to semantically rich, natural, stimuli, such as faces, naturalistic scenes, objects of everyday life, etc. (e.g., Hannula et al., 2012; Ryan et al., 2000; Johansson & Johansson, 2014). Rather, it appears that spatial attention also plays a role in the retrieval of (learned) artificial laboratory stimuli, such as visual search displays that are, in essence, meaningless arrangements of letter stimuli.

5.6.2 Explicit recognition in contextual cueing revisited

The present finding of above-chance recognition of the (substituted) target quadrant in a repeated display can be attributed to eye guidance towards this quadrant. Interestingly, above-chance recognition in contextual cueing has also been reported in other studies, suggesting the operation of a single, explicit memory system – a view recently put forward by Vadillo et al. (2016). They supported their proposal by a systemic comparison (meta-analysis) of a host of contextual cueing studies. These studies collectively show that the results of recognition tests (and the conclusions drawn from these tests) are strongly dependent on their statistical power.

An increase in power – by an increase of the number of recognition trials in a single study or the aggregation of individual studies in a meta-analysis – yields robust (above-chance) explicit recognition performance. Vadillo and colleagues (2016) interpreted these findings as an expression of a single memory system that supports both the contextual cueing effects in the visual search task as well as observers' conscious reports in the recognition task.

One testable prediction that can be derived from this proposal is that of a correlation between contextual cueing of visual search and explicit recognition of repeated displays, which should come to the fore specifically in very large samples for which non-systematic (random) influences on the two measures would be expected to be rather small. This was examined by Colagiuri and Livesey (2016), who, however, failed to find evidence of a reliable correlation between indirect and direct measures of contextual cueing, even if only a few repeated (i.e., learned) displays were included in the analysis. Their finding of effectively a null-correlation with large samples prompted Colagiuri and Livesey (2016) to postulate a dual-memory account, which the cueing effect in the visual search task being aided by an implicit memory system and observers' ability to consciously tell apart repeated from non-repeated displays by an explicit system.

However, the present result pattern is hard to explain by accounts assuming a division of long-term context memory into a conscious and nonconscious system. To recap the results: Representations from context memory can be fed rapidly into the (guidance of the) ongoing search task, accompanied by rapid shifts of the eyes towards the quadrant of the (substituted) target in the recognition task (Experiment 1). Furthermore, eye movements did not only index detection of the corresponding representations in context memory; rather, they were (also) critical for the retrieval of this information from context memory, especially when difficult, conscious decisions had to be made about the information that was relevant for the search task (Experiment 2). Visual search for a target in a repeated display and both free and restricted viewing of this display in an attempt to determine the (substituted) target position would thus be mediated by spatial, context memory. – This idea was supported by significant correlations between the context-based facilitation of search reaction times and awareness about repeated displays. Interestingly, the direction of the correlation was dependent on whether conscious decisions, under restricted viewing of a specific quadrant, were either made about that quadrant or about a quadrant distinct from the fixation quadrant (positive and negative correlations, respectively).

With regard to previous findings, of only a null correlation between context effects in visual search and recognition (e.g., Colagiuri & Livesey, 2016), we surmise that the relation between contextual cueing of visual search and explicit recognition of learned context cues is mediated by additional factors relating to the viewing regime and the type of recognition test. Concerning the viewing conditions, it is possible that explicit knowledge comes to the fore in the generation task only if participants are made to fixate, that is, focus attention on, the (potential) target quadrant. Otherwise, explicit memory may only be weak, as in the current Experiment 1. If this is ensured, even the ‘standard’ yes-no recognition test (e.g., Chun & Jiang, 1998) may reveal explicit knowledge. Concerning the type of recognition test, Colagiuri and Livesey (2016) used a standard yes-no test in addition to a two-alternative forced-choice test in which observers had to indicate which one of two simultaneously presented visual search displays, one being a (previously) repeated and the other a novel, foil display, had actually been shown in the previous visual search task. Of note, in both the standard yes-no task and the display-comparison task, observers are shown either one (yes-no task) or two displays (comparison task) in which all items, the distractors and the target, are present and have to (more or less) simply indicate whether or not they have seen the display (yes-no task) or which one of the two displays they have seen (comparison task) already during the previous search task. Given a target is present in the test display(s), a recognition response may be given on the basis of other processes than those being at work in the actual search and the target-quadrant generation task. For instance, observers may rely for their recognition response on their ‘familiarity’ with the presented display (yes-no task), or their ‘relative familiarity’ with the two displays (comparison task). That is, successful recognition may actually be supported by memory that is different from the contextual representations facilitating reaction times and fixations in the visual search (and the target-quadrant generation) task. In addition, or alternatively, successful recognition may be influenced, or driven, by perceptual properties of the current test displays – which may include objective display parameters, such as the distance of the targets from the display center or the hemifield of the target in the repeated and foil display (hemifield differences might arise, e.g., because of a preference to scan in the reading direction; Olson & Chun, 2002), and more subjective parameters, such as observers’ estimation of the ‘goodness’ of the test displays (Ogawa & Watanabe, 2011) or the (subjective) ‘fluency’ (see, e.g., Johnston, Hawley, & Elliot, 1991) with which they process the test displays and detect the (visible) targets within it. Of note, fluency-based decisions have been reported previously, particularly with two-alternative forced-choice tasks (e.g., Voss, Baym, & Paller, 2008; Voss & Paller, 2010). In Voss at al. (2008), observers had to judge which one of two simultaneously presented, perceptually highly similar kaleidoscope stimuli was shown in an initial learning phase. Interestingly, observers in the (kaleidoscope) task had relatively low confidence in their memory response, while at the same time their actual memory accuracy was quite high. Voss and collaborators (2008, 2010) attributed the negative relationship between memory confidence (a mark of explicit memory) and memory accuracy in their two-alternative forced-choice task to the operation of fluency- or perceptually-based ‘recognition’ processes, rather than proper recognition. In the present context, reliance on processing fluency and perceptual properties may be particularly marked in the display-comparison task, even though these factors would also play a role in the standard yes-no task.

