Determinants and Restrictions of the Processing and Reorganization of Spatial Configurations in Visual Working Memory

Dissertation

der Mathematisch-Naturwissenschaftlichen Fakultät

der Eberhard Karls Universität Tübingen

zur Erlangung des Grades eines

Doktors der Naturwissenschaften

(Dr. rer. nat.)

vorgelegt von

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Tübingen

2021

Gedruckt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der Eberhard Karls Universität Tübingen.

Tag der mündlichen Qualifikation:	21.06.2021
Dekan:	Prof. Dr. Thilo Stehle
1. Berichterstatter:	Dr. Frank Papenmeier
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Summary

Humans interact with several objects every moment of their lifetime. In order to process single objects, humans rely on inter-object relations to maintain and update a network of different objects at once. This mental network is called a (global) spatial configuration, which is also represented in visual working memory (VWM) based on the locations and relations of the objects contained. Previous research revealed that spatial configurations are supposed to be represented mentally flexible and there might be the possibility that a global spatial configuration can be split up into a relevant part and an irrelevant part. The present dissertation connects with this assumption, and the objective was to deepen the understanding of this mechanism including determinants and restrictions of the processing of spatial configurations in VWM. The aim was to have a closer look at the organization and reorganization of spatial configurations. With the help of empiric behavioral testing via a location change detection paradigm as well as an investigation of overt visual attention induced by eye movements and the influence of retro cues, I conducted four experimental series including eleven experiments and about 500 participants. This revealed that humans are able to reorganize spatial configurations and reduce information leading to (ir-)relevant partial configurations. Furthermore, the (non-)availability of eye movements and contextual information restricted this process whereas other mechanisms such as the individual VWM capacity threshold and limited possibility of overt visual attention across different processing stages did not restrict the configuration advantage described. I had a look at different determinants and restrictions, but in general, humans are able to reorganize a global spatial configuration into a relevant partial one in VWM, induced by an informative retro cue. Importantly, participants needed eye movements to handle this process. While a total enforced fixation reduced the configuration advantage heavily, participants showed a comparable one to free view conditions with a partially restricted fixation. Thus, whereas the processing of spatial configurations in VWM is boosted by the ability of performing shifts of overt visual attention, configurational processing does not rely on these shifts occurring throughout the task. Future research should investigate these findings in order to approach a more precise understanding of the link between the visual sensorium and VWM. In summary, this dissertation supports and extends the idea of a rather flexible mental representation of single objects arranged in a (global) spatial configuration.

Zusammenfassung

Der Mensch interagiert in jedem Moment seines Lebens mit mehreren Objekten. Um mit einzelnen Objekten umgehen zu können, ist der Mensch auf die räumlichen Beziehungen zwischen den Objekten angewiesen, um ein Netzwerk gleichzeitig zu verarbeiten. zu speichern und zu aktualisieren. Dieses mentale Netzwerk wird als (globale) räumliche Konfiguration bezeichnet, die u.a. im visuellen Arbeitsgedächtnis auf der Grundlage der Positionen und Relationen der enthaltenen Objekte dargestellt wird. Bisherige Forschung hat gezeigt, dass räumliche Konfigurationen mental flexibel dargestellt werden und dass die Möglichkeit besteht, dass eine globale räumliche Konfiguration in einen relevanten und einen irrelevanten Teil aufgeteilt werden kann. Die vorliegende Dissertation knüpft an diese Annahme an mit dem Ziel, das Verständnis dieses Mechanismus einschließlich der Determinanten und Einschränkungen bei der Verarbeitung von räumlichen Konfigurationen im visuellen Arbeitsgedächtnis zu vertiefen. Ziel war es, die Organisation und Reorganisation von räumlichen Konfigurationen genauer zu betrachten. Mit Hilfe empirischer Testung mittels eines Paradigmas zur Erkennung von Positionswechseln sowie einer Untersuchung des Einflusses von Hinweisreizen und offener visuellen Aufmerksamkeit führte (und veröffentlichte) ich vier Experimentalserien mit insgesamt elf Experimenten und etwa 500 Teilnehmer*innen. Die Studien zeigten, dass der Mensch in der Lage ist, räumliche Konfigurationen zu reorganisieren und Informationen zu (ir-)relevanten Teilkonfigurationen zu reduzieren. Darüber hinaus schränkte die (Nicht-)Verfügbarkeit von Augenbewegungen und Kontextinformationen diesen Prozess ein, während andere Mechanismen wie die individuelle Arbeitsgedächtnis-Kapazitätsschwelle und die begrenzte Möglichkeit der offenen visuellen Aufmerksamkeit über verschiedene Verarbeitungsstufen hinweg den beschriebenen Konfigurationsvorteil nicht einschränkten. Ich habe mir verschiedene Determinanten und Einschränkungen angesehen, aber verallgemeinert sind Menschen in der Lage, eine globale räumliche Konfiguration in eine relevante Teilkonfiguration im visuellen Arbeitsgedächtnis umzuorganisieren, die durch einen informativen Hinweisreiz induziert wird. Wichtig ist, dass der Mensch Augenbewegungen benötigt, um diesen Prozess zu bewältigen. Ein vollständiger Verlust der Verfügbarkeit von Augenbewegungen konnte nicht kompensiert werden, aber mit einer teilweise eingeschränkten Möglichkeit der Blickbewegungen zeigten die Versuchsteilnehmer*innen immer noch einen Konfigurationsvorteil. Während also

die Verarbeitung räumlicher Konfigurationen im Gedächtnis durch die Fähigkeit zur Durchführung von Verschiebungen der offenen visuellen Aufmerksamkeit gefördert wird, ist die Konfigurationsverarbeitung nicht davon abhängig, dass diese Verschiebungen während der gesamten Aufgabe auftreten. Zukünftige Forschung sollte diese Ergebnisse aufgreifen, um sich einem präziseren Verständnis der Verbindung zwischen dem visuellen System und dem damit verbundenen Arbeitsgedächtnis anzunähern. Zusammenfassend unterstützt und erweitert die vorliegende Dissertation die Idee einer eher flexiblen mentalen Repräsentation einzelner Objekte, die in einer (globalen) Raumkonfiguration angeordnet sind.

Abbreviations

AR – **A**ugmented **R**eality

CH – **C**olor **H**ex Code (additive RGB color model)

Lm – **L**u**m**inance

VR – **V**irtual **R**eality

VWM – **V**isual **W**orking **M**emory

1. Introduction

Humans receive visual input in almost every situation of their life. In order to interact with their environment, humans need a reliable system to maintain, highlight, and update relevant information. One important part of this system is the visual working memory (VWM). Imagine you are at the breakfast table and look for the jam. As soon as you detect it, someone shouts from the kitchen and you look into that direction. In the meantime, your child has taken the sugar next to the jam and placed it somewhere else afterwards. Then your attention is drawn to the table again, but you have trouble to find the jam again as the setting has changed. To successfully locate the jam in the new unfamiliar context, you access and update your mental representation in VWM. Now you can grab it and finally enjoy it.

In this dissertation, I focused on this mechanism: how to update or more specifically, reorganize your mental representation. First, I will reflect on previous research and how my experimental series were motivated by the theoretical groundwork. In detail, I will explain generally what VWM is, how objects form a spatial configuration in VWM, and I will give an overview of different accounts regarding inter-object relations. Next, I will describe how VWM is accessed via retro cues and how the reorganization process is defined before turning the focus on VWM capacity, the role of overt visual attention as well as contextual influences on the (re-)organization of spatial configurations in VWM. Afterwards, I will wrap this up and describe the processing and (re-)organization of spatial configurations in VWM and the objectives of the experimental series in detail. Second, there is a description of each experimental series including procedures, results, and short discussions. Finally, I will discuss all the results in light of the theoretical groundwork mentioned before and give an overview of future research possibilities as well as a final conclusion of the work presented.

1.1 Visual Working Memory and Spatial Configurations

As described in the example above, the VWM is part of humans' memory resources, which is described in many different models. More than 50 years ago, one of the first and most influential models of this memory system was postulated (Atkinson & Shiffrin, 1968). Back then, the three common memory stores were introduced as the sensory, the short-term and the long-term store. These stores are different in time and capacity characteristics. While the sensory store is temporally very limited, its capacity is very vast. This is a common characteristic with the long-term store, which has a tremendous (almost unlimited) capacity, but one piece of information can be retrieved after decades of time. The most fragile and rapid store is the short-term one. Its time range is limited to seconds and the capacity declines with the more seconds the access requires (Atkinson & Shiffrin, 1968). Modern research differentiates between different chronologically ordered short-term stores, which in turn differ also in time and capacity. There is evidence of a high-capacity time-limited fragile store and of a low-capacity robust store, which operates at a longer time interval (Sligte et al., 2008). However, current research questions this and suggests rather a practice effect than a basic distinction regarding these assumptions. In detail, classic capacity limits can be increased by means of intensive training (Matsukura & Hollingworth, 2011). Modern literature subdivides the short-term store into several sub stores, for example the visual short-term store. While early models already used the term working memory synonymously with the short-term store (Atkinson & Shiffrin, 1968), more recent research also proposed several types of working memory (Baddeley & Hitch, 1974; Cowan, 2001). Current research postulated the *core knowledge architecture model,* which distinguishes between three main buffer systems in VWM. In detail, VWM retains spatiotemporal information, snapshot information, and object identity information. These findings build a bridge between VWM and visual cognition, which moves further away from a universal visual short-term store model (Wood, 2011). Similar assumptions can be made by having a look at more recent neuroimaging studies. In particular, working memory and short-term store should be differentiated because different areas of the prefrontal cortex are activated. Nevertheless, the short-term store does not enable the organization and processing of the stored content (Diamond, 2013). However, both mechanisms are dependent on each other and there has been a long, unresolved debate about the differences as well as the term(s) and so I will stick to *VWM* in order to ensure a rigorous narrative in this dissertation (see e.g. Bateman et al., 2018; Hollingworth & Rasmussen, 2010; Matsukura & Hollingworth, 2011; Matsukura & Vecera, 2015; Van der Stigchel & Hollingworth, 2018 for further information about this debate). The study of VWM is mostly investigated by means of a three-stage paradigm. At the beginning of an experimental trial, the objects of interest are visible for a certain time after stimulus onset. Participants are instructed to encode the visible stimuli. This stage is called *Encoding* in the present work, although there are different terms for the three stages in VWM literature (e.g. Brady & Alvarez, 2011; Jiang et al., 2000; Papenmeier et al., 2012; Sligte et al., 2008). The second stage is a blank phase, in which no objects are visible. This stage is called *Maintenance* in the present work and this stage is essential for the investigation of VWM processes. The third and last stage is called *Retrieval*. The objects are visible again and there might be a manipulation compared to Encoding, depending on the condition. The display itself can be described as *Probe Display* because one object is probed at retrieval. This stage ends when the participants give a response and the next trial begins after a short break with a new Encoding stage. Using this paradigm, VWM processes and organization are broken down.

The organization of VWM content is closely associated with the processing of the spatial locations of objects maintained. Simultaneously memorized single objects are not represented independently from each other but are rather maintained as a network based on the relations between them. This construction is known as spatial configuration which contributes significantly to the organization of spatial information in VWM (Jiang et al., 2000). Previous research revealed that humans automatically process a spatial configuration of multiple objects. Jiang and colleagues (2000) found evidence of this mechanism in their studies. The participants’ task was to encode single objects independently. At retrieval, participants were instructed to detect whether one probed object changed its location or not. Moreover, the probed object was either shown alone or accompanied by other objects that were also memorized (the spatial configuration). Importantly, participants were better at the detection of location changes of a single object when the object was presented within a spatial configuration instead of being shown alone. This mechanism is called a configuration effect, configuration benefit or configuration advantage. These spatial configuration advantages are not limited to simple objects such as squares (Jiang et al., 2000; Papenmeier et al., 2012) but can also be found in more natural settings (Hollingworth, 2007; Papenmeier & Huff, 2014).

1.2 Snapshot Account and Independent Configurational Processing

The literature review of VWM research reveals that there are (at least) two important contrary models of the processing of spatial configurations. In short, either inter-object relations are supposed to be interdependent on the single objects included and this might have a strong influence on processing spatial configurations or they might be obtained from a separate, independent store (Cowan, 2001; Halford et al., 1998; Palmer, 1990; Palmer et al., 1993, 2015; Wilken & Ma, 2004). One approach which is suggested by previous research is a snapshot-based, thus independent processing and mental representation of spatial configurations in VWM. It is called the snapshot account, because the whole scene is supposed to be remembered at once (e.g. Papenmeier & Huff, 2014; Wood, 2011). There is some empirical evidence of this assumption as, for example, changes in perceptual grouping objects, which are actually irrelevant to the task procedure were shown to affect participants' memory performance (Jiang et al., 2004). In detail, participants had to encode several objects with different features. The participants' location change detection performance decreased when the task-irrelevant orientation of the objects was altered at retrieval (Jiang et al., 2004). This reflects a formation of a spatial configuration based on the perceptual grouping of the objects encoded. Moreover, spatial configuration advantages could not be referred to the presence of additional reference points only, because the presentation of random partial configurations (e.g. half of the objects compared to the configuration encoded) did not lead to an improvement in location change detection performance (Jiang et al., 2000; Papenmeier et al., 2012). Finally, contextual information was found to be view-dependent (Papenmeier & Huff, 2014; Wood, 2011). Participants were shown different spatial configurations at the beginning of the experiment. They were instructed to respond to a location change detection task, while the point of view (0° & 60°) and the spatial configuration (global & no) were manipulated at retrieval. The memory benefit for the global spatial configuration was not shown with a viewpoint change despite memory for individual objects (Papenmeier & Huff, 2014).

Referring to the VWM organization itself, previous research focused on the mental representation of features and objects as well as on the impact of inter-object relations like summary statistics or spatial configurations on VWM representations. Until now it remains unclear if features like location, shape and color are represented as an integrated object (Luck & Vogel, 1997) or if these features are maintained separately and bound via attention (Wheeler & Treisman, 2002). Moreover, previous studies showed that there is an impact of inter-object relations on VWM maintenance, like the configuration benefit mentioned above (Jiang et al., 2000) or summary statistics for feature storage bias toward the group average, in which, for example, the size of a colored object is matched to the sizes of the other objects which are encoded into a specific color group (Brady et al., 2011; Brady & Alvarez, 2015; Papenmeier & Timm, 2021). In contrast, there is little knowledge about the mental representations of inter-object relations themselves. The snapshot account is an expansion of the core knowledge architecture model of VWM (Wood, 2011), which proposed the existence of functional storage within VWM which maintains view-dependent snapshots as mentioned above. These snapshots might possess the global configuration as a whole rather than a network of single objects and thus, are not contingent on similar VWM capacity thresholds. In summary, this research dealing with inter-object relations provides rather evidence of a maintenance as a global snapshot in VWM and the independent storage of spatial configurations in VWM.

1.3 Flexibility Account and Interdependent Configurational Processing

In contrast to the snapshot account, recent studies emphasized a rather flexible eye movement-based approach, in which spatial VWM content is rather processed interdependently. An important point is that spatial configurations are only generated by relevant objects and not by all visible objects in this paradigm. Jiang and colleagues (2000) found evidence of that by instructing participants to memorize a colored subset surrounded by other objects. Altering the irrelevant objects had no effect on memory performance for the memorized objects (Jiang et al., 2000). This speaks against a snapshot processing of the entire scene. Moreover, a lot of recent eye movement studies proposed the need for saccades and fixations to process VWM representations, which stand in contrast to a rigid perceptual snapshot system (e.g. Bays et al., 2009; Bays & Husain, 2008; Berman & Colby, 2009; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kalogeropoulou et al., 2017; Ohl & Rolfs, 2017; Van der Stigchel & Hollingworth, 2018). Early experiments used a dual-task paradigm, which included a letter-discrimination task and more importantly, a saccade assignment. This study revealed that object recognition and saccade target selection set up a joint attention mechanism (Deubel & Schneider, 1996). Recent research corroborated this evidence including different mechanisms such as gaze correction during item research at retrieval, target selection, maintenance as well as feature conservation during and after a saccade (Van der Stigchel & Hollingworth, 2018). Next to the mentioned importance of eye movements regarding VWM processes in general, recent research also showed evidence of the explicit advantage of overt visual attention when processing spatial configurations. In detail, memory performance is influenced by both spatial memory and non-spatial memory. This is modulated by selective attention, but the explicit role of eye movements is still unclear (Sun & Gordon, 2009, 2010). Furthermore, overt visual attention impacts processing spatial memory components including the distances and relations to other objects, which are essential for VWM processes (de Vito et al., 2014; Laeng & Teodorescu, 2002).