In contrast, the target-quadrant generation task used in the present study differs from these tasks in that the target in the (single) test display presented was substituted by an additional distractor item (i.e., no target item was ‘findable’). Consequently, fluency- or perceptually-based based decision processes would play a lesser role in this task (e.g., when there is no target, it is harder to derive a fluency estimate), and recognition decisions would genuinely have to involve retrieval from memory of the spatial arrangement of the stimuli (i.e., spatial configuration recognition). For this reason, arguably, the generation task is more suited (‘valid’) for the investigation of spatial context memory (e.g., Chun & Jiang, 2003; Smyth & Shanks, 2008). Given this, it is possible that failures to find a correlation between explicit recognition performance, measured by means of, say, a display-comparison task, and contextual cueing, measured in a visual search task, is owing to the relatively low validity of this type of recognition task, rather than observer’s general inability to intentionally access context memory.

In summary, while reaction time performance in visual search and explicit target localization performance in a generation task is influenced by spatial context memory (with the latter coming to the fore under guided viewing), recognition performance in a display-comparison task or a standard yes-no task may, to a large extent, be driven by the perceptual properties of the (learned and the) test stimuli, including objective and subjective factors. This implies that contextual memory influences in the search task do not necessarily have to correlate with memory performance in the forced-choice task.

5.7 Conclusion

The present study revealed that contextual cueing of visual search and explicit reports about the (substituted) target in repeated visual search displays are related memory phenomena. Contextual cueing was observed in terms of facilitated reaction time performance in the visual search task and extended fixational dwell times in the target-quadrant recognition task. These measures also showed a significant positive correlation. Furthermore, a manipulation of gaze direction showed that deployment of attention to the quadrant of the (substituted) target enhances explicit recognition, that is, attention serves a critical role for conscious retrieval from context memory. The latter finding, in particular, suggests that, in perceptual (i.e., incidental) learning in visual search, attention is the mechanism by which the output of the first retrieval stage (‘ecphory’) is made available to the second, conscious retrieval stage. Additional correlation analysis between contextual cueing of visual search and awareness about repeated displays confirmed this assumption. Crucially, the (positive, negative) direction of the correlation was dependent on observers’ eye fixation of the to-be-recognized or a different quadrant. With regard to the differences in explicit recognition in contextual cueing between the present and prior studies, we suggest that additional factors relating to visual inspection of the test displays or the ability of the recognition test to reveal ‘true’ spatial memory should be taken into account when drawing inferences about the operation of explicit memory in contextual cueing of visual search.

5.8 References

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5.9 Acknowledgements

This research was supported by a grant of the German Research Council (DFG) to Thomas Geyer (GE 1889/3-1, RTG 2175). Questions concerning data acquisition and data analysis should be sent to Efsun Annac. Please contact Xuelian Zang in case you have questions relating to the technical implementation of the experiments.

Chapter 6:

General Discussion

The present dissertation reveals a view of context learning, in which there is a bi-directional and a dynamic relationship between attention and long-term context memory. This relationship was investigated in four aspects of spatial contextual cueing: (1) grouping-based guidance of attention and contextual cueing; (2) the role of an attention-demanding secondary task on contextual cueing; (3) attention-independent context memory and the development of memory-based automaticity in dual-task settings; (4) the influence of selective, focal, attention in the explicit retrieval from context memory. In the following, the findings of the four empirical studies are critically discussed including sketches for future investigations.

6.1 Study 1: Spatial grouping interferes with the adaptation of contextual cues

Repeated encounter with invariant target-distractor associations facilitates memory for contexts, and this context memory guides visual attention to the target location in the next encounters (contextual cueing). Previously, it was claimed that contextual memory is highly resilient and long lasting (e.g., Chun &Jiang, 1998; Jiang, Song, & Rigas, 2005), however forming context memory representations for new target-distractor associations was shown to be rigid and inflexible. That is, target location changes in learned distractor configurations result in impaired contextual cueing performance, and context-related gains in visual search recover only slowly with massive training of relocated displays (e.g., Zellin, Conci,von Mühlenen, & Müller, 2013). Study 1 used a manipulation of attention grouping to better understand why adaptation fails. This approach was based on the idea that stimulus-based processes (i.e., spatial grouping), may obscure the contribution of memory-based processes (contextual cueing) to perform visual search. In the experiments, repeated search displays were presented with two types of local target-distractor arrangements as sparse and dense displays. In sparse displays, the target context consisted of only a single distractor, whereas in dense displays, the target's immediate context consisted of three distractors. Experiment 1 of study 1 was a baseline experiment intended to replicate the lack-of-adaptation effect in contextual cueing. In the learning phase, participants encountered a set of (8) repeated displays intended for the acquisition of context memory for target-distractor associations. In test phase, targets were presented at novel locations in a nevertheless constant distractor layout in order to examine the ability of context memory to associate a new target position with an existing distractor representation. Experiment 1 found reliable cueing for initial, but not changed, target positions, demonstrating a typical lack-of-adaptation effect. Experiment 2 tested the influence of local item density in contextual adaptation. In learning, in each repeated display there were two distractors in the target's local context. In test, target position changes were introduced in a way that for half of the learned displays, targets were presented together with only a single distractor in its immediate context (local-sparse condition) or three distractors (local-dense condition) in the other half. Results showed that sparse, but not dense, displays exhibit contextual cueing adaptation. In Experiment 3, local-sparse and local-dense displays were presented only in the learning phase in order to investigate density effects in initial context learning (rather than context adaptation, which was the focus of Experiment 2). It was found that contextual cueing was larger for sparse contexts, though dense contexts also exhibit a reliable context effect. This result pattern suggests a gradual modulation of contextual cueing by item density with these effects being more pronounced in the adaptation of learned contextual cues. Experiment 4 went on examining density effects on the learning of entirely new set of repeated displays (rather than adaptation of existing context memory), To this end, observers were trained with one set of repeated displays (density level: 2 items) and tested with a new set of repeated displays, with 50% containing local-dense and 50% containing local-sparse distractor contexts (density levels of 3 and 1 items). Under these conditions, contextual cueing effect was found for both local-dense and -sparse contexts (though it was again smaller for dense than sparse contexts). Again, this suggests a gradual modulation of contextual cueing by density, with density effects being larger in the adaptation of learned contextual cues. Overall, the results suggest that contextual cueing is an adaptive mechanism. However, contextual adaptation works when the number of items surrounding the relocated target is only low. In contrast, if the relocated target has a dense surrounding, then the target and the dense distractors may be grouped together and effectively trigger bottom-up search mechanisms of attention. This idea receives support from a second important finding of study 1: reaction times were always reliably faster for dense compared to sparse displays. As a result, not enough time would be left for in-depth processing of the relocated target, which is equivalent with a failure of contextual cueing adaptation. In other words, the results suggest that *spatial grouping* plays a detrimental role in the adaptation of context memory by effectively guiding attention towards the target location and thus curtailing the time required for the learning of a changed target location in relation to an existing distractor representation. An alternative though not mutually exclusive view is that the efficient guidance of attention towards the changed target location leaves not enough incentive for contextual cueing adaptation in changed displays. It is important to note that spatial grouping does not interfere with contextual cueing per se (indicated by a reliable cueing effect in Experiment 3 which presented local-sparse and -dense contexts in initial learning) or the learning of entirely new set of repeated displays (Experiment 4). In sum, local-sparse displays produce reliable cueing whereas local-dense displays interfere with contextual adaptation of learned contexts. Given that dense contexts produced faster reaction times than sparse context, the failure of context adaptation with dense displays is likely to be due to the bottom-up attentional capture by the clustered region. In a sense, contextual adaptation is effective only under situations, when visual search is effortful and requires time to process new information. Consequently, we suggest that a reliable proportion of the lack-of-adaption effect in previous studies can be attributed to spatial grouping and effective guidance of attention towards the grouped region of the relocated target. In this regard it is worth mentioning that previous studies did not control for this (grouping) factor.

However, one may consider other possibilities such as *pattern recognition* or *crowding* as the origin of the lack-of-adaption effect We think that these explanations are unlikely for the following reasons: Pattern recognition implies that context-based memory in visual search requires related memories to be activated and whenever there is a change in the display, this might make the display easy/difficult to recognize, resulting to influence contextual memory representations. For example, in the learning phase of Experiment 2, participants encountered displays with two distractors in the vicinity of the target and in the test (relocation) phase, the target appeared together with one or three distractor items in its immediate context. Re-locating the target from 2-distractor contexts to 3-distractor (dense) regions does not necessarily make the region more familiar or recognizable; instead this kind of familiarity would have been expected with fewer items around the target item, i.e., 1-distractor (sparse) displays. The reason for this comes from the fact that target location changes modify the overall summary statistics of the display towards the dense region (e.g., items' center of mass; Alvarez & Oliva, 2008). Assuming this, a dense display should overall be relatively dissimilar to the original learned display, which would reduce interference at the level of memory retrieval. Thus, the pattern recognition account would predict reliable contextual cueing after target location changes in dense displays (due to the absence of interference between initially learned and adapted context representations). However, this is not what we observed. Instead, cueing was functional in sparse but not dense contexts in the adaptation of learned contextual cues.

According to the notion of *visual crowding*, a cluster of items (i.e., dense local context) may hamper visual search and learning performance (Levi, 2008). Visual crowding is a limitation of visual processing concerning the identification and search for objects in the peripheral visual field. Objects in the periphery become considerably more difficult to recognize when they appear together with other items (distractor) in close spatial proximity. Applying it to contextual cueing, it would be expected that crowding makes visual search less efficient, and deteriorates contextual cueing. However, in our experiments RTs were always faster, by some 100 milliseconds, for dense displays.