Referring to the VWM organization itself, previous research dealing with this approach considered that the hierarchical organization and objects features are stored dependently from each other as a part of a higher order representation in VWM (Bae & Luck, 2017; Brady et al., 2011; Brady & Alvarez, 2011, 2015; Orhan & Jacobs, 2013; Papenmeier & Timm, 2021). For example, participants had to maintain the sizes of different colored objects and it was shown that they did not only remember the single object sizes but rather clustered the objects into the corresponding color groups leading to a recall of single object size being biased toward the mean of the particular group (Brady & Alvarez, 2011). Whereas one might consider that inter-object relations like hierarchical representations are represented interdependently of the objects they are derived from, previous research dealing with hierarchical representations rather highlighted the impact of spatial configurations or summary statistics on single and individual objects respectively (Brady et al., 2011). Therefore, the way in which these mental representations are maintained in VWM as a network of individual objects, thus the spatial configuration, remains an open question.

1.4 (Re-)Organization of Spatial Configurations in VWM

One method to investigate VWM processes is the retro cue paradigm, which has established itself as a reliable measure when investigating VWM manipulations (e.g. Griffin & Nobre, 2003; Landman et al., 2003; Lepsien et al., 2005; Makovski et al., 2008; Makovski & Jiang, 2007; Sligte et al., 2008; Souza & Oberauer, 2016; Williams & Woodman, 2012). As described in the beginning, VWM processes are often investigated via a three-stage task (encoding, maintenance, retrieval). An informative cue informs participants which part of the display will be investigated or has to be attended (Matsukura & Hollingworth, 2011). Research distinguishes here between three types of cues. The iconic cue is shown during encoding and is therefore an indicator of attention processes. The retro cue is shown during maintenance. As this is a blank phase, the retro cue is used to investigate VWM processes as well. A cue during retrieval is called post cue (Sligte et al., 2008). As mentioned above, the main focus of this work is put on VWM processes. The retro cue induces a deliberate attention shift to the objects highlighted by the retro cue. On the one hand, previous research suggested that a retro cue leads to a more robust representation of the highlighted object (Sligte et al., 2008). In detail, directing attention to a single object in VWM decreases the configuration advantage at retrieval and this might be interpreted as a reorganization of the spatial configuration to the highlighted single object (Sligte et al., 2008). On the other hand, previous research suggested that a retro cue leads to the deletion of the originally memorized and now irrelevant objects from memory (Williams, Hong, Kang, Carlisle, & Woodman, 2013). In detail, cueing was also linked to the benefit of forgetting single objects within the spatial configuration and thus, this mechanism might be interpreted as the irrelevance of spatial configurations after cueing (Williams, Hong, et al., 2013; Williams & Woodman, 2012). In summary, despite the debate about the process details, previous research already showed evidence that mental VWM representations can be updated but, importantly, preceding research dealt with the fate of single objects mainly. Thus, the open question remains, whether the global spatial configuration can be reorganized into a relevant partial configuration, focusing on multiple objects instead of the fate of one single object. Reorganization is hereby defined as a similar memory performance of participants using a partial configuration rendered relevant by a retro cue compared to the memory performance using the global configuration. In detail, the configuration advantage can be applied with the relevant configuration shown at retrieval only, after being highlighted with a retro cue. Recent research already revealed that shifting attention via retro cues can affect the mental representations of two simultaneously memorized objects in VWM. In detail, Bae and Luck (2017) investigated the sequential presentation of two differentially oriented objects and showed that a retro cue influenced the reproduction at retrieval. Interestingly, the cued object influenced the uncued object but not vice versa. This emphasizes that an attention shift is relevance-dependent, which could also enable a reorganization process. Previous research showed already that both top-down and bottom-up attentional components influence the processing of spatial configurations in VWM (Jiang et al., 2000), but it still remains unclear whether the reorganization of a global spatial configuration into a relevant partial configuration is also possible in VWM.

There are a few possible determinants and restrictions which have to be taken care of when it comes to the investigation of VWM processes. In detail, the VWM capacity, contextual influences and the already described overt visual attention are important accompanying factors which can influence and sometimes moderate VWM mechanisms. VWM capacity has been studied a lot in cognitive science. Previous research described a VWM slot model with a strict maximum threshold (e.g. Dempere-Marco et al., 2012; Engle, 2002; Gurariy et al., 2016; Luck & Vogel, 1997; Matsukura & Hollingworth, 2011; Matsuyoshi et al., 2012; Rolls et al., 2013; Turner & Engle, 1989; Vogel & Machizawa, 2004; Zhang & Luck, 2008). As mentioned above, either inter-object relations are supposed to be interdependent on the single objects included, and this might have a strong influence on a possible reorganization of spatial configurations, or they might be obtained from a separate, independent store and this should less impact the possible reorganization effect (Cowan, 2001; Halford et al., 1998; Palmer, 1990; Palmer et al., 1993, 2015; Wilken & Ma, 2004). Thus, different set sizes might influence the possible reorganization of spatial configurations in VWM. If the storage of inter-object relations were interdependent of the objects they are derived from, higher set sizes would lead to a less accurate retrieval of individual object representations (e.g. location) within the spatial configuration (Brady & Alvarez, 2011; Treisman & Zhang, 2006; Zhang & Luck, 2008) or to a mental representation consisting of a subset of single objects when the capacity threshold is surpassed (Luck & Vogel, 1997). If the storage of inter-object relations were separate and independent of the objects they are derived from, higher set sizes would not necessarily lead to a less accurate retrieval of individual object representations (e.g. location) within the spatial configuration, but rather be dependent on the properties of the particular storage (Brady et al., 2011; Greene & Oliva, 2009; Wood, 2011).

In addition, contextual information itself (non-probed objects) might have an essential influence on processing spatial configurations in VWM. As already mentioned, previous research showed that contextual information in VWM is processed view-dependently because manipulating the viewing angles of a spatial configuration maintained in VWM led to a decrease in memory performance (Papenmeier & Huff, 2014). Moreover, preceding studies found evidence that the global spatial configuration, but not partial configurations, affects the memory performance for a single probed object (Jiang et al., 2000; Papenmeier et al., 2012) and spatial configurations still impact this memory performance with larger set sizes (Jiang et al., 2000). Furthermore, memory performance for a single probed object also decreases when task-irrelevant perceptual grouping cues have been changed between encoding and retrieval (Jiang et al., 2004). In summary, spatial VWM content is processed via binding into a relational coordinate system which increases the memory performance (Oberauer, 2009) because the VWM content is maintained in parallel chunks (Halford et al., 1998; Palmer, 1990; Palmer et al., 1993, 2015; Wilken & Ma, 2004). Souza and Oberauer stated that “attended representations are strengthened in WM, … not-attended representations are removed from WM, … a retro-cue to the retrieval target provides a head start for its retrieval before decision making, and … attention protects the selected representation from perceptual interference” (Souza & Oberauer, 2016, p. 1839). Therefore, the knowledge about the processes during a possible reorganization of spatial configurations in VWM does not include the investigation of the relevant partial configuration only, but also the irrelevant partial configuration as well as the influence of the contextual information. Previous research already found evidence that irrelevant spatial configurations decrease memory performance in a feature change detection task (Boduroglu & Shah, 2009). While some preceding studies focused on direct changes in motion (Sun et al., 2015) or categorical relation (Dent, 2009) to diminish the configuration advantage, recent studies focused on how altered locations influence the building of partial configurations (Bateman et al., 2018). In detail, altering the relative positions between items of a partial group drives this process and the decreased memory performance can be less likely referred to a changed position of the partial group in general (Bateman et al., 2018). The contextual information can thus impair a possible reorganization if the specific non-probed objects are relationally linked to the mental VWM representation of the probed object.

Importantly, as the term VWM already describes, the visual sensorium should also be focused on when studying VWM. Processing spatial configurations and overt visual attention induced by eye movements are often associated. As described above, there are contrary accounts explaining processing spatial configurations. On the one hand, there is evidence of a snapshot-based VWM content, which rather speaks against the need of eye movements done as, for example, the memory content depends on the angle from which the remembered items are viewed (Papenmeier & Huff, 2014; Wood, 2011). On the other hand, a lot of recent eye movement studies proposed the need for saccades and fixations to process spatial VWM content, which stand in contrast to a rigid perceptual snapshot system (e.g. Bays et al., 2009; Bays & Husain, 2008; Berman & Colby, 2009; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kalogeropoulou et al., 2017; Ohl & Rolfs, 2017; Van der Stigchel & Hollingworth, 2018). Therefore, it remains unclear if a possible reorganization of spatial configurations is based on multiple saccades and fixations and is induced by overt visual attention or if eye movements are not needed because the mechanism is processed via snapshots.

To summarize the preceding chapters, the processing and reorganization of spatial configurations in VWM is a worthwhile topic to investigate in order to answer the subsequent open questions and to compare different theoretical frameworks. The organization of the VWM and the processing of spatial configurations is still unclear as there are different approaches regarding inter-object relations. I focused on the comparison of the flexible network including interdependent configurational processing and the snapshot account including independent configurational processing. Another important subject of investigation is whether and how a reorganization into partial spatial configurations in VWM can be induced via a retro cue and what role is played by restrictions and determinants such as VWM capacity, contextual influences, and overt visual attention. In detail, the role of eye movements is unclear in terms of its general need for establishing content in VWM regarding the different approaches of this mechanism as well.

2. Present Research and Objectives

As mentioned above, a lot of open questions regarding the (re-)organization of spatial configurations in VWM remain. Are humans able to reorganize a global spatial configuration into a relevant partial configuration in VWM without losing the ability to detect location changes? Are spatial configurations stored independently (snapshot account, Chapter 1.2) or interdependently (flexibility account, Chapter 1.3)? In order to broaden the knowledge about the (re-)organization of spatial configurations in VWM, four experimental series were conducted (see Tables 1 - 4).

Table 1

Experimental Series I – Reorganization of Spatial Configurations in VWM

Experiment	*N*	Source
1 - Reorganization of Spatial Configurations in VWM	28	(Timm & Papenmeier, 2019a)
2 - Impact of Set Size on Reorganization	28	(Timm & Papenmeier, 2019a)
3 - Impact of Eye Movements on Reorganization	56	(Timm & Papenmeier, 2019a)

The first experimental series (Chapter 3.1, see Table 1) was conducted to see if the process of reorganization of spatial configurations can be performed in VWM and to approach the mechanisms that takes place during this reorganization. First, I investigated whether reorganizing spatial configurations in VWM is possible in general. Second, I had a first look at possible determinants and restrictions, namely the influences of set sizes and eye movements on the reorganization process. By using the retro cue paradigm, I investigated whether drawing attention to a subset of objects in a global spatial configuration during maintenance leads to reorganization into a relevant partial configuration in VWM. I refer to the reorganization as the mechanism in which a global spatial configuration is encoded in the first place and the number of objects and the corresponding relations are reorganized into a highlighted partial configuration after encoding following a retro cue, as described in the introduction.

Table 2

Experimental Series II – Influence of Set Size on the Reorganization Effect

Experiment	*N*	Source
4a - Influence of Set Size 1	28	(Timm & Papenmeier, 2019b)
4b - Influence of Set Size 2	28	(Timm & Papenmeier, 2019b)
4c - Influence of Set Size 3	28	(Timm & Papenmeier, 2019b)

The second experimental series (Chapter 3.2, see Table 2) was conducted to increase the understanding of the influence of set size on the possibility of building, reorganizing and splitting up global spatial configurations into partial configurations, which adds information about the processing of VWM content. In detail, I tested participants' capability of changing mental representations based on inter-object relations in VWM across different set sizes. Previous research points out at least two different accounts of possible VWM representations based on inter-object relations. On the one hand, the storage might be interdependent of the objects it is derived from (Feigenson, 2008; Halberda et al., 2006). On the other hand, the storage might be separate and independent of the objects it is derived from (Brady et al., 2011; Greene & Oliva, 2009; Wood, 2011). These are the two accounts of interest as they provide different assumptions about how inter-object relations affect the reorganization process in VWM. On the basis of previous research suggesting that the number of objects displayed in the test array may affect relational processing by itself (Udale et al., 2018b), I examined whether set size might affect the reorganization process.

Table 3

Experimental Series III – Influence of Cue Procedure and Contextual Objects

Experiment	*N*	Source
5 – Influence of Retro Cue Presence & Capacity	56	(Timm & Papenmeier, 2020)
6a – Influence of Contextual Objects 1	56	(Timm & Papenmeier, 2020)
6b – Influence of Contextual Objects 2	56	(Timm & Papenmeier, 2020)

The third experimental series (Chapter 3.3, see Table 3) was conducted to increase the understanding of the influence of contextual objects, the retro cue impact and the VWM capacity on the reorganization of spatial configurations and VWM's configurational processing in general. In summary, I had a look at the reorganization process in different environments. Therefore, I tested this mechanism in a partial and a whole display context. In detail, while preceding experiments on the reorganization of spatial configurations in VWM manipulated only the presence or absence of global or partial configurations, with the present set of experiments I also manipulated the positions of the non-probed objects at retrieval. These dislocations may diminish memory performance for the probed object if the accompanying non-probed items are relationally connected to the memory representation of the probed object. Thus, these experiments extend the research of the objects rendered relevant and irrelevant by the retro cue following the reorganization of spatial configurations in VWM. This was done using partial displays and also within a global display. As mentioned above, previous research suggested that the number of objects displayed in the test array may affect relational processing by itself (Udale et al., 2018b). So, next to the general set size, the processing within a whole display can give us more understanding about VWM mechanisms.

Table 4

Experimental Series IV – Overt Visual Attention in Configurational Processing

Experiment	*N*	Source
7 - Influence on Spatial Configurations	56	(Timm & Papenmeier, under review)
8 - Influence on VWM Processing Stages	60	(Timm & Papenmeier, under review)

The fourth experimental series (Chapter 3.4, see Table 4) was conducted in order to further investigate the influence of overt visual attention induced by eye movements on the processing of spatial configurations in VWM. As described above, there are contradictory findings regarding the visual processing of spatial configurations. On the one hand, previous research suggested a snapshot-based processing and mental representation of spatial configurations in VWM. This research suggested that humans do not need eye movements to remember a configuration, but rather fixate the center of a configuration. This is called the snapshot account, because the whole scene is just remembered at once (e.g. Papenmeier & Huff, 2014; Wood, 2011). On the other hand, recent studies emphasized a rather flexible eye movement-based process. Mental representations emerge from saccades and fixations leading to a more flexible network. This research suggested the need for eye movements. Saccades and fixations of and between the different parts of the configuration might help to store the information in VWM (e.g. Bays et al., 2009; Deubel & Schneider, 1996; Ohl & Rolfs, 2017; Van der Stigchel & Hollingworth, 2018).

3. Experimental Series

The current chapter focuses on my empiric research giving an overview of each experimental series including (theoretic) derivations, procedures, results and specific discussions as well as conclusions. All experiments were preregistered on OSF.

3.1 Experimental Series I – Reorganization of Spatial Configurations in VWM

In the first experimental series, I investigated whether attentional retro cues could trigger a reorganization of spatial configurations in VWM. If a global spatial configuration can be reorganized into partial configurations, guiding attention to a subset of objects during maintenance should lead to an increased performance in location change detection for single object location changes by the presence of a partial configuration encompassing the attended objects at retrieval. If, nonetheless, a reorganization of spatial configurations was not possible, only the presence of the global spatial configuration consisting of all encoded objects at retrieval should lead to a higher performance. Furthermore, I had a first look at possible determinants and restrictions, namely the influences of set sizes and eye movements on the reorganization process (Timm & Papenmeier, 2019a).