In conclusion, our results hint to a trade-off between stimulus-based and memory-based search processes. Spatial grouping, which is an instance of a stimulus-based search process, makes a local (dense) region more salient, which would not leave enough time for contextual memory to adjust itself to the new target-distractor associations. On the other hand, when there is a small amount of items surrounding the new target location, contextual adaptation may be observed. With respect to future experiments, we suggest that Gestalt Factors relating to the grouping of display items should be considered in the learning versus adaptation of context memory. Also, these influences may not be limited to item density. Instead, they may encompass other grouping cues, such as the color or orientation of the items or combinations of both. For instance, Feldmann-Wüstefeld and Schubö (2014) have shown that contextual cueing is larger with homogeneously relative to heterogeneously-oriented distractors. Based on this finding they suggested that grouping of items can help contextual cueing. The ultimate question that arises from this proposal is whether orientation grouping does also have a positive effect on contextual cueing adaptation.

6.2 Study 2: The interference of secondary spatial working memory task on contextual cueing

Previously, it was shown that configural learning is independent of attention (e.g., Jiang & Leung, 2005). This idea was further examined in the field of divided, or resource-based, attention to understand whether contextual cueing and a secondary working memory (WM) task share a common or distinct processing resource (e.g., Kahneman, 1973). Vickery, Sussman, and Jiang (2010) conducted a study by combining contextual cueing task with various secondary WM tasks in an overlapping fashion. They found that attention load by a secondary WM task did not influence contextual cueing, which led them to propose the idea that contextual cueing is independent from divided attention. Vickery at el (2010) divided their experiment in two distinct – training and test – phases and applied the secondary WM tasks only in the training phase (intended for the acquisition of context memory). In the test phase (intended for the expression of, or retrieval from, context memory), they removed the secondary WM tasks and let observers perform only the visual search task. For the reason that Vickery et al. (2010) applied the secondary WM task only in the training phase, their finding of an intact contextual cueing effect in the test phase would mean that only the learning, but not retrieval, of contextual cues is independent from divided attention. The in-/dependency of contextual cueing from WM load was thus further investigated in a series of subsequent studies. To name just a few: Manginelli, Geringswald, & Pollmann, 2011; Manginelli, Langer, Klose & Pollmann 2013 and Travis, Mattingley, & Dux, 2013. Importantly, these studies applied a secondary WM in both the training and test phases. Therefore, these studies made it possible to study the role of divided attention selectively in the learning versus expression of learned contextual cues. Study 2 of this dissertation took the divided attention approach further and investigated whether specifically a secondary (spatial) WM task interferes with the learning or the expression of learned contexts. Seven experiments were conducted in study 2. We asked the question whether any effects of the additional spatial WM task results from reduced spatial or executive WM resources. All 7 experiments were divided into learning and test phase. Each experiment was prepared as in the following: In every phase, observers either performed the visual search task in isolation (no load condition) or together with a concurrent spatial WM task (WM load condition). For example, if the secondary WM task was administered in the learning phase, it was removed in the later stage of the experiment, that is; observers were required to perform only the single visual search task in the test phase. On the contrary, if learning started with the single visual search task, the spatial WM task was added in test so that observers were required to perform both the visual search and the spatial WM task in the test phase. One experiment (Exp. 1) served a special (baseline) status in that observers performed only visual search without any load of a secondary WM task. The aim was to show baseline (‘standard’) cueing in both phases (as in Jiang & Chun, 1998). In the other experiments (Exp. 2-7), visual search displays were presented before, during, or after the spatial WM task. In WM task, observers had to maintain the locations of four black squares in their working memory. Further, their verbal WM was loaded by an additional articulatory suppression task. The logic of the before, during, and after conditions was to load spatial WM at different time points while observers were performing the visual search task and thus to decompose executive WM load (in the before, during and after conditions, observers would have to coordinate the two tasks, which is a process that requires executive capabilities; cf. Experiment 4 of Lavie, Hirst, De Fockert, Viding, 2004) from spatial WM load (only in the during condition, since observers would have to buffer the WM items during their visual search). Further, in half of the experiments, the spatial WM task was presented concurrently with the visual search task in training and test. With this full-factorial design, we could thus disentangle the contribution of executive versus spatial WM load (factor 1) in the learning versus retrieval (factor 2) of repeated search arrangement. The critical findings were: (1) Contextual cueing was reliably smaller (relative to the baseline) when observers’ spatial WM was loaded during initial – learning – trials of the search task. (2) The cueing effect recovered, and achieved baseline level, when the spatial WM task performed was removed in later trials (test phase). (3) Contextual cueing was unaffected by whether the spatial WM load was given before or after the search task. (4) The independency of cueing from spatial WM load was found for both learning and test phase in before and after conditions. Altogether, the findings indicate that spatial WM load interferes with the retrieval of context memory and this effect is independent of executive WM capabilities. Unlike previous studies (Vickery et al, 2010), the results indicate that contextual cueing is not attention-independent, that is divided attention modulates contextual cueing and this effect is larger during the expression of learned information. Based on these findings we suggest a model in which resource-limited attention is necessary to retrieve learned display arrangements from long-term memory. Under this account, WM is an important buffer that links the current search display with representations stored in long-term context memory. Therefore, when spare WM stores are occupied by the secondary task, then contextual cueing is interfered and the reason underlying this would be that there is not enough capacity left to hold target-distractor associations in working memory. As a result, contextual cueing breaks down if the search task is performed concurrently with a spatial WM task.

Future experiments may examine WM effects in contextual cueing under different set sizes. Unfortunately, at this stage we cannot say much to this issue, given that set size was always constant in our experiments. A set size manipulation could reveal a more gradual influence of spatial WM load on contextual cueing in a sense that the effect parametrically scales with varying amounts of WM load (cueing should be smaller with high compared to low WM load). Further, it would be interesting to explore at which stage (pre-attentive versus post-selective) of the visual-search process WM effects manifest. The current result, of an effect of spatial load on the expression of contextual cueing, is compatible with the idea of WM exerting an effect on both guidance and / or decision variables in the process of visual search. Based on the results of Woodman, Vogel, and Luck (2001) one may expect WM effects on the intercept rather the slopes of the function relating RTs to set size. Another interesting issue would relate to training of contextual cueing under a spatial WM task. For instance, Schneider and Shiffrin (1977) have argued for a distinction of automatic versus controlled memory or search processes. Concerning particularly the former one, an automatic process was defined as the activation of a representation that “nearly always becomes active in response to a particular input configuration” and that “is activated automatically without the necessity for active control or attention by the subject” (p. 2). This ability for a process to occur in the absence of active control or attention may have implications for contextual cueing. Assuming that in our visual search task, target and the distractor features were held constant across trials (according to Schneider & Shiffrin, 1977, an important pre-condition for the development of automaticity), with sufficient practice on the visual search task, also the retrieval from context memory can become an automatic process. This could mean that the effect is relatively independent from controlled processes (attention) and thus immune against a secondary spatial WM load. This idea was tested in study 3.

6.3 Study 3: Contextual cueing as a form of memory-based automaticity

Study 3 investigated the possibility that a secondary WM task may not always impair contextual cueing, and context memory can become independent from resource-limited attention. Schneider and Shiffrin (1977) showed that search performance improves with task practice but this practice-dependent improvement of visual search is dependent on the characteristics of a given task. They suggested a distinction as automatic and controlled processes to explain variations in observers’ search performance. In automatic processing, attention is directed efficiently (automatically) to the target without capacity limitation. Controlled processing, on the other hand, has a limited capacity and requires the operation of attention. In this regard, contextual cueing has been suggested as a special form of procedural – or skill – learning, which is typically considered as an automatic process (Chun & Phelps, 1999). Assuming this, it is possible that automatic contextual cueing can be further trained up to a level, where the effect is almost independent from attention control processes. This means that a certain display input may trigger the retrieval of learned display representations automatically, without requiring WM as buffer for linking the current search display with representations stored in context memory. If so, the question is how contextual cueing can be trained to achieve ‘full’ automatic level. Schneider and Fisk (1982) implemented two conditions termed as consistent- and variable-mapping in order to test the development of automaticity. In the consistent mapping condition, the target and the distractors were held constant across trials. There were two separate stimulus sets, one containing target and the other distractor items. In the variable mapping condition, by contrast, the identity of the target and distractors varied across trials. For instance, if the target on one trial was the letter B, then this letter could appear as a distractor item in subsequent trials. Hence, in the variable-mapping condition, target and distractors could come from the two stimulus sets. This means that observers could not constantly associate a certain target/distractor letter with one of the two sets (which was however possible in the constant-mapping condition). Consequently, Schneider and Fisk (1982) surmised a practice-dependent improvement of search performance (indexing the development of automaticity) in the constant- but not variable-mapping condition and the results confirmed this prediction. Moreover, in their attempts to further study training effects, they introduced conditions in which the constancy versus variability of target/distractor set was manipulated within a single experiment. In more detail, in this experiment there were single and combined blocks. In single blocks, observers performed either the constant- or variable-mapping search task. In combined blocks, each trial was equally likely to be a constant- or variable-mapping trial (observers were informed about the respective condition at the beginning of each trial). In both conditions, participants’ search performance was improved in consistent-mapping, but not in variable-mapping trials. Interestingly, the practice-dependent gains of constant-mapping task were even greater in the combined condition. This led Schneider and Fisk (1982) to argue that controlled processing can act as a "training wheel" for the development of automatic processing. Restated: “Limited controlled processing resources are used to develop cost-free automatic processes." (p. 277). Applied to contextual cueing, this could lead to the somewhat paradoxical prediction that learned display representations are automatically retrieved when there is pressure on controlled processes. More specifically, automaticity of contextual cueing may develop when the single search task and the combined search (with WM task) are performed across individual trials rather than performing the single- or dual-task search task across an entire experimental session. This trial-wise approach was adopted in study 3. In our single-task condition, participants were encouraged with visual search without any spatial WM load. In dual-task condition, the visual search task was administered concurrently with the spatial WM task (as in study 2). A prior (unpublished) experiment showed that it was relatively difficult for observers to switch their task set (search-only task, search and WM task, see chapter 3) across individual trials. For this reason, we administered the single- versus dual-task in a block-wise fashion (with one block containing 12 trials). Two experiments were conducted in Study 3: In the first experiment; we investigated the development of automaticity in contextual cueing with two alternating tasks using the very same set of (12) repeated displays. The results revealed a reliable contextual cueing effect even under WM load. However, since in both (single, dual) tasks the very same repeated displays were shown, it was possible that at least parts of the cueing effect under the dual-task condition was developed in the single-task condition. Thus, the finding of a reliable contextual cueing effect under WM load might be due to learning of the repeated displays (and practicing their retrieval) in the single task. For this reason, in the second experiment we used different sets of (6) repeated displays in the single- and dual-task. Again in the second experiment, the results showed reliable contextual cueing effect under the dual-task (and single-task) condition. At the end we suggested that contextual cueing is a form of *memory-based automaticity*.