The aim of Experiment 1 was to provide a first evidence that a retro cue can induce a reorganization of spatial configurations in VWM. I presented six squares which were gray (Color Hex Code, additive RGB color model - *CH*: #777777, Luminance - *Lm*: 28.5 cd/m²) and measured 1.5° × 1.5° (degrees of visual angle). At the beginning of each trial, participants were told to view a centric fixation cross (CH: #000000, Lm: 0.1 cd/m²) and objects could appear in 20° × 20° area at the center of the screen (background: CH: #FFFFFF, Lm: 152.4 cd/m² & array border: CH: #000000, Lm: 0.1 cd/m²). Furthermore, I generated random object locations for each trial with the same number of squares equally placed on each side, with a minimum center-to-center distance of 1.5 times the diameter of a square. In order to guarantee that all locations used within a trial, including the new location of the probed object in change trials, were subject to the same restrictions, such as minimum distance, four object locations were generated on each side of the array, with only three being visible for each side during encoding. In change trials, the invisible fourth location at the cued side was made visible at retrieval and the original location of the probed object was made invisible (Timm & Papenmeier, 2019a).

Each trial consisted of the three standard stages introduced above, used to investigate VWM processes (see Figure 1). In the first stage (encoding), six squares were shown. Three squares were presented on each side for 2s. Afterwards, the objects disappeared and left a blank display. This blank second stage (maintenance) lasted also 2s. In the third stage (retrieval) the objects were shown again, and one object was marked with a red frame (CH: #FF0000, Lm: 29.1 cd/m²). Participants had to press one out of two buttons on a keyboard (1 = new location, 9 = old location) as to whether the location of this object had changed. I used a cue and a retro cue (CH: #E6E6E6, Lm: 118.7 cd/m²) of 0.1 s, which covered either the whole left-hand side or the whole right-hand side of the stimulus array, either 1s into encoding (cue) or 1s into maintenance (retro cue), to shift attention to a subset of objects. The cue and the retro cue were always informative as the probed object would appear on this side. Objects in the cue condition were still visible when the cue appeared. The retro cue during maintenance was the main manipulation as I was interested in VWM processes, while the cue during encoding was added for reasons of comparison. Thus, I was able to compare memory performance between the cue and retro cue conditions. The cue condition was used as manipulation check, to see if participants could perform the task. The configurations were defined as follows:

- Global: Presence of probed object and all other objects that were present during encoding.

- Relevant: Presence of probed object and all other objects that were (retro) cued.

- Irrelevant: Presence of probed object and all other objects that were not (retro) cued.

- No: Presence of probed object alone.

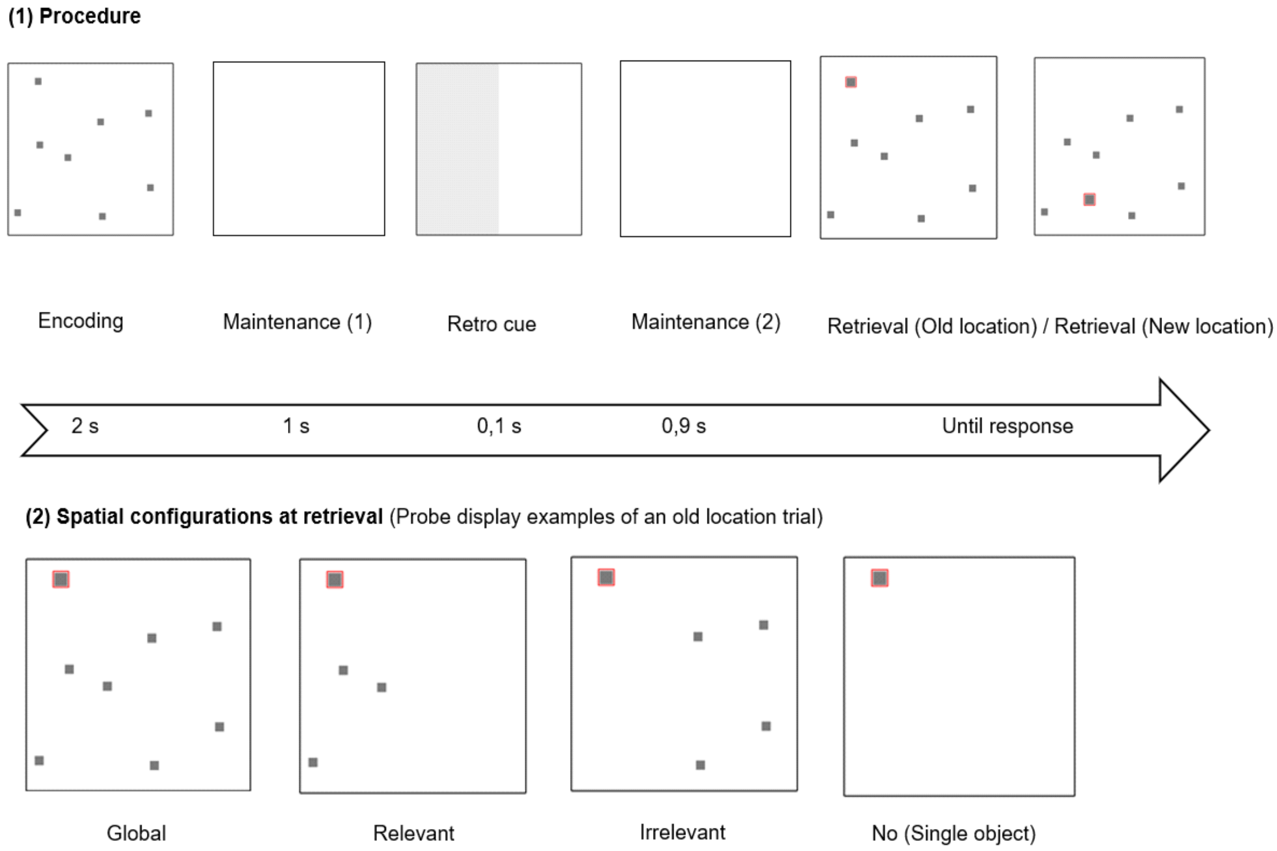

Figure 1 Procedure and manipulations of the standard location change detection task with retro cue. One of the retrieval panels was shown as probe display, intermixed within the experiment. Spatial configurations are hereby shown as examples in an old location trial (adapted from Timm & Papenmeier, 2019b).

Whereas all visible non-probed objects were always located at their old locations, the probed object could change its location between encoding and retrieval. In summary, I manipulated the (retro) cue side (left, right), the moment of cue presentation (encoding, maintenance), the location of the probed object at retrieval (new, old), and the configuration of the objects at retrieval (global, relevant, irrelevant, no). The (retro) cue was always informative and so the probed object at retrieval was always one of the objects indicated by the (retro) cue. Participants were assigned to all conditions and trials were presented in a randomized order with the restriction that each condition occurred equally often within each block and within the whole experiment (Timm & Papenmeier, 2019a).

If a reorganization of spatial configurations is possible in VWM, participants should utilize the retro cue in order to update their mental spatial representation. Thus, the memory advantage of a spatial configuration should also take place with a reorganized partial configuration following the appearance of an informative retro cue. Indeed, I found evidence of this mechanism (see Figure 2).

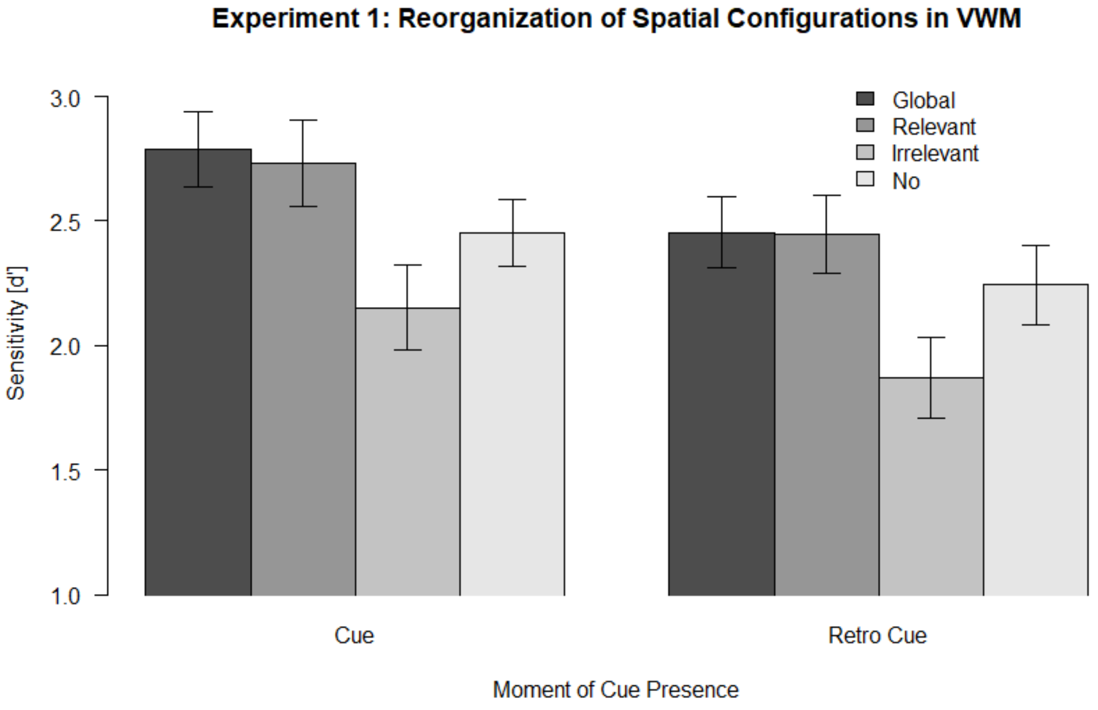

Figure 2 Sensitivity (d′) across participants for Experiment 1 (SEM error bars; adapted from Timm & Papenmeier, 2019a).

When the retro cue appeared during maintenance, I observed a configuration effect of the cued partial configuration on a level comparable to the global spatial configuration. In detail, presenting a retro cue during maintenance caused a similar pattern of results for presenting the cue during encoding. Thus, I conclude that it is possible to reorganize spatial configurations to a subset of objects by shifting attention to these objects in VWM in general (Timm & Papenmeier, 2019a).

In Experiment 1, participants showed very high sensitivity values across all conditions. Thus, I concluded that the location change detection task was rather easy with the set size of six objects. In order to further investigate the reorganization of spatial configurations under more challenging conditions, I conducted a second experiment with a doubled set size of 12 objects (Timm & Papenmeier, 2019a). The results of Experiment 2 also indicate a configuration effect during encoding due to a higher location change detection performance for the global configuration compared to no configuration. Moreover, participants reorganized the spatial configurations following a cue while encoding. These results confirm previous findings that the formation of spatial configurations during encoding can include a subset of objects by shifting attention to these objects. However, I did not observe a reorganization of spatial configurations during maintenance following a retro cue in contrast to Experiment 1. A reorganization was not possible during maintenance and thus, I ran a cross-experiment analysis. I compared location change detection performances across experiments. Most importantly, there was no significant three-way interaction including moment of cue presentation, configuration, and set size. Taking the Experiments 1 and 2 into account, it was possible for participants to shift their attention to a relevant partial configuration during encoding with both six and 12 objects. During maintenance, a reorganization was possible with six objects, but not with 12 objects. As I did not observe the significant three-way interaction of moment of cue presentation, configuration, and set size in a cross-experiment analysis, I cannot draw the clear conclusion that set size influences the reorganization process during maintenance (Timm & Papenmeier, 2019a). Therefore, I performed Experiments 4a-4c, which I present in Chapter 3.2 and which were specifically designed to investigate this influence (Timm & Papenmeier, 2019b).

Experiment 3 within the present series was the first experiment with a focus on eye movements. I investigated if and how overt visual attention influences the reorganization of spatial configurations in VWM. As described above, there are different approaches and findings regarding the link between eye movements and the VWM system. A snapshot processing would lead to the assumption that fixating the center (only) of the configuration evokes a memory advantage at retrieval when the probed object is accompanied by the global configuration. A rather flexible network suggests the need for saccades in order to process the configurations in VWM. Therefore, I tested these approaches against each other in the present experiment (Timm & Papenmeier, 2019a).

The standard location change detection procedure was shown by means of the following changes: Importantly, I manipulated fixation enforcement between participants. One group had to fixate on the center of the screen throughout a trial, and the other group was allowed to move their eyes freely. For the fixed gaze group, fixations were monitored throughout a trial, and a trial was aborted and repeated at the end of a block if a participant did not fixate correctly. A centered fixation point was shown and if gaze samples were recorded outside of an invisible surrounding circle with a radius of 1.5° for more than 0.25s, then a trial was aborted and repeated. Participants started each trial by fixating the center for 0.5s in both groups. I used a between-design, as I was concerned, that participants would show carryover-effects depending on the manipulation, in which they were tested first. In detail, I was concerned that participants who had to fixate during the first block, would also fixate during the free view block, which could skew the results. Furthermore, I also manipulated set size (6, 12) within participants, because there is some evidence that set size effects might be confounded with eye movements as larger set sizes elicit more eye movements (Zelinsky, 2001). This was also done as a comparison of the results of the cross-experiment analysis because six objects were shown in Experiment 1 and twelve objects were shown in Experiment 2.

The results of Experiment 3 indicate that the location change detection performances in the two eye movement groups were differentially affected by the presence of spatial configurations at retrieval. While participants showed a configuration and a reorganization effect within the free view condition, enforced fixation interfered with both effects. In detail, I observed reduced contextual processing in the absence of eye movements (fixed gaze). This speaks for a rather flexible network processing instead of a snapshot processing. Furthermore, consistent with Experiment 1 as well as the cross-experiment analysis of Experiments 1 and 2, reorganization took place and was not affected by set size. This experiment provided a first hint that overt visual attention does not only affect the reorganization of spatial configurations, but also the configurational processing in general. Thus, I performed Experiments 7 and 8 which I present in Chapter 3.4 and which were specifically designed to investigate this influence (Timm & Papenmeier, 2019a).

In summary, this first experimental series provided evidence that humans can reorganize a global spatial configuration into a relevant partial one in VWM via retro cue. Furthermore, there were also first hints of some determinants and restrictions of the processing and reorganization of spatial configurations in VWM (Timm & Papenmeier, 2019a). Therefore, the influences of set size and overt visual attention were focused in the following experimental series.

3.2 Experimental Series II – Influence of Set Size on the Reorganization Effect

In the second experimental series conducted, I was interested in the influence of set size, because – as described in the introduction – working memory maintenance is not infinite and collapses relatively quickly. The first experimental series showed a first evidence that set size might not affect the reorganization, yet a clear conclusion could not be drawn and only two different set sizes were used. Thus, by means of the following experiments, I specifically investigated the influence of different set sizes on the reorganization of spatial configurations in VWM. In Experiments 4a to 4c I manipulated the retro cue side (left, right), the set size (4, 8, 12, 16), and the position of the probed object at retrieval (new, old). Importantly, there was only a retro cue shown (during maintenance) and there was no cue (during encoding) because the focus lay on the processes in VWM. This retro cue-only procedure was applied to the following experiments as well. The aim of this experimental series was the influence of set size on the reorganization effect and I tested the configurational processing under different circumstances. In Experiment 4a, I manipulated the spatial configurations shown at retrieval as follows: global, relevant, irrelevant. In Experiment 4b, I manipulated the spatial configurations shown at retrieval as follows: no, relevant, irrelevant. In Experiment 4c, I manipulated the spatial configurations shown at retrieval as follows: relevant and irrelevant (Timm & Papenmeier, 2019b).