Earlier studies claimed that a concurrent spatial WM load interferes with contextual cueing of visual search. However, it was known that a demanding task does not always impair visual search, instead visual search can be improved with sufficient amounts of training. In our experiments, observers became better in context-based guidance of visual search even under a condition in which spare short-term memory resources were occupied by the WM task. However, at the same time the WM task was also engaged in attentional control processes more actively/ dynamically, which could have reinforced the development of automaticity in context-based guidance of visual search (Schneider & Fisk, 1982). This does not mean that spatial WM load never impairs contextual cueing (Manginelli et al, 2013, Annac et al 2013). But we think that task characteristics, i.e., the application of WM load task, have a modulatory, 'automaticity-building', effect on contextual cueing performance.

6.4 Study 4: Conscious retrieval from context memory depends on focal attention

The memory underlying contextual cueing is typically considered as implicit (Chun & Jiang, 1998). This view receives support from findings showing that observers exhibit an improvement in their search performance for repeated relative to non-repeated displays while they are unable to discern repeated from non-repeated displays. However, in recent years, the idea of implicit cueing has become a controversial issue (see, e.g., Smyth & Shanks, 2008; Schlagbauer, Müller, Zehetleitner & Geyer, 2012; Vadillo, Konstantinidis, & Shanks, 2016). One argument against implicit cueing was that 'standard' recognition tests in contextual cueing typically consists of only a very few number of (24) recognition trials. As a consequence, explicit memory effects would have to be very large to be substantiated statistically with only small numbers of recognition trials. – Recall that contextual cueing in the search task is typically assessed within hundreds of trials (e.g., 576 trials in Chun & Jiang, 1998). This power problem of current recognition tests was addressed in a recent meta-analytic study (Vadillo et al., 2016). It was showed that contextual cueing yields above-chance performance in the recognition of repeated displays. Consequently, previous non-significant results were likely due to insufficient statistical power of the respective recognition tests. In this regard, it was claimed that contextual cueing is supported by a single – explicit and implicit – memory system (Smyth & Shanks, 2008). One way how such a single memory system of the contextual cueing effect may work is to conceive memory retrieval as a two-stage process, involving a fast, non-conscious process (‘ecphory’) and a second, slower process in which the output of the first stage becomes consciously accessible (e.g., Moscovitch, 2008). As regards to contextual cueing, successful retrieval at the first stage may be revealed by indirect measures, such as the facilitation of reaction times due to learned target-distractor arrangements in the visual search task, or increased fixational dwell times for repeated versus non-repeated displays in an explicit recognition task. Concerning the latter, an increasing number of studies show that eye movements, in particular fixation locations, provide highly sensitive memory measures that can distinguish learned from non-learned displays, even in the absence of participants’ conscious awareness (e.g., Ryan, Althoff, Whitlow, & Cohen, 2000; Hannula & Ranganath, 2009; Hannula, Baym, Warren, & Cohen, 2012). Further, the explicit recognition task can itself provide direct measures of retrieval at the second stage, such as observers’ ability to correctly report the display region (quadrant) where the target had previously presented in a visual search display (a so called *generation task*; cf. Chun & Jiang, 2003). On this view, even though there is only poor recognition at the second stage (standard finding of contextual cueing experiments; see above), retrieval of contextual cues may nevertheless be revealed (at the first stage) when more sensitive, oculomotor measures are employed. This issue was tested in study 4 of this dissertation. Specifically, we recorded eye movements during the explicit generation task. Note that in the generation task the target is substituted by an additional distractor, so observers were expected to guess the possible target quadrant. With this target substitution technique, one can effectively query the memory that facilitates target detection in the visual search task. Any effects of this memory on eye movements should be reflected by increased fixational dwell times towards the (substituted) target quadrant. Specifically, we analyzed dwell times for hit and false alarm responses. Correct judgment of the (substituted) target quadrant was considered as a hit response and an incorrect judgment of a given quadrant as the former target quadrant was considered as a false alarm response. By comparing measures of eye movements between these two conditions, we observed that quadrant-specific dwell times were higher for hit compared to false alarm responses. This suggests that context memory about target-distractor relations can be reliably expressed in eye movements. In the next experiment we went on and examined the correlative versus causal nature of retrieval-related eye movements in the recognition of contextual cueing. Experiment 1 examined eye movements only under free-viewing conditions, so it could not differentiate whether eye movements serve a functional role for explicit reports, or provide a correlational link for the underlying processes of retrieval. For instance, fixation locations – indicating where (overt) attention is allocated to – may well be a mediating factor for enhanced memory accuracy (e.g., Ferreira, Apel, & Henderson, 2008). Consequently, eye movements might be a necessary condition for the explicit retrieval of learned contextual cues. To investigate this, in Experiment 2 participants again performed an explicit generation task (after they were trained on the repeated configurations in the visual search task, as in Experiment 1). However, this time, they had to maintain eye fixation in a display quadrant that was (statistically) either coincident or non-coincident with the to-be-recognized target quadrant (cf. Johansson & Johansson, 2014). In the consistent condition, the quadrants that are relevant for fixation and recognition were spatially identical (overlapping). In the inconsistent condition, by contrast, the two quadrants were spatially different (non-overlapping). If eye movements were to play a critical role for the conscious retrieval from context memory, we expected to observe high accuracy in observers' correct reports of the (substituted) target quadrant under the consistent condition. The results of Experiment 2 confirmed this prediction. The implication of this finding is that fixations on the target quadrant are needed for conscious recollection. A more general suggestion in relation to the two-stage model of recollection in contextual cueing is that eye fixations must somehow be an essential element in the transition from unconscious to conscious knowledge. Thus, the information learned in contextual cueing (a) is initially unconscious, but (b) can possibly become conscious with the intervention of visual attention. While assumption (b) is supported by the findings from Experiment 2, assumption (a) was tested in a final experiment (Experiment 3). Here, we showed that contextual cueing is functional even in the absence of fixations on the target quadrant. To achieve this, we let observers perform the visual search task (with 50% repeated displays) but this time they were prevented from fixating on the target quadrant. This was achieved by the use of gaze-contingent eye tracking: Whenever observers made a fixation in the target quadrant, this quadrant was 'masked' so that the information present in this quadrant was no more visible to observers. Thus, although observers could not see the target, they could nevertheless exhibit a reliable contextual effect under these limited-viewing conditions. This suggests indeed that contextual cueing is initially an unconscious, i.e., fixation-independent, process.

6.5 Conclusion

The current thesis provides sufficient evidence for bi-directional links between attention and long-term context memory. Particularly, study 1 reveals that grouping-based attentional guidance interferes with the memory-based attentional guidance specifically in the adaptation of learned contextual cues. We suggest that grouping of search elements effectively captures attention towards these elements and thus effectively curtails the time required for contextual adaptation. Study 2 demonstrates the importance of divided attention for contextual cueing retrieval in which the effect was diminished in the presence of a secondary spatial working-memory task. This decrease of the cueing effect by the occupation of spare short-term memory resources results from reduced spatial rather than executive capabilities. The former, spatial, resource is a requirement for the comparison of a given display input with representations stored in long-term memory. The latter is a consequence of dual-task coordination. However, the dependency of the cueing effect from spare working memory resources is not ultimate: Study 3 shows that contextual cueing can circumvent the requirements for attentional control processes if the retrieval from context memory has achieved a high degree of automatization. Such a memory-based automaticity of contextual cueing was achieved by a specific dual-task training, in which the secondary spatial WM task was combined with or taken away from the visual search task across individual trials. Study 4 reveals that fixational eye movements, or overt attention; serve an important functional role for the explicit retrieval from context memory.

7. References (General introduction and General discussion)

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Curriculum Vitae (CV)

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Education

2012 - 2018	**Ph.D. Graduate School of Systemic Neurosciences** –Ludwig Maximilians Universität München
2010 - 2012	**M.Sc. Neuro-cognitive psychology** - Ludwig Maximilians Universität München: *Elite Network Bayern Alumni 2012*
2005 - 2010	**B.A. Psychology (Honors)** - Dogus University Istanbul

Professional Experience

Jun 2013- Dec 2017	**Scientific research assistant** - Department of psychology - Ludwig Maximilians Universität
Feb 2011-Apr 2013	**Junior administrator** - Department of psychology - Ludwig Maximilians Universität
Sep 2009-2011	**Volunteer** - Youth Re-autonomy Foundation of Turkey Youth Education Center
June-Aug 2008	**Internship** - Bogazici University Psychobiology Laboratory
Oct 2007-June 2008	**Internship** - Bakırkoy Hospital for Psychiatric Illnesses
June-July 2007	**Internship** - Industrial Application Software (IAS), Sales department

Teaching Experience

Winter Semester 2016/17

Tutorial course of “Classical Psychological Methods 1 - Reaction time & psychophysical methods”

Summer Semester 2014

Supervision “Neuro-cognitive psychology Research project 1”

Winter Semester 2013/14

Tutorial course of “Basic Neuro-cognitive psychology 1”

List of Publications and scientific contributions

Journal Articles

Annac, E., Pointner, M., Khader, P. H., Müller, H. J., & Geyer, T. (in preparation). Recognition of contextual cueing of visual search is supported by fixational eye movements.

Annac, E., Zang,X., Müller, H. J., & Geyer, T. (under review). A secondary task is not always costly:context-based guidance of visual search can benefit from a demanding working-memory task

Annac, E., Conci, M, Müller, H. J., & Geyer, T. (2017). Local item density modulates adaptation of learned contextual cues, *Journal of Visual Cognition*: 1-16.