First, I found the general configuration advantage across all experiments, Second, whereas I found an interaction effect of set size and configuration in Experiment 4a, I could not find this interaction effect in Experiments 4b and 4c (see Figure 3). In order to further investigate the contradictory findings regarding the influence of set size on reorganization across my experiments, I calculated a cross-experiment analysis across the experiments including the retro cue conditions only, which did not reveal an interaction of set size and spatial configurations. In order to quantify the evidence of the absence of the interaction of set size and configuration, I calculated the Bayes factor comparing a basic model (H0) including the main effects (set size + configuration) only, to a full model (H1) including both main effects (set size + configuration) and the corresponding interaction (set size x configuration). Both models included *participant* as a random effect. The Bayes factor was $BF_{10} = 0.13$ suggesting that my data provide evidence of the absence rather than presence of the interaction of set size and configuration, which is in accordance with the frequentist results. Thus, there was no reliable influence of set size on the successful reorganization of spatial configurations in VWM across the experiments (Timm & Papenmeier, 2019b).

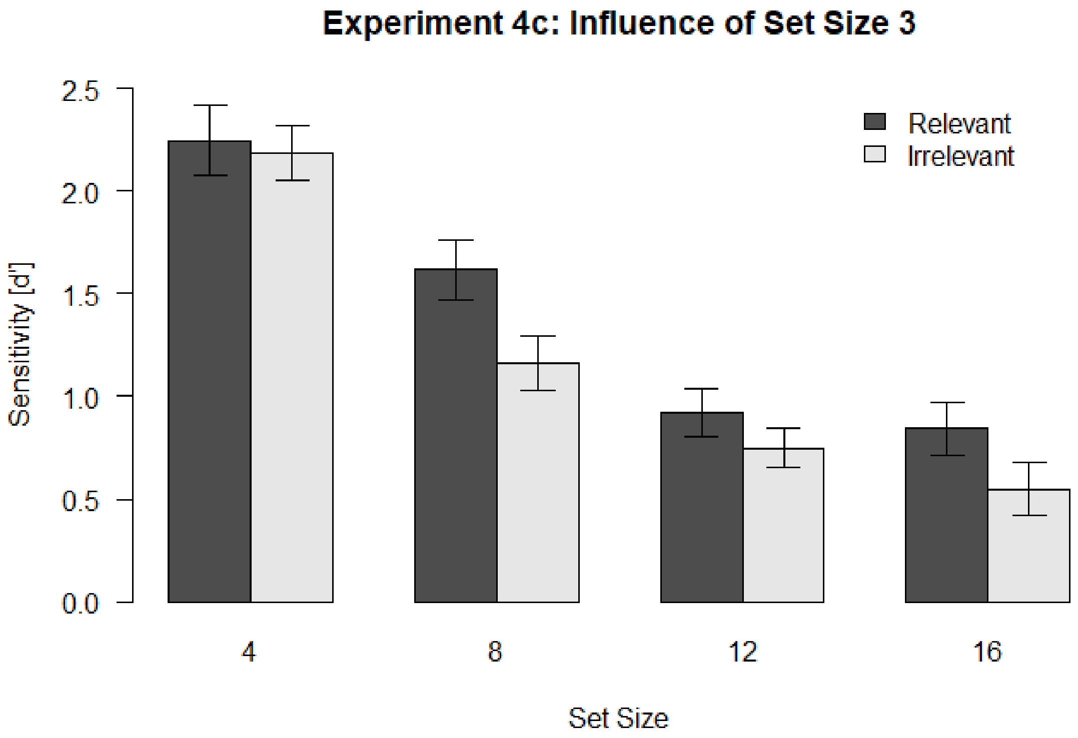

Figure 3 Sensitivity (d′) across participants for Experiment 4c (SEM error bars; adapted from Timm & Papenmeier, 2019b).

In summary, the first and second experimental series including (Bayesian) cross-experiment analyses could not provide evidence that the reorganization effect vanishes with an increase in set size. Thus, I conclude that reorganization of spatial configuration is largely unaffected by set size, at least within the range of set sizes investigated, that is up to sixteen objects (Timm & Papenmeier, 2019a, 2019b). This shows first evidence of a rather independent storage of spatial configurations in VWM, because the similar processing of higher set sizes compared to lower set sizes is contrary to common VWM capacity thresholds. This will be further discussed in the general discussion.

3.3 Exp. Series III – Influence of Cue Procedure and Contextual Objects

In this experimental series, I had a look at further possible general determinants and restrictions regarding the (re-)organization of spatial configurations in VWM, as mentioned in the introduction. Thus, Experimental Series 3 was designed to improve the knowledge about the retro cue, the VWM capacity and the influence of contextual objects. This experimental series focused on the reorganization effect but did also reveal some insights into the organization of spatial VWM content in general (Timm & Papenmeier, 2020).

The following experiments were conducted using a retro cue again in order to focus on processes in VWM like in Experimental Series 2. In Experiment 5, I used the same experimental logic as before manipulating the position of the probed object at retrieval (new, old), but manipulated the presence of the retro cue (yes, no). I counterbalanced and showed one block with the informative retro cue as well as one block without a retro cue to investigate if the retro cue procedure could be adapted automatically, thus leading to a difference in memory performance caused by the block order. Afterwards, I measured the participants' VWM capacity with a Corsi Blocks Task (CBT; Corsi, 1972; Kessels et al., 2000). In particular, I measured memory for spatial sequences with the length of sequence adaptively increasing or decreasing, depending on the performance of the participants (Timm & Papenmeier, 2020). The estimation of participants' VWM capacity was based on the mean of the last ten correct trials of the CBT (adapted from Grinschgl et al., 2020).

Another discussable point is that the distance or proximity between objects might induce or benefit reorganization instead of the retro cue. In detail, if the proximity only triggers the memory advantage of the relevant partial configuration, a retro cue would have no effect on the location change detection performance of the participants. Nevertheless, the results of Experiment 5 indicate that the reorganization of spatial configurations in VWM is indeed triggered by the informative retro cue. Without the retro cue, I found a global configuration benefit only, but I did not find evidence of a successful reorganization next to an absent interaction with block order. This leads to several conclusions. First, the reorganization is indeed only induced by the retro cue and the relevant configuration only leads to a comparable memory benefit when highlighted by the retro cue first. Second, the retro cue procedure did not transfer into situations without a retro cue and is therefore necessary to cause this effect despite the fact that the participants practiced splitting a global spatial configuration up. Furthermore, VWM capacity did not moderate the reorganization process and the process seems to be independent of individual capacity thresholds (Timm & Papenmeier, 2020). This will be further discussed in the general discussion.

With Experiments 6a and 6b, I had a look at the influence of the contextual objects. Hereby, I focused on the fate of the objects rendered relevant and irrelevant by the retro cue and the subsequent influences on the reorganization process caused by displacements in the periphery. In detail, I manipulated the locations of the non-probed objects. In the previous experiments, the probed object could change the location only. These manipulations were performed in order to investigate the influence of the non-probed objects' locations on the reorganization mechanism. In Experiment 6a, participants performed the standard location change detection task as before. This time, I manipulated the following variables: context locations (same, changed), the position of the probed object (new, old) and the configuration of the objects (global, relevant, irrelevant, no). The informative retro cue (left, right) appeared in every trial (Timm & Papenmeier, 2020).

The results of Experiment 6a indicate that the reorganization of spatial configurations in VWM was indeed strongly influenced by context location changes. While I replicated the reorganization of spatial configurations based on the retro cue when context locations stayed the same at encoding and retrieval, changing context locations interfered with a successful reorganization. In detail, I further analyzed the influence of context locations on memory performance within each configuration condition. This finding indicates that the spatial association between the probed object and irrelevant non-probed objects was diminished to such a degree that location change detection performance for the probed object was not influenced positively. In contrast, similar effects regarding the global configuration and relevant configuration were found when manipulating the context shown, indicating that the importance of the spatial association between the probed object and relevant non-probed objects were intensified to such a degree that location change detection performance for the probed object was strongly influenced (Timm & Papenmeier, 2020).

In Experiment 6b, I had a look at the influence of the contextual objects in an enriched environment. Thus, in contrast to Experiment 6a and any other experiment before, I tested the reorganization process within a whole display setup in order to extend the knowledge about contextual influences and the inter-object relations. Therefore, I used the same material as in Experiment 6a but manipulated the partial configurations within a whole display setting. Participants performed a standard location change detection task as before. This time I manipulated context locations and configurations within a global configuration. I tested the five following test displays: (Global-) Same, Global-Changed, Relevant-Changed, Irrelevant-Changed, Single Object (see Figure 4). Again, the retro cue was always informative, and configurations were defined as follows:

- Same: Presence of the probed object and all contextual objects that were present during encoding. All contextual objects are located at the same locations compared to encoding.

- Global-Changed: Presence of the probed object and all contextual objects that were present during encoding. All contextual objects are located at changed positions as compared with encoding.

- Relevant-Changed: Presence of the probed object and all contextual objects that were present during encoding. All contextual objects on the retro cue-relevant side are located at changed locations as compared with encoding, and all contextual objects on the retro cue-irrelevant side are located at the same locations as compared with encoding.

- Irrelevant-Changed: Presence of the probed object and all contextual objects that were present during encoding. All contextual objects on the retro cue-relevant side are located at the same locations as compared with encoding and all contextual objects on the retro cue-irrelevant side are located at changed positions as compared with encoding.

- Single: Presence of the probed object only.

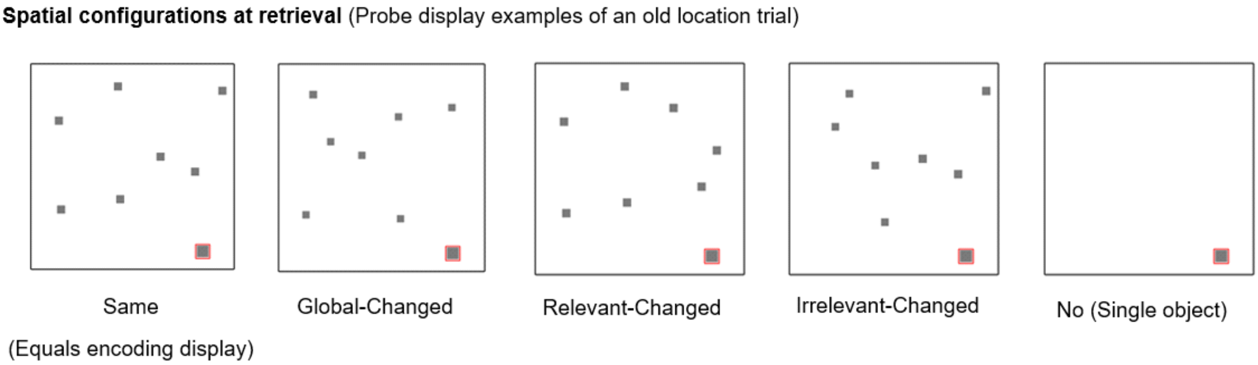

Figure 4 Whole display manipulations of spatial configurations in the location change detection task used in Experiment 6b (adapted from Timm & Papenmeier, 2020).

As before, a general configuration effect could be observed (see Figure 5). Importantly, a maximum change of the context (Global-Changed) impaired location change detection performance to a similar degree as a change of the relevant objects only within the global configuration (Relevant-Changed). This is in accordance with my previous conclusions suggesting a complete reorganization of the relevant objects after retro cue. Interestingly, a change of the location of the irrelevant objects within a whole display setup (Irrelevant-Changed) also diminished location change detection performance in comparison to the Same (global configuration) condition, although the relevant objects as indicated by the retro cue stayed on their locations. For the assumption of a full reorganization a location change of the irrelevant objects should not have impaired location change detection performance. Nevertheless, the performance for the Irrelevant-Changed condition was still higher in comparison to both the Global- and Relevant-Changed conditions (Timm & Papenmeier, 2020).

Whereas the first two experimental series indicate a rather independent processing, the current findings show evidence of an interdependent configurational processing. Further potentials for configurational processing are discussed in the general discussion.

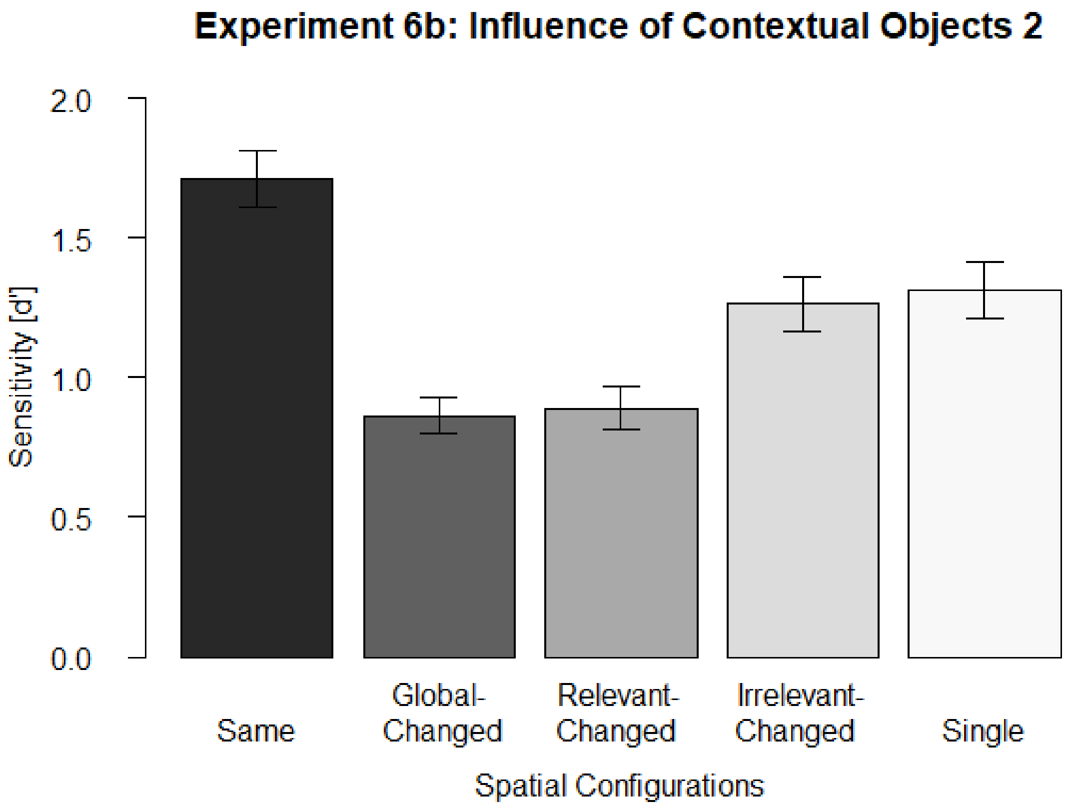

Figure 5 Sensitivity (d′) across participants for Experiment 6b (SEM error bars; adapted from Timm & Papenmeier, 2020).

In summary, the third experimental series showed, that a retro cue is needed to induce a reorganization of spatial configurations in VWM, while VWM capacity does not interact with the ability to reorganize spatial VWM content. Furthermore, these experiments provided evidence of the importance of the spatial association between the probed object and relevant non-probed objects in both a partial display and a whole display setting (Timm & Papenmeier, 2020).

3.4 Exp. Series IV – Overt Visual Attention in Configurational Processing

In the first experiment regarding eye movements (E3, Chapter 3.1), I found a link of processing spatial VWM content and the need of overt visual attention. This Experiment did not only reveal that eye movements are needed for the reorganization itself but rather for processing spatial configurations in general. Therefore, the aim of the present experimental series was to extend the findings by having a look at the general configuration effect, eye movement specific block order effects and influences of overt visual attention regarding different VWM processing stages. In Experiment 7, participants performed a location change detection task with the standard three stages (encoding, maintenance, retrieval). A retro cue was not used in this experimental series in order to focus on the configuration benefit. The probed object at retrieval was either accompanied by all objects (global configuration) or shown without a configuration (single object) investigating the basic configuration advantage. I further manipulated the possibility of eye movements (fixed gaze, free view) in a within design and the position of the probed object at retrieval (new, old). One block was performed without any restrictions regarding eye movements while the other block was performed with a controlled fixed gaze and the order of the blocks was counterbalanced across participants. The results provide evidence of the fact that shifts in overt visual attention eased the processing of spatial configurations. In the free view condition, participants had a greater advantage in memory performance using the configuration compared to the fixation group, which speaks against a snapshot-based processing of spatial configurations again (Timm & Papenmeier, under review). In summary, overt visual attention supports both a reorganization (E3) and a configuration effect (E3 & E7).

The aim of Experiment 8 was to understand in which processing stage overt visual attention is essentially needed for processing spatial configurations. Participants performed the standard location change detection task as in Experiment 7. I further manipulated the overt visual attention during the respective task stage. Next to a free view condition as in Experiment 7, I included three stages with a fixed gaze (encoding, maintenance, retrieval) and manipulated the position of the probed object at retrieval (new, old). For example, participants were instructed to fixate the center of the screen at retrieval and had a free view during encoding and maintenance. All participants performed the free view condition as the first experimental block. The fixed gaze stages were presented counterbalanced across participants. I controlled that participants fixate the center in the respective stage and that they performed at least one saccade during the other stages leading to an obligatory eye movement. Thus, participants could not fixate during the whole trial (Timm & Papenmeier, under review). Previous research already compared free view versus fixed gaze conditions but did not control for obligatory eye movements in free view trials so far. Thus, participants could have not moved their eyes when they were supposed to do so (e.g. Williams, Pouget, et al., 2013).

The results showed no evidence that the overt visual attention in one specific processing stage is essential for enabling a configuration benefit (see Figure 6). This leads to the assumption that although the capability of organizing and executing shifts of overt visual attention with eye movements boosts the processing of spatial configurations, it is not the eye movements within a specific processing stage that are provoking the configuration advantage (Timm & Papenmeier, under review).

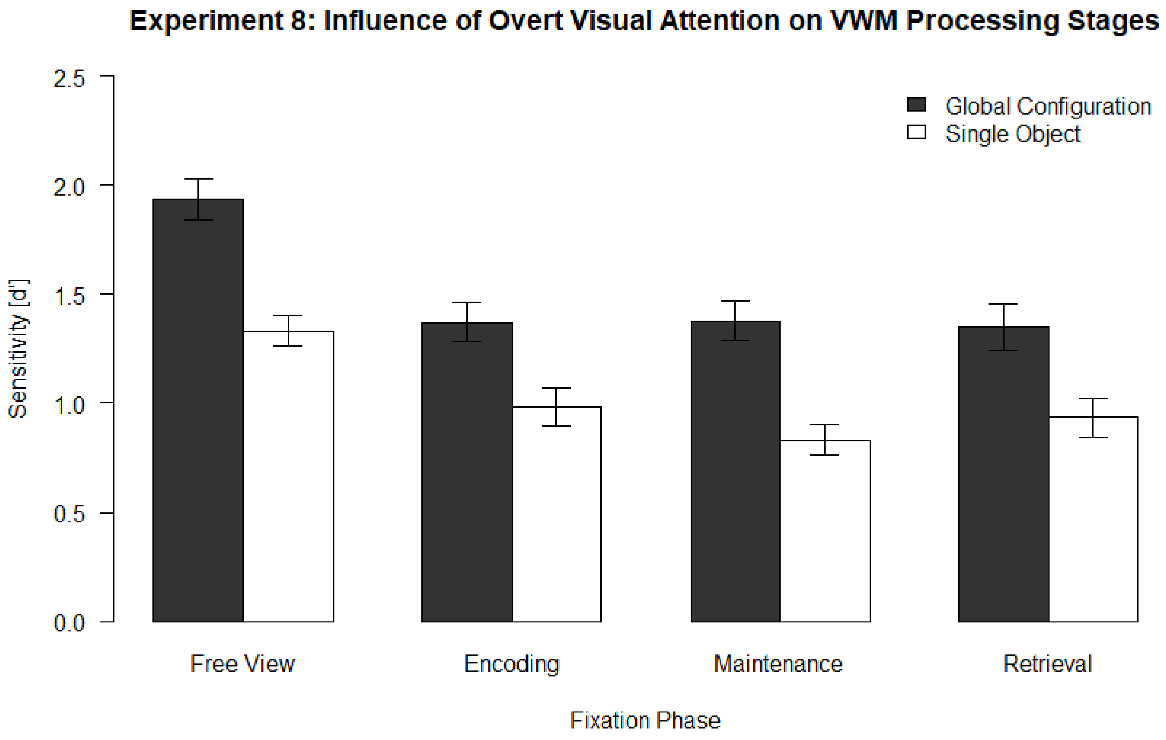

Figure 6 Sensitivity (d′) across participants for Experiment 8 (SEM error bars; adapted from Timm & Papenmeier, under review)

In summary, participants applied the capability of executing shifts of overt visual attention to boost their memory performance. Experiments 3 and 7 demonstrated that eye movements ease the configurational processing of object locations in memory. Although participants in Experiment 8 showed a lower overall performance in the conditions including stages of a fixed gaze, the magnitude of the configuration advantage was equivalent across conditions. In conclusion, although the capability of executing shifts of overt visual attention with eye movements support the processing of spatial configurations, this configurational processing does not depend on these shifts arising throughout the task (Timm & Papenmeier, under review, 2019a). These mixed findings do neither favor a snapshot not a flexible processing of spatial configurations in VWM. Further potential implications regarding the configurational processing are discussed in the general discussion.

4. General Discussion

In the final part of this dissertation, I will recap and discuss the implications following the experimental series as well as the strengths and limitations, before concluding the present work.

4.1 Summary

In summary, I stated some open questions in the beginning, which were investigated throughout four experimental series. The organization of the VWM and the processing of spatial configurations were still unclear, as there are different approaches to this mechanism. I focused on the comparison of the flexible network and the snapshot account. Another important subject of investigation was whether and how a reorganization of spatial configurations in VWM can be induced and what is the role played by restrictions and determinants such as VWM capacity, stimulus set size, contextual influences and overt visual attention. Furthermore, the impact of eye movements was also unclear in terms of its need for establishing content in VWM.

The first experimental series (Chapter 3.1) was conducted to see if the process of reorganization of spatial configurations in VWM is possible and to approach the process that takes place during this reorganization. First, the experiments showed that humans are able to reorganize global spatial configurations into partial relevant configurations and into irrelevant partial configurations. Second, the experiments gave a first hint that the reorganization and processing of spatial configurations in VWM rely on some determinants and restrictions, namely overt visual attention and set size (Timm & Papenmeier, 2019a).

The second experimental series (Chapter 3.2) was conducted to increase the understanding of the influence of set size on the possibility of building, reorganizing and splitting up global spatial configurations into partial configurations. In detail, I had a look at participants' capability of changing mental representations based on inter-object relations in VWM across different set sizes. In summary, the first and second experimental series including (Bayesian) cross-experiment analyses could not provide evidence that the reorganization effect disappears with an increasing set size. Thus, I conclude that the reorganization of spatial configurations is largely unaffected by set size, at least within the range of the investigated set sizes; that is, up to sixteen objects (Timm & Papenmeier, 2019a, 2019b).

The third experimental series (Chapter 3.3) was conducted to increase the understanding of the influence of contextual objects, the retro cue impact as well as the influence of VWM capacity on the reorganization of spatial configurations, and VWM's configurational processing in general. In summary, I observed the reorganization process in different environments. I investigated if the retro cue induces the reorganization only and whether VWM capacity moderates this mechanism or not. Furthermore, these experiments were supposed to extend the research of the objects rendered relevant and irrelevant by the retro cue following the reorganization of spatial configurations in VWM (Timm & Papenmeier, 2020). This was done with partial displays and also within a global display, as previous research suggested that the number of objects displayed in the test array may affect relational processing by itself (Udale et al., 2018b). Concluding, the third experimental series showed that a retro cue is needed to induce a reorganization of spatial configurations in VWM, while VWM capacity does not interact with the ability to reorganize spatial VWM content. Furthermore, these experiments provided evidence of the importance of the spatial association between the probed object and relevant non-probed objects in both a partial display and a whole display setting (Timm & Papenmeier, 2020).

The fourth experimental series (Chapter 3.4) was conducted in order to investigate the influence of overt visual attention and eye movements respectively on the reorganization and processing of spatial configurations in VWM. As described above, there are contradictory findings regarding the visual processing of spatial configurations. Experiment 3 showed that the reorganization process needs eye movements to develop. Importantly, Experiments 3 (between subjects) and 7 (within subjects) led to the conclusion that even configurational advantages are significantly higher when overt visual attention is available. Interestingly, Experiment 8 showed that although the capability of executing shifts of overt visual attention provokes the processing of spatial configurations, this configurational processing does not depend on such shifts arising throughout the task (Timm & Papenmeier, under review, 2019a).

Taken together, humans are able to reorganize spatial configurations in VWM and the (re-)organization of VWM content is dependent on some determinants and has also some restrictions, which are discussed in the next chapters.

4.2 Theoretical and General Implications

In this chapter, the experimental data is discussed with regard to existing literature and underlying models. In detail, I will have a look at the reorganization process itself and which factors restrict and determine this process as well as the corresponding implications for processing spatial configurations in general.

Reorganization of Spatial Configurations in VWM

Conducting these experimental series was intended to broaden the knowledge of whether and how humans can reorganize spatial configurations in VWM. A lot of preceding work investigating the organization of VWM demonstrated that adherent spatial processing is built upon a configurational network for both basic objects and features (e.g. Jiang et al., 2000; Papenmeier et al., 2012; Papenmeier & Huff, 2014) as well as in scene perception (Hollingworth, 2007; Klinghammer et al., 2015, 2017). First, the experimental series increased the knowledge of VWM organization and strengthened the approach of a configurational network. The experimental data show evidence of the fact that there is a stable memory benefit when the global spatial configuration is present instead of a single object. Recent studies showed already initial evidence demonstrating that features in VWM can be updated via a retro cue and my experimental series extend that finding to inter-object relations of spatial positions (Bae & Luck, 2017; Timm & Papenmeier, under review, 2019a, 2019b).

Presenting a cue (during encoding) resulted in the extension of former research, which indicated that attention direction during encoding led to the updating of spatial VWM content (Jiang et al., 2000). Presenting a retro cue (during maintenance) showed first evidence of the mechanism that humans can reorganize spatial configurations in VWM in general. As there was no hint of the side of interest before the appearance of the retro cue, I propose the possibility of a reorganization process. As written above, reorganization is the process in which an encoded global spatial configuration is split up into partial configurations due to an informative retro cue, including the update of the number of objects and the spatial relations. My result patterns strengthen this approach. While participants' location change detection performance with the relevant configuration was on the same level as with a global configuration, the presence of the irrelevant configuration at retrieval resulted in a reduced location change detection performance on the same level or even lower than with no configuration (Timm & Papenmeier, 2019a, 2019b, 2020).

Participants could reorganize the global configurations into relevant partial configurations and altering the locations of relevant objects, but not of irrelevant objects, disrupted location change detection performance at retrieval within a partial display task (see Experiment 6a). Moreover, altering locations of all contextual objects within global configurations led to a decrease in memory performance to the same degree as altering locations of the relevant context in a global configuration. This leads to the assumption that global configurations were entirely reorganized into partial configurations in VWM following an informative retro cue. Interestingly, location change detection performance decreased when the locations of the irrelevant objects were changed within the global configurations and performance decreased to the same level of performance with no configuration. Nevertheless, location change detection performance within this condition was still higher compared to the level of performance in changed global configurations and to the level of performance in the changed relevant configurations. These results challenge a completely successful reorganization account. Presenting a retro cue with highlighted relevant and irrelevant objects results in an attention change. This influences the represented VWM content and protects the cued items from disruptions (Astle et al., 2012; Bae & Luck, 2017; Griffin & Nobre, 2003; Jiang et al., 2000; Kalogeropoulou et al., 2017; Makovski & Jiang, 2007; Timm & Papenmeier, 2019a, 2019b, 2020). Thus, rather than erasing originally memorized global configurations from VWM reorganizing content, it might also be possible that highlighting partial configurations via retro cues leads to a formation of additional spatial content in VWM based on the cued items. In light of the existence of two parallel configurations, the results of Experiment 6b suggest that changing locations led to the mental representation of both the originally memorized global spatial configuration and the highlighted relevant spatial configuration. Thus, a change of locations in these conditions would lead to a greater impairment than for the irrelevant configuration. This is because the first change provided dysfunctional context compared to both represented spatial configurations (global/relevant), whereas the latter change provided functional context only disagreeing with one represented configuration (Timm & Papenmeier, 2020). This will be further discussed at the end of the chapter.

Snapshot (Independent Processing) vs. Flexibility (Interdependent Processing)

The presented experimental series were also conducted in order to broaden the knowledge about how humans process spatial configurations in general. In the introduction I described that there are (at least) two contrary models of the processing of spatial configurations in VWM. That is, either inter-object relations are supposed to be interdependent on the single objects included, strongly influencing processing spatial configurations, or they might be obtained from a separate, independent store (Cowan, 2001; Halford et al., 1998; Palmer, 1990; Palmer et al., 1993, 2015; Wilken & Ma, 2004). The first account was proposed by recent studies that emphasized a rather flexible eye movement-based approach, in which the spatial configurations are processed rather interdependently (e.g. Bays et al., 2009; Bays & Husain, 2008; Berman & Colby, 2009; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kalogeropoulou et al., 2017; Ohl & Rolfs, 2017; Van der Stigchel & Hollingworth, 2018). The second account which was suggested by previous research proposed a snapshot-based, thus independent processing and mental representation of spatial configurations in VWM (e.g. Papenmeier & Huff, 2014; Wood, 2011). In the beginning, I will discuss the several determinants and restrictions investigated in the current work. I will also present the conclusions which can be drawn from the results. In the end, I will summarize all conclusions and will integrate them into an account of how humans process spatial configurations in VWM.

I manipulated set size to investigate its influence on the reorganization of spatial configurations in VWM. Previous literature suggested that location change detection performance is decreased the more objects a spatial configuration is made of, and my experimental results support this evidence (Jiang et al., 2000; Luck & Vogel, 1997). Nevertheless, there was no stable link of spatial configuration benefit and set size in the current experiments. One might argue that the experienced set sizes were, for example, perceived as three and six and not six and twelve, as labeled in Experiment 2. However, a retro cue was presented during maintenance only in half of the trials. Thus, participants should have encoded all objects prior to the retro cue, as there was no hint at the side of the relevant partial configuration beforehand. Therefore, set size was defined based on the object number visible at the start of the trial. Yet the question remained if VWM capacity is valid for either the spatial configuration in general or the reorganization process in particular. Former research proposed a VWM slot model with a fixed threshold for VWM capacity (Dempere-Marco et al., 2012; Engle, 2002; Gurariy et al., 2016; Luck & Vogel, 1997; Matsukura & Hollingworth, 2011; Matsuyoshi et al., 2012; Rolls et al., 2013; Turner & Engle, 1989; Vogel & Machizawa, 2004). The current work investigates the impact of set size on humans' capacity for mental representation based on inter-object relations in VWM. I had a detailed look at the capability of participants for the reorganization of spatial configurations in VWM following the highlighting via a retro cue. I compared two suggested accounts of how inter-object relations are mentally represented. One approach suggests that this representation is interdependent of the items, from which they are formed, and a contrary approach suggests that the representation is separate from the items (Brady et al., 2011; Wood, 2011). The first approach would have resulted in a high impact of set size on the reorganization of spatial configurations in VWM. In contrast, the second approach would not. The current results support the latter account, a rather independent repository of spatial configurations in VWM as set size did not have a significant impact on the reorganization process across experiments. One model which further supports the independent repository evidence is the view-dependent snapshot repository featured in the VWM's core knowledge architecture model (Wood, 2011). Based on the evidence of a reorganization of spatial configurations in VWM, this repository cannot be classified, however, as keeping VWM representations of spatial configurations as a rigid or frozen snapshot (Higuchi & Saiki, 2017; Papenmeier & Huff, 2014; Wood, 2011). A more congruent explanation is that spatial configurations are stored rather flexibly within a global snapshot or as a part of a rather flexible hierarchical VWM representation (Timm & Papenmeier, 2019a, 2019b, 2020).

I also had a look at the impact of participants' VWM capacity on the reorganization process. Previous research already suggested a dependency of memory performance on the VWM capacity and VWM load (Alvarez & Cavanagh, 2004; Dempere-Marco et al., 2012; Engle, 2002; Gurariy et al., 2016; Matsukura & Hollingworth, 2011; Öğmen et al., 2013; Turner & Engle, 1989; Udale et al., 2017, 2018a, 2018b; Vogel & Machizawa, 2004; Wilken & Ma, 2004). The current results support the idea of this link, as there was a main effect of VWM capacity. In detail, participants with a higher VWM capacity showed an increase in location change detection performance in general. Nevertheless, there was no evidence of an interaction between the participants' VWM capacity and the reorganization process investigated in the current work. Thus, I suggest that there is no impact of the individual VWM capacity on the reorganization of spatial configurations in VWM. This is congruent with my findings that set size does not modulate the reorganization process (Timm & Papenmeier, 2019a, 2019b). One limitation of this evidence is that set size was sometimes not consistent within one trial. In detail, the definition of the partial configurations as relevant and irrelevant is based on the specific side of the display. Thus, set size processes should be investigated further and with more caution to display specific arrangements.

Another explanation for the effects found could be that the relevant configuration and the irrelevant configuration are equivalent to the near objects and the far objects in relation to the probed object. In the presented experimental series, I randomized the location of the objects. Thus, relevant objects had the same chance to be further away from the probed object than irrelevant objects. For example, the object which is a part of the irrelevant configuration could have been placed next to the center and an object that is a part of the relevant configuration could have been placed in the corner of the array. As I did not track the locations set in the experiment, I simulated a number of random locations based on the particular random location generation algorithm in the programming code and calculated a material analysis based on the simulations. I chose, for example, the three nearest objects with a global set size of eight due to the relevant configuration consisting of a probed object, which was accompanied by three additional objects. Then, I checked if those three chosen objects were all part of the relevant configuration or if at least one of them was part of the irrelevant configuration. In about 2/3 of all trials simulated, one to three of the closest objects were part of the irrelevant configuration in relation to the probed object. Thus, distance and relevance were different, because the closest objects and the objects building the relevant configuration were not identical (Timm & Papenmeier, 2019b). These findings are consistent with previous research which suggested that intact spatial configurations are more important than the distance of objects or the absolute location (Jiang et al., 2000). Nevertheless, that does not indicate that distance is not important for binding objects into a spatial configuration at all. More importantly, the findings described in the current work cannot be explained by a pure distance paradigm (Timm & Papenmeier, 2019b).

The present findings indicate the dependence of VWM content on overt visual attention via eye movements. As mentioned above, previous research suggested different and even contrary approaches regarding the need of overt visual attention for the maintenance of spatial VWM content. If spatial configurations were stored as a perceptual snapshot (e.g. Higuchi & Saiki, 2017; Papenmeier & Huff, 2014; Wood, 2011), fixed gazes should not have led to a non-existent or decreased configuration benefit. The experimental data shows that overt visual attention supports – at least partially or temporarily – the configuration benefit. This matches with previous research, that suggested the need of overt visual attention for an operative VWM system. That includes but is not limited to maintenance, target selection, gaze correction while searching items during retrieval and feature conservation while and after executing a saccade (Van der Stigchel & Hollingworth, 2018). Moreover, brain imaging studies showed that visual brain areas are active when humans encounter spatial representations and selective attention (Berman & Colby, 2009). Other literature suggested that there is a link between overt visual attention and VWM resources and processes (Bays et al., 2009; Bays & Husain, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kalogeropoulou et al., 2017; Ohl & Rolfs, 2017). In particular with the help of a dual-task paradigm including a letter-discrimination task as well as a saccade assignment, it was shown that there is evidence of an attentional common denominator of object recognition and saccade target selection (Deubel & Schneider, 1996). More precisely, the link seems to be even deeper with regard to the capacity of the VWM resources, that are modulated by both visual direction and selective attention (Bays & Husain, 2008). Furthermore, there is empirical evidence that overt visual attention regulates VWM content (Ohl & Rolfs, 2017). Concluding, overt visual attention stabilizes VWM content and a lack of eye movements leads to problems in processing spatial content.

In summary and as already mentioned in the paragraphs before, the results of all experimental series lead to the assumption that VWM could maintain both the global spatial configuration and the highlighted partial spatial configuration in parallel. Parallel processing in VMW is also supported by previous literature. Hollingworth and Rasmussen (2010) stated an adapted object-reviewing paradigm, which proposed two systems of object position processing in dynamic scenarios consisting of a highly sensitive object file system and a rather robust object-position binding. Whereas the previous paradigm can be applied to dynamic scenes, the current experiments showed that memory performance was supported by both the updated spatial configuration and the originally displayed spatial configuration shown in the beginning within a static environment (Timm & Papenmeier, 2019a, 2019b, 2020). Informative retro cues were already associated with the phenomenon of irrelevant objects being part of the encoded representation. When previous irrelevant configurations became relevant again, memory performance was still higher in this condition (Kalogeropoulou et al., 2017). Furthermore, the memory benefit due to the retro cue is rather based on attention than memory decay or a reduction of interference (Makovski et al., 2008) and attention can lead the VWM content processing despite of the relevance (Matsukura & Vecera, 2015). Concluding, the maintenance of relevant and irrelevant configurations is dependent rather than absolute. Thus, all partial configurations still impact the processing of spatial VWM content; also, when the spatial focus is limited due to attentional shifts (Timm & Papenmeier, 2019a, 2019b, 2020). While previous research and the current findings support the idea that the mental representation of objects positions relies on spatial configurations in VWM (Jiang et al., 2000, 2004; Papenmeier et al., 2012; Papenmeier & Huff, 2014), it remains unclear if the features of objects like shapes, orientation, and colors are represented based on the spatial map of the particular objects and to what degree they do so, and under which circumstances (Udale et al., 2017, 2018a, 2018b). Regardless of the open question of whether features are bound to positions, evidence was found of the importance of inter-object relations for the mental representation of the described features, for example, binding the spatial information into a structural gist (Vidal et al., 2005). In accordance with the structural gist model, the theory of VWM being constructed of several parallel feature repositories (Wheeler & Treisman, 2002) should be expanded to incorporate the mental representation of relational information inside each feature range, such as information about all the shapes and all the colors shown in a display. If VWM is indeed constructed to store more than object positions based on spatial configurations, namely, object features based on specific feature configurations, this leads to the question whether the construction of inter-object relations as well as the reorganization of inter-object relations rendered by retro cues are regulated by similar or even the same process for spatial information and features. On the one hand, similar processes might indeed be involved, as manipulating spatial context within the same range leads to similar impairments for location change detection (Jiang et al., 2000) as well as for feature change detection (Vidal et al., 2005). Moreover, for both locations (Bateman et al., 2018) and features (Udale et al., 2017, 2018a, 2018b; Vidal et al., 2005) decreased memory performance cannot be explained by advanced decision noise because of changed spatial context. On the other hand, guiding attention at encoding led to different findings regarding the construction of spatial configurations and the constructed feature relations. Thus, while selective attention to a subset of relevant items at encoding leads to the construction of a spatial configuration consisting of the attended objects (Timm & Papenmeier, 2019a), the features shown seem to be regulated into the relational information within the specific feature range regardless of selective attention at encoding (Vidal et al., 2005). Moreover, previous research dealing with the topic of ensemble perception found evidence of the parallel existence of a low-level ensemble representation like color and a separate, independent ensemble representation like average facial expressions (Haberman et al., 2015). Therefore, it is indeed possible that feature relations as well as spatial relations are regulated via separate processes.

In summary, neither the snapshot account nor the flexibility account can predict the experimental results and thus, based on the data collected, I propose that objects (as part of a configuration) are processed flexibly in VWM and that humans can access parallel configurations to detect location changes. This *flexible parallelism account* (see Figure 7) suggests that, next to an allocentric reference for single objects, a global spatial configuration is encoded and will stay in VWM while a retro cue can highlight an attended part of this configuration which also enhances location change detection. Regarding the results dealing with set size effects, the first interdependent approach would have resulted in a high impact of set size on the reorganization of spatial configurations in VWM and, in contrast, the second independent approach would not. There was evidence that set size does not modulate the reorganization process, which supports a rather independent processing. Nevertheless, humans were able to reorganize spatial configurations in general, which leads to the assumption of a flexibility when processing spatial configurations. Thus, a more congruent explanation is that the spatial configurations are stored rather flexibly and parallelly. This stands in line with the results regarding the VWM capacity, as the reorganization did not interact with different thresholds and the contextual influence, because rather than erasing originally memorized global configurations from VWM with reorganizing content, it might be possible that highlighting partial configurations via retro cues leads to a formation of additional spatial content in VWM based on the cued items.

In detail, I propose that two parallel representations are already formed at encoding. First, the allocentric reference of each individual object remains intact throughout the process but is rather imprecise compared to the configuration benefit. Nevertheless, humans can generally detect changes with a single object only. Second, a global configuration is formed during encoding, containing all objects including their relations within the spatial network. This global configuration also remains intact until retrieval and leads to the configuration benefit as location changes are easier to detect with a relative location of the probed object within the intact global configuration.

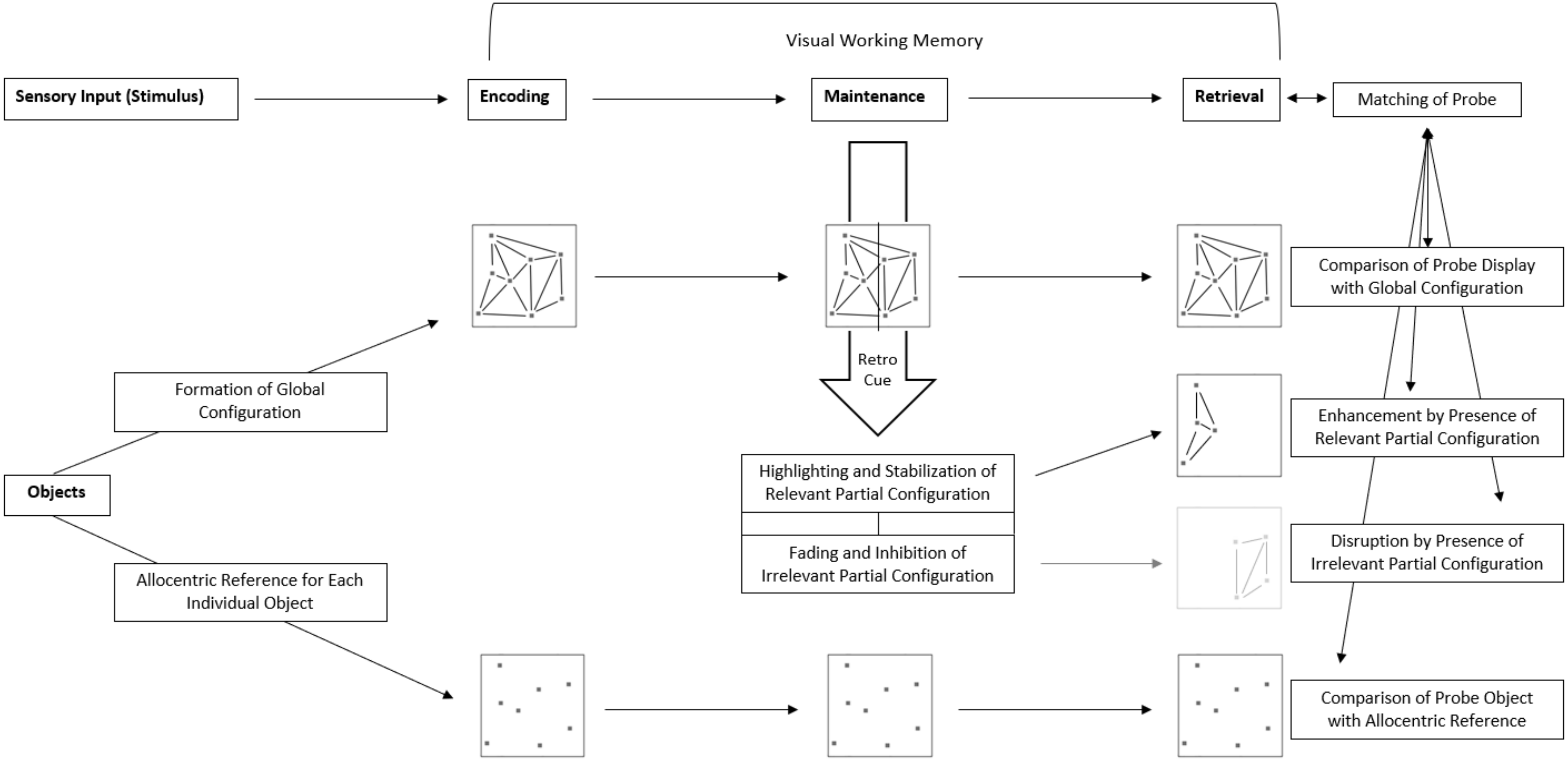

Figure 7 Flexible Parallelism Account. The upper path depicts the three stages of the standard location change detection task, which represents the processing in VWM. The lower path depicts the processing of objects within the spatial configuration during the task.

While the global configuration and the allocentric reference remain intact throughout the trial, data suggests that the retro cue triggers the building of a parallel, stored, relevant partial configuration in VWM. This relevant configuration is highlighted and stabilized at maintenance via the retro cue and is built upon the mental representation of the global spatial configuration. Whereas the irrelevant configuration fades and is inhibited, the relevant configuration also remains intact throughout the process. At retrieval several mechanisms interact with the probe. First, there is a comparison of the probe object with the allocentric reference. When a global configuration is present, there is also a comparison of the probe object regarding the relations within the probe display. Furthermore, the location change detection is also enhanced when the relevant partial configuration is presented at retrieval, while the presence of the irrelevant partial configuration disrupts location change detection. This flexible and parallel access to different kinds of references for the probe assures the human to correctly detect changes in his/her visual field. The flexible parallelism account merges the snapshot and the flexibility account by building a bridge between both research lines.

Next to the evidence provided by my current data, the proposed account can also explain why previous research found evidence of both the independent storage and the interdependent storage because parts of both accounts seem to be valid and are now combined into the described flexible parallelism account. In addition to that, overt visual attention supports both the reorganization and the processing of spatial configurations. Nevertheless, enforced fixations in the specific processing stage did not reduce the configuration benefit. Thus, the lack of eye movements can be compensated, and a lone eye movement-based account cannot predict these findings. Therefore, the proposed flexible parallelism account can access different parts of the configuration which can compensate a short, limited ability of performing eye movements. In summary, there has been a long-lasting debate in which the snapshot account and the eye movement-based flexibility account have been proposed and evidence for both approaches was found. The current results could also not decide in favor of one account. Integrating the results of my experimental series and previous research leads to the assumption that a mix of both accounts might be the executed VWM process. Thus, the flexible parallelism account is proposed which can explain more findings than the other two accounts. Future research should further investigate the mechanisms underlying this flexible parallelism account.

While the proposed flexible parallelism account explains a lot of the mechanisms and tendencies found with the data collected, there are still some open questions and discussable points left. On the one hand, the account depicts a rather complex way of several, parallel cognitive processes, whereas the human brain often tends to access and handle information using mental shortcuts and heuristics to decrease cognitive load in different processes (e.g. Bellur & Sundar, 2014; Meyerhoff, Jardine, Stieff, Hegarty, & Franconeri, 2021). As the proposed account works under a more complex assumption – in contrast to mental shortcut approaches – future research should collect more data to find either evidence for a more efficient flexible parallelism account or to find evidence why such a complex system is used to process spatial information in VWM. Nevertheless, a merger of both the snapshot account (independent processing) and the eye movement-based flexibility account (interdependent processing) seems more likely than the existence of a single account only. In detail, the collected data shows consistently across all experimental series, that participants had a global configuration benefit which speaks for the comparison of the probe display with the global configuration. Corresponding to that, participants could still perform the task when no configuration was present, but with lower overall performance, which speaks for the comparison of the probe display with the allocentric reference. However, especially the third experimental series showed, that this simplified approach cannot explain the entire participants' performance and corresponding strategies. Especially the third experimental series showed that the presence of the relevant partial configuration enhances performance and that the presence of the irrelevant partial configuration disrupts performance. Thus, these processes need to be included separately from the existing global configuration benefit effect. On the other hand, future research should also have a look at conflicting representations and if there might be a hierarchal processing of spatial configurations in VWM. Especially the whole display manipulation (Exp. 6b) showed that the presence of manipulated partial configurations within the global configuration disrupted memory performance but that a changed global configuration led to the lowest memory performance. This is a first hint, that a hierarchal processing might underly the matching of the probe while handling spatial configurations in VWM. In summary, the proposed flexible parallelism account is the first try of merging the two conflicting accounts, the snapshot account (independent processing) and the eye movement-based flexibility account (interdependent processing). Future research should further investigate the individual mechanism paths as well as the hierarchical structure, which might be involved at retrieval.

Future prospects

The current experimental series could answer numerous open questions presented in the introduction. Nevertheless, a few questions still have to be addressed. Future research can build on our findings and, for example, investigate whether there might be a relation between a parallel spatial configuration repository and a high capacity VWM repository, which is rather fragile and was supported by former research (Sligte et al., 2008). A possible manipulation would be the appearance of backward masks at the beginning of the maintenance stage (Timm & Papenmeier, 2019b). Another interesting addition to that research is the question whether partial configurations vanish after a longer amount of time. This could also provide more information about temporally different VWM repositories (Sligte et al., 2008). Moreover, future research can further evaluate the role of the distance between objects within a spatial configuration, also when highlighting objects with the help of a retro cue and the following reorganization process (Timm & Papenmeier, 2019b). As mentioned above, I calculated a stimuli analysis across the distances, but empiric research could underline the suggested evidence that the effects cannot be explained by distance only.

If a reorganization of spatial configurations in VWM was not taking place, then the investigated partial configurations – namely, the relevant configuration, the irrelevant configuration and also no configuration – would lead to a similar level of location change detection performance. Nonetheless, there were some boundary conditions, which should be investigated in future research. In general, set size seems to have no impact on the reorganization process but, for example, Experiment 2 showed that the reorganization could not be done entirely successfully with twelve objects occurring on the display. Also, the relationship of eye movements and the (re-)organization of VWM should be included in future research. In summary, whereas reorganization of spatial configurations in VWM is possible in general, future research can broaden the understanding of this process. For example, future research should have a deeper look into the process guiding the reorganization process. In detail, if reorganization results from the attended objects, which mental representations are strengthened by the retro cue and a simultaneously neglected mental representation of the irrelevant items, or a different mechanism. Moreover, participants might maintain several partial configurations from the beginning and the retro cue might lead to a highlight of the partial configuration cued rather than inducing an entire reorganization of VWM content. Thus, the open question remains, whether reorganization is the removal of irrelevant VWM content or the highlighting of relevant VWM content. Having a look at this research question could provide a deeper understanding of the mechanism.

I encountered diverse effects in the irrelevant configuration condition following the retro cue. The retro cue application led to an attention shift to one side of the display of the global configuration. Previous research suggested that shifting attention to a single object in VWM decreases the spatial configuration benefit afterwards (Sligte et al., 2008). Thus, equivalent levels of location change detection performance in the irrelevant configuration condition and the no configuration condition seem plausible. Nonetheless, I observed a lower level of location change detection performance in a few experiments regarding the irrelevant configuration condition compared to any other condition. However, this finding is congruent with other literature, in which (retro) cues and corresponding attention shifts showed an impact on the interdependencies of a spatial VWM representation. For example, the retrieval of a stimulus, retro cued as irrelevant was disrupted by stimuli retro cued as relevant (Bae & Luck, 2017). The current findings lead to similar assumptions that relevant and irrelevant configurations still interact with each other. The reorganization process resulted sometimes in a disruption of VWM content when the irrelevant configuration was shown at retrieval. As the irrelevant partial configuration led to several different result patterns regarding memory performance, future research should further investigate the reorganization of spatial configurations in VWM and focus on the concrete influence of unattended, forgotten, and irrelevant objects respectively.

4.3 Technical Implications

Next to a lot of essential additions and directions for general and theoretical models and accounts, the present work also provides some technical implications to be considered in future scenarios and constellations.

First, when planning and designing an enriched environment for both Augmented Reality (AR) and Virtual Reality (VR), we learned that overt visual attention is needed (at least temporarily or partially) for the processing of spatial configurations in VWM. Thus, future design should take care of a functioning environment with regard to eye movements in order to allow for configuration benefits and a possibility for a reorganization of spatial configurations in VWM. Second, previous research supports the advantage of a present spatial configuration in order to execute grasping actions, especially in VR (Fiehler et al., 2014; Klinghammer et al., 2015, 2016, 2017) Furthermore, with a high number of objects and a higher set size (up to 16) respectively, the configuration benefit does not vanish. Therefore, it is possible to design a richer and also more realistic environment in AR/VR, but as the contextual influences differ between a partial display and the presentation within a whole display, the conceptualization should be made carefully of these restrictions to avoid misinterpretations. The present results are interesting for VR, but are even more essential regarding the application to AR. The reorganization and retro cue paradigm should be considered when AR is enforced for example with a Heads Up Display in traffic situations or learning environments. In flight simulations as well as on real planes, the design, segmentation and highlighting of the display content should be in accordance with the results and conclusions of the experimental series conducted in the present work. In detail, as described above, overt visual attention should be possible, and the number of components can be constructed in accordance to our highest set size, at least. Also, aerial highlighting can be implanted but the fate of the objects rendered relevant and irrelevant should be considered while designing this driving of attention. This can also be adapted to future designs of AR on the windscreen of cars and similar vehicles for navigation systems and advanced driver-assistance systems such as lane assistance (see Brookhuis et al., 2001 for an overview). Furthermore, this can be adapted to other Heads- Up Displays such as Google glasses or other smart visual aids, which can use AR in future settings. Moreover, these design suggestions cannot only be applied to VR and AR, but to any digital design in general, for example in video games. However, designers should keep some restrictions in mind such as the contextual influences and also the impact of and on irrelevant content, which might become relevant again or is irrelevant at all, but still has an impact on the retrieval of VWM content. However, the transfer of the experimental results and following conclusions should be viewed with caution and needs more research.

In general, the laboratory results observed in the present work should be first applied to and investigated in field research for a better, more precise and more efficient design and application of the introduced and other not described but possible scenarios before working and using the implications outside of the laboratory. Nevertheless, the experimental data provides some thought-provoking impulses, which lead to the mentioned technical implications. These can be connected and investigated in future research and scenarios based on and connected with the present work.

4.4 Limitations

While this dissertation provides essential evidence of processing and reorganizing spatial configurations in VWM and answers most of the questions raised above, the present work cannot cover the entire field of research. Thus, I discuss some limitations of the dissertation, which can also drive the focus of future research investigating this specific topic. Readers should keep these limitations in mind before generalizing the current results too broadly.

There are some general limitations regarding the samples tested within the experimental series. The samples drawn from the population are very homogenous, which is a reoccurring problem in modern science leading to the generalization of a “Western, Educated, Industrialized, Rich, and Democratic” (Henrich et al., 2010, p. 61) sample or population for all humans (Henrich et al., 2010). Other common backgrounds of the participants were a study of psychology and/or being member of the institutional data base, which results in participants that have already taken part in other cognitive science experiments. Moreover, my sample sizes were restricted to a maximum age of 45 years and humans with normal or corrected-to-normal vision (depending on the experimental setup). This was done due to the cognitive decline at a higher age and to avoid confounding factors due to a deviant vision. These socio-demographic and corresponding factors as well as practical features should be kept in mind when discussing and referring to the results and following conclusions.

One of the conclusions of the first experimental series was that there is no impact of set size on the reorganization of spatial configurations in VWM, but this is limited in some points. Participants only showed an entire reorganization of spatial configurations with four objects in Experiment 4b but not in Experiments 4a and 4c. A possible explanation for this phenomenon is that a reorganization is inefficient due to a cost-benefit decision, as there might be a minimum number of objects when single objects are relegated into a spatial configuration. In detail, in the four-object conditions the partial configurations consisted only of two objects each. Potentially, two objects are not held in VWM as spatial configuration and therefore, participants cannot reorganize the global configuration into partial ones. Preceding studies showed that single objects were not formed into a spatial configuration when only two objects were displayed. There was no evidence of a configuration benefit (Udale et al., 2018b). This is congruent with most of my results, showing that a small number of objects did not lead to a robust spatial configuration effect. Nevertheless, I found a configuration advantage in Experiment 4b and thus, the minimum number at which objects relegate into a spatial configuration could not be fully resolved yet and future research should focus this mechanism (Timm & Papenmeier, 2019b).

Another limitation which should be focused by future research is the retro cue procedure itself. First of all, there are at least two mechanisms in which driving attention via retro cue might influence VWM processes. The retro cue can lead to a restructuring of mental representations by highlighting the object cued and screening it against disturbances (Astle et al., 2012; Griffin & Nobre, 2003; Makovski et al., 2008) or it can be used as a pre cue for the test display, which drives the attention to the area of interest beforehand. However, the experiments cannot differentiate between the two mechanisms, but my results provide a basis for discussion, because they were designed to test the first mechanism to reorganize spatial configurations in VWM with the help of a retro cue. In congruence with this mechanism, the experimental data show that a relevant partial configuration led to the same configuration benefit as a global configuration present at retrieval. This was shown with the help of a comparison of a cue paradigm and a retro cue paradigm (Experiments 1 & 2) as well as with the help of a comparison of a no cue paradigm and a retro cue paradigm (Experiment 5). Moreover, changing the highlighted contextual objects decreased memory performance on the same level as changing the contextual objects within the global configuration (Experiments 6a & 6b). Therefore, I proposed the possibility for humans to reorganize spatial configurations in VWM following the appearance of a retro cue, also because, as I discussed before the primarily encoded global spatial configuration might not be completely replaced by the relevant partial configuration but is rather stored in parallel. This observation is congruent with previous research which proposed that an informative retro cue can be associated with the process of irrelevant objects still remaining a part of the mental representation in VWM. In detail, the irrelevant objects suddenly became relevant again during the task and they still led to a benefit in memory performance (Kalogeropoulou et al., 2017). Nevertheless, a pre cue approach leading to a drive of attention during maintenance for the encoding stage might explain some of the experimental data. For example, the irrelevant configuration led to a decreased location change detection performance without a retro cue, but not with a retro cue (Experiment 5). Also, changing the contextual information within the irrelevant configurations in Experiments 6a and 6b led to small effects in location change detection performances compared to altering the contextual information within both the global spatial configuration and the partial configuration rendered relevant by the retro cue. Nevertheless, this approach cannot explain other findings such as the location change detection performances being equivalent without a spatial configuration in Experiment 5 showing a retro cue and not showing retro cue. A pre cue should have driven attention to the area of interest and so, the location change detection performance should have been higher with a retro cue because the area of the probed object was known to the participants in a pre-cue account. Moreover, altering the contextual information within the irrelevant configuration led to a decreased location change detection performance in Experiment 6b. Therefore, I found more evidence of a retro cue mechanism based on the current data. Nevertheless, future research should investigate both mechanisms to deepen the understanding of the organization of the VWM content. Other approaches should be included as well, such as the encoding of the configurations themselves. As the retro cue was always informative and consistent throughout the task, participants might have only encoded both partial configurations instead of one global configuration and used the highlighted one at retrieval. However, Experiment 5 clearly showed that, when a block without a retro cue was worked on after a block with an informative retro cue, location change detection performance with a relevant configuration was not on the same level as with a global configuration. There was also no interaction effect regarding the block order and thus, a partial encoding should not have taken place. Nonetheless, this mechanism is interesting and there remain some open questions with regard to the retro cue procedure and thus, future research should investigate this paradigm further in order to unravel this process.

4.5 Conclusion

In the present work, I have reported eleven experiments that investigated the processing and reorganization of spatial configurations in VWM. In summary, humans are able to reorganize global spatial configurations into (relevant) partial configurations in VWM induced by a retro cue. In addition, I came across some determinants and restrictions regarding the reorganization process as well as the architecture of spatial configurations in VWM in general. I demonstrated in Experiments 1 and 5 especially that participants reorganized a global configuration into a relevant partial configuration only when their attention was shifted by using retro cues to the relevant part of the former global spatial configuration in VWM. In the introductory literature review, I excerpted two contrary approaches, which are frequently used to describe the processing of spatial configurations in VWM. Both the independent and the interdependent approach could not completely explain the experimental results. Thus, I proposed that both approaches should be merged into a flexible parallelism approach, which can explain more processes and combines two different approaches. In addition, eye movements have an influence on the architecture of the spatial configuration held in VWM and the reorganization mechanism. Humans profit by the capability of executing overt visual attention shifts using eye movements to enlarge their memory performance of a single probed object. Experiments 3 and 7 indicated that overt visual attention induces the configurational benefit as well as the reorganization of spatial configurations in VWM. While participants showed a lower memory performance in Experiment 8 overall, the amplitude of the configuration benefit was similar across the used different conditions of a fixed gaze. Therefore, while the capability of executing overt visual attention shifts induces the processing of spatial configurations, the configurational benefit is not committed to these shifts occurring throughout the whole process. Nevertheless, future research should further investigate the link between eye movements and the processing of spatial configurations.

To summarize, the reorganization of spatial configurations was observed with a higher memory performance in the relevant partial configuration conditions than in the irrelevant partial configuration conditions across the set size Experiments 2, 4a, 4b, and 4c. I conclude that next to the overall decrease in memory accuracy the reorganization process was reliable across these experiments and not affected by the set sizes displayed in this dissertation. By the manipulation of the locations of the contextual objects in the test array, investigated in both a partial display (Experiment 6a) and a whole display (6b), a strong impact of the contextual objects on memory performance was shown when a retro cue rendered the relevance of the partial configurations. More importantly, when the locations within the irrelevant configuration were changed, maintaining the locations within the relevant configuration, memory performance was also decreased, but at a lesser degree. Thus, I propose that the reorganization process should not be understood as a total reorganization leading to a complete disappearance of the originally represented global spatial configuration. I rather propose that a retro cue induces a development of an advanced partial configuration based on the cued relevant part of the global configuration next to the originally represented global spatial configuration. Moreover, both stored representations affect the location change detection performance. Taken together, I propose a rather flexible and parallel storage and usage of spatial configurations in VWM due to the role of inter-object relations and overt visual attention based on the experimental data and its integration into the existing literature. The evidence speaks against both a sole eye movement-based, flexible and against a rigid snapshot-based account.

5. List of Included Manuscripts

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7. Acknowledgments

The present work was made possible because of the support and encouragement of a number of wonderful people, who I want to thank in this final chapter. First and foremost, I would like to thank Frank Papenmeier for being an open, patient, demanding and encouraging support and supervisor, who navigated me through this multi-year process and becoming a friend eventually. Thank you for helping me to develop my thinking, my programming skills, my writing and related scientific skills. Second, I want to thank Stephan Schwan for being a great mentor, providing theoretical input and guidance, as well as for improving the dissertation. Thank you both for your support, for having a sympathetic ear and offering encouragement whenever needed. You provided an open and encouraging work environment as the basis of this work. Furthermore, I want to thank my other colleagues at the Department of Psychology and the IWM. I really enjoyed working, sharing time, and experiencing a lot of social events with you. In particular, I would like to thank my colleagues at the research group of Applied Cognitive Psychology (and Media Psychology) including Friedrich W. Hesse, the Knowledge Exchange Lab (AG 4) including Markus Huff, the statistical and technical support as well as the Realistic Depictions Lab (AG 2) for all the formal and informal discussions and for giving me input on my work. I want to thank Rosemarie Croizier and Luitgard Fink especially for making me feel at home. I also thank the other doctoral candidates, especially Sandra Grinschgl and Gabriela Orellana Corrales, for sharing ideas, information and typo hunting as well as having fun. I would also like to thank all student assistants, especially Selina Galefski and Nele Vagt, for their support with data collection and data preparation. I also thank Anneliese Bähr-Böhm for proofreading my works and being a lifelong support including her family. Importantly, I want to thank my father and my mother, my family and my friends, especially, Nico, Patrick, Martin, Raphi, Chrissy, Jonas, Aron, Martin, Andi, and all other friends not mentioned in particular for being supportive in every situation faced in this world. Finally, I would like to thank my girlfriend and team partner for her longstanding support, encouragement and patience. Last but not least I want to thank coffee, nature, music, sports, especially EC KAC, VfL Bochum 1848, Oakland/Las Vegas Raiders, Michael Jordan and the Sony Playstation(s) for making life easier (most of the time). Carpe Diem.

8. Manuscripts

1. Timm, J.D. & Papenmeier, F. (2019). Reorganization of spatial configurations in visual working memory*. Memory & Cognition, 47*(8), 1469-1480. doi.org/10.3758/s13421-019-00944-2.

Memory & Cognition (2019) 47:1469–1480
https://doi.org/10.3758/s13421-019-00944-2

Reorganization of spatial configurations in visual working memory

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Abstract

Human beings have to constantly process multiple objects in visual working memory (VWM). Positional relations to other objects known as spatial configurations contribute significantly to the organization of information in VWM. The aim of our study was to clarify whether spatial configurations can be reorganized to a subset of objects during maintenance. Participants were shown an array of objects, and afterwards the objects disappeared. A valid cue was shown either during encoding or maintenance to highlight the side of the following probed object. Afterwards, the objects reappeared and participants were instructed to detect whether or not a particular object changed its location. We manipulated the configurations at retrieval regarding the number of objects, ranging from all objects to a single object. Our first and second experiment investigated reorganization for a number of six and 12 objects, respectively. In the third experiment, we used a retro cue only and manipulated eye movements (free view vs. enforced fixation). While showing that reorganization of spatial configurations during maintenance is possible in principle, we found some boundary conditions. There was no spatial configuration effect when participants had to fixate. Thus, eye movements are required for a configuration effect to occur.

Keywords Short term memory · Attention · Context effects · Eye movements · Working memory

Background

Fifty years ago, the multistore model of memory was proposed, which distinguishes between three different memory stores. These stores differ in capacity, duration, and chronological order, and others. Three stores were postulated: sensory, short-term memory, and long-term memory (Atkinson & Shiffrin, 1968). With our present research, we focused on the short-term store. Already, back then, the term *working memory* was used to describe the short-term store (Atkinson & Shiffrin, 1968). Later, more detailed differentiations were made, including several types of working memory (Baddeley & Hitch, 1974). Neuroimaging studies lead to similar assumptions. Short-term and working memory are distinguished nowadays because they claim different areas of the prefrontal cortex. Working memory leads to the ability to simultaneously manipulate the information stored and work with it. Short-term memory, however, is only a short-term store, but does not allow the organization and processing of the stored content (Diamond, 2013). This leads to the assumption that working memory can be seen as the tool you can use to access content of the short-term store. With our present research, we extend the understanding of processing mechanisms regarding the working memory system by studying the reorganization of spatial configurations during maintenance in the short-term store.

In visual working memory (VWM), single objects are not processed individually, but the relations to other objects, known as configurations, have a strong impact. These spatial configurations contribute significantly to the organization of information in the VWM. For example, viewers automatically process the spatial configuration of multiple objects, even if they are asked to independently memorize the locations of objects (Jiang, Olson, & Chun, 2000). Previous work on spatial configurations focused exclusively on the encoding and retrieval of information (e.g., Dent, 2009; Jiang, Chun, & Olson, 2004; Jiang et al., 2000; Papenmeier, Huff, & Schwan, 2012). But how are spatial configurations represented in VWM, and what operations can observers perform on memorized configurations? With the present set of experiments, we studied this question by investigating whether

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observers can reorganize spatial configurations during maintenance. We refer to encoding as the time when objects are visible, and to maintenance as the time when objects are no longer visible, after encoding and before retrieval. By addressing this research question, we want to clarify whether spatial configurations determine the encoding of information alone, or whether they also affect maintenance of information in VWM. In the following, we will first review the literature on the influence of spatial configurations during encoding and retrieval.

In an influential work on the importance of spatial configurations for organizing VWM, participants were asked to individually memorize the locations of several presented objects and to ignore the spatial configuration of all objects (Jiang et al., 2000). Although the participants were asked to detect the location change of a single object, they typically failed to memorize single objects only, but rather a spatial configuration including all objects memorized (Jiang et al., 2000; Papenmeier et al., 2012). Thus, they observed an improved detection performance for the location change of a single object if it was presented within the global spatial configuration of all objects memorized, but not alone. This was not caused by the presence of additional reference points in the displays only, because the presentation of a partial configuration (e.g., three of six memorized objects) did not improve the detection of the displacement of the individual object (Jiang et al., 2000; Papenmeier et al., 2012). Such configuration effects are not limited to the maintenance of abstract stimuli such as squares (Jiang et al., 2000; Papenmeier et al., 2012); they are also evident in the presentation of natural stimuli, such as images of lamps, cars, or chairs (Hollingworth, 2007; Papenmeier & Huff, 2014).

Importantly, spatial configurations are formed only on the basis of relevant objects and not on all objects visible on the display. This was shown in an experiment (Jiang et al., 2000) in which participants were instructed to memorize a color-coded subset of the visible objects only. The change in the location of the remaining objects between encoding and retrieval had no effect on the memory performance for the objects memorized. Thus, the spatial configuration effects are not caused by a perceptual snapshot of the entire scene. Nonetheless, multiple studies suggest that spatial configurations might be rigid representations based on the global perceptual grouping of the encoded objects. First, the change of task-irrelevant perceptual grouping stimuli on the memorized objects between encoding and retrieval has been shown to affect memory performance (Jiang et al., 2004). The formation of spatial configurations is, thus, closely linked to the perceptual grouping of the encoded objects. Second, whereas the presence of the global spatial configuration of all encoded objects at retrieval results in a memory benefit, the presentation of partial configurations at retrieval does not. This suggests that a partial configuration cannot access the represented overall spatial configuration, even if the partial configuration contains four out of six memorized objects (Papenmeier et al., 2012). Third, the view dependence of contextual information (Papenmeier & Huff, 2014; see also Wood, 2011) also supports the idea of a rigid perceptual snapshot of the encoded objects. In this study, participants were shown several objects lying on a virtual table, and one object was highlighted at retrieval for a location-change-detection task. Spatial configurations (full, no) and the point of view (0°, 60°) in the test image were manipulated. Configuration effects disappeared with a change in point of view of 60 degrees (Papenmeier & Huff, 2014).

Are spatial configurations, thus, only represented as rigid images of the encoded perceptual grouping, or can spatial configurations in VWM be reformed and reorganized? The retro-cue paradigm has established as a successful method of studying memory manipulation during maintenance (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Sligte, Scholte, & Lamme, 2008; Souza & Oberauer, 2016; Williams & Woodman, 2012). During the delay period—that is, after the stimuli have disappeared—participants are presented with an indication of which of the objects will be interrogated. This leads to a deliberate shift of attention to the highlighted objects. This leads, on the one hand, to a more stable representation of the highlighted objects (Sligte et al., 2008) and, on the other hand, to the deletion of the originally memorized and now irrelevant objects from memory (Williams, Hong, Kang, Carlisle, & Woodman, 2013). Previous results from retro-cue research show that directing attention to a single object during maintenance reduces context effects at retrieval (Bae & Luck, 2017; Sligte et al., 2008). In Bae and Luck's (2017) study, for example, participants had to memorize the orientations of two sequentially presented objects. The reproduction of the orientation of objects had influenced each other. If one object was cued, however, the influence of the uncued object on the cued object was reduced.

By applying the retro-cue paradigm to spatial configurations, we aim to investigate whether directing attention to multiple objects of a spatial configuration during maintenance results in reorganization. We refer to reorganization as the process in which a global spatial configuration of objects is encoded in the beginning, and the number of objects and their relations are updated into the cued partial configuration during maintenance. In the following, we present three experiments investigating the reorganization of spatial configurations during maintenance. In Experiments 1 and 2, we do so by comparing the effects of a retro cue during maintenance with the effects of a cue during encoding. In Experiment 3, we further investigate set-size differences and eye movements to gain a deeper understanding of the retro-cueing effects and thus the structure of VWM.

Experiment 1

In Experiment 1, we compared the effect of attentional cues that appeared during either maintenance or encoding. If spatial configurations can be reorganized to a subset of objects during maintenance, directing attention to a subset of objects during either encoding or maintenance should cause an increased location-change-detection performance for single object displacements by the presence of a partial configuration encompassing the cued objects at retrieval. If, however, a reorganization of spatial configurations to a subset of objects during maintenance is not possible, only the presence of the complete configuration containing all encoded objects at retrieval should cause a configuration effect despite attention cues during maintenance. Nevertheless, attention cues during encoding should still result in configuration effects by partial configurations encompassing the cued objects only at retrieval, because only those objects should be encoded in the first place.

Method

We performed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on the Open Science Framework: https://osf.io/cwr9t/.

Participants We used the R-Package Powerbydesign (Papenmeier, 2016) to conduct a power analysis. Our goal was to obtain at least a power of .90 at the standard of .05 alpha error probability. The group means and standard deviations used in this power analysis were taken from previous data of our lab and led to a sample size of 28 participants. We preregistered the following exclusion criteria: Participants identified as not doing the task (always pressing the same button or a performance level that does not deviate from chance) as well as any participants not completing the whole experiment were supposed to be removed from the data set and replaced by new participants. No participants were excluded for this particular experiment. Eventually, 28 participants took part in this experiment, receiving course credit or monetary compensation of 2€ per 15 min. All participants had normal or corrected-to-normal vision, and their age ranged from 19 to 32 years (*M* = 24.3 years, *SD* = 3.5). Up to three participants were tested at the same time on different computers. Simultaneous testing and monetary compensation were consistent throughout all experiments. The research was conducted in accordance with APA standards for ethical treatment of participants and with approval of the Institutional Review Board of the University of Tübingen.

Stimuli and materials We presented six squares on a 24-in. computer screen (Fujitsu Display B24-8 TE Pro) with an unrestricted viewing distance of about 57 cm using PsychoPy 1.85.6 (Peirce, 2007). Each square was gray (RGB color hex code: #777777) and measured 1.5° × 1.5° (degrees of visual angle). At the beginning of each trial, participants were told to view a centric fixation cross. The objects could appear in 20° × 20° area at the center of the screen. Furthermore, we generated random object locations for each trial with the same number of squares equally placed on each side, with a minimum center-to-center distance of 1.5 times the diameter of a square. In order to guarantee that all locations used within a trial—including the new location of the object probed in change trials—were subject to the same restrictions, such as minimum distance, we programmatically generated four object locations on each side of the array, with only three being visible for each side during encoding. In change trials, the invisible fourth location at the cued side was made visible at retrieval and the original location of the object probed was made invisible. The luminance was as follows: square: 28.5 cd/m^2, cue: 118.7 cd/m^2, fixation cross: 0.1 cd/m^2, red probe: 29.1 cd/m^2, array border: 0.1 cd/m^2 and background: 152.4 cd/m^2.

Procedure Each trial consisted of three phases (see Fig. 1). In the first phase (encoding), six squares had to be encoded. Three squares were presented on each side for 2,000 ms. Thereafter, objects disappeared and left a blank image. The second phase (maintenance) lasted 2,000 ms. Participants had

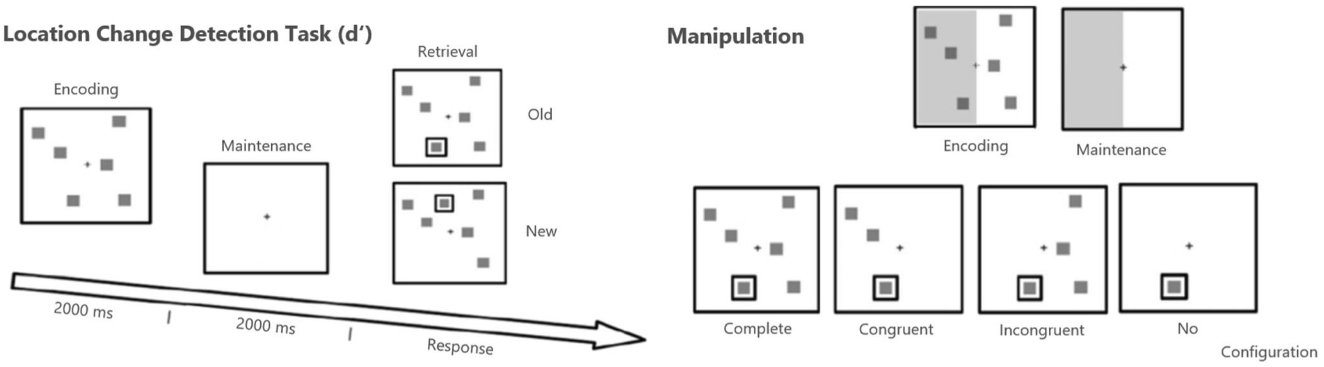

Fig. 1 Experimental procedure and manipulations in Experiment 1

to maintain the object locations. Afterwards they reappeared, and one object was marked with a red frame (RGB color hex code: #FF0000) during this last phase (retrieval). Participants had to press one of two buttons on a keyboard as to whether or not the location of this object had changed. We used a cue of 100 ms, which covered either the whole left-hand or right-hand side of the stimulus array, either during encoding or maintenance, to shift attention to a subset of objects. Participants were told that the cue would be valid as the object probed would appear on this side. Each cue (RGB color hex code: #E6E6E6) occurred 1,000 ms after the start of the respective phase. Furthermore, the number of objects varied at retrieval, as four different spatial configurations were used. The configurations were defined as follows:

- Complete: presence of object probed and all other objects that were present during encoding
- Congruent: presence of object probed and all other objects that were cued
- Incongruent: presence of object probed and all other objects that were not cued
- No: presence of object probed alone

Please note that the notion of configuration refers to the number of objects present during retrieval. Whereas all visible nonprobed objects were always located at their old locations, the object probed could change its location between encoding and retrieval, which is a prerequisite to measure participants' location-change-detection performance.

In a nutshell, we manipulated the cue side (left/right), the moment of cue presentation (during encoding/maintenance), the location of the object probed at retrieval (new/old), and the configuration of the objects at retrieval (complete/congruent/incongruent/no). The cue was 100% valid, thus the object probed at retrieval was always one of the objects indicated by the cue. Participants were assigned to all conditions (within-subjects design). Trials were presented in randomized order with the restriction that the experiment consisted of five blocks containing 64 trials each leading to 320 trials in total. Each condition occurred equally often within each block and also within the whole experiment. Thus, we showed 10 trials per experimental condition (configuration, cue presentation, location, cue side). The experiment duration was one hour.

Design and analysis We compared location-change-detection performance as indicated by the sensitivity measure (*d*′) across conditions using a 2 (moment of cue presentation: encoding, maintenance) × 4 (configuration: complete, congruent, incongruent, no) repeated-measures ANOVA. We calculated sensitivity (according to signal detection theory) as a dependent measure across the responses to the old/new probe location trials. That is, sensitivity d' is defined as $d' = \Phi^{-1}(phits) - \Phi^{-1}(pfa)$ with *phits* being the proportion of hits and *pfa* being the proportion of false alarms (Stanislaw & Todorov, 1999). Hits refer to the accurate detection of old locations, and false alarms refer to responding "old" to a new location. Note that sensitivity cannot be calculated for either *phits* or *pfa* having values of 0.0 and 1.0. Thus, we corrected such values to the proportions equaling half a trial correct or half a trial incorrect, respectively.

Results and discussion

All analyses have been preregistered. We performed a repeated-measures ANOVA, with sensitivity (*d*′) as the dependent variable and cue presentation and spatial configuration as the independent variables (see Fig. 2). There was a significant main effect for moment of cue presentation, $F(1, 27) = 12.20$, $p = .002$, $\eta_p^2 = .31$, and