Annac, E., Manginelli, A.A., Pollmann, S., Shi, Z., Müller, H. J., & Geyer, T. (2013) Memory under pressure: Secondary-task effects on contextual cueing of visual search, *Journal of Vision*,*13*(13):6, 1-15, doi: 10.1167/13.13.6

Annac, E., & Bahcekapili, H.G. (2012). Understanding and Acceptance of Evolutionary Theory among Turkish University Students, *Dogus University Journal*, *13*(*1*), 1-11

Ongoing projects

Kurcyus, K., **Annac, E.,** Henning, N., Oeltzschner, G., Pilatus, P., Edden, E., & Riedl, V. (under review). Different baseline states of GABA and glutamate in the human brain and their relation to visual input processing.

Gokce, A., Zinchenko, A., **Annac, E**., Conci, M., & Geyer, T. (in preparation). Affective modulation of the working memory retention: The role of positive and negative emotions

Gokce, A., Zinchenko, A., **Annac, E**., Geyer, T., & Conci, M. (in progress). The effect of (negative) emotions on working memory acquisition and recall.

Zang, X., Assumpcao, L., **Annac, E.**, Müller, H. J., & Geyer, T. (in progress). Contextual cueing of visual search in two targets displays.

Conferences

Oral presentations

Annac, E. “Visual attention and memory systems” (2017) – 15 x 4 Munich, Germany

Annac, E. “Psychological research”(2015) *9. Psychologie Kongress - Psychologie in Beruf und Praxis e.V. 2015*,Munich,Germany

Annac, E., Miller, J., Zang, X., Müller, H. J., & Geyer, T. (2015) "Secondary-task effects on contextual cueing of visual search", *1st Joint Turkish-German Symposium on Human Neuroscience ,Max-Planck Institute,* Berlin, Germany

Annac, E., Miller, J., Zang, X., Müller, H. J., & Geyer, T. (2014) "Secondary-task effects on contextual cueing of visual search", *11th International Cognitive Neuroscience Meeting*, Istanbul, Turkey

Poster presentations

Annac, E., Conci, M, Müller, H. J., & Geyer, T. (2017) "Local item density modulates adaptation of learned contextual cues" *40th European conference of visual perception 2017*, Berlin, Germany

Annac, E., Conci, M, Müller, H. J., & Geyer, T. (2015) "Multiple target location learning in repeated visual search: adaptation or new learning?" *European conference of visual perception, University of Liverpool*, Liverpool, England

Annac, E., Pointner, M., Khader, P. H., Müller, H. J., & Geyer, T. (2015) "What eye movements can reveal about the coupling of attention and context memory in visual search", *18th European conference on eye movements , University of Vienna,* Vienna, Austria

Annac, E., Manginelli, A.A., Pollmann, S., Shi, Z., Müller, H. J., & Geyer, T. (2013) "Memory under pressure: secondary-task effects on contextual cueing of visual search" *Tagung experimentell arbeitender Psychologen (TeaP 2013),* Vienna-Austria

Annac, E., Manginelli, A.A., Pollmann, S., Shi, Z., Müller, H. J., & Geyer, T. (2012) "Memory under pressure: secondary-task effects on contextual cueing of visual search" *Visual Search and Selective Attention (VSSA III)* ,Holzhausen am Ammersee-Munich,Germany

Annac, E., Manginelli, A.A., Pollmann, S., Shi, Z., Müller, H. J., & Geyer, T. (2012) "Memory under pressure: secondary-task effects on contextual cueing of visual search" *Amsterdam Memory Slam*, Amsterdam, The Netherlands

Annac, E., Müller, H. J., & Geyer, T. (2011) "Relations between working memory gender, perceptual grouping, and long-term memory in visual search" *Multisensory perception symposium*, Holzhausen am Ammersee-Munich,Germany

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Affidavit/Eidesstattliche Versicherung

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation „Bi-directional relationship between attention and long-term context memory“ 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 „Bi-directional relationship between attention and long-term context memory“ is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

Munich, München	30.10.2017	Efsun Annaç
Place/Ort	Date/datum	Signature/Unterschrift Efsun Annaç

Declaration of author contributions

All projects were done under the supervision of Thomas Geyer (TG)

Chapter 2 published in Visual cognition (Annac, Conci, Müller & Geyer 2017). Efsun Annac (EA), TG and Markus Conci (MC) conceived the question and designed the experiments together. EA and TG prepared the display manipulation, MC programmed the experiments. EA carried out the experiments and did the analysis. EA, MC, Hermann J. Müller (HJM) and TG discussed the results and wrote the paper together.

Chapter 3 published in Journal of Vision (Annac, Manginelli, Pollmann, Shi, Müller & Geyer, 2013). EA and TG conceived the question and designed the experiments together with Stefan Pollmann. Angela A. Manginelli and Zhuanghua Shi programmed the experiments. EA collected the data and did the analysis. EA, TG, and HJM wrote the paper.

Chapter 4 EA, TG and HJM conceived the question. EA and TG designed the experiments. Xuelian Zang (XZ) programmed the experiments. EA collected data, did the analysis and wrote the paper together with XZ, TG and HJM.

Chapter 5 TG conceived the question and the design of the experiments. Mathias Pointner (MP) and EA ran the experiments. TG and XZ implemented the experiments. EA and TG discussed the results. EA, Patrick Khader, HJM and TG wrote the paper together.

Munich, October 2017

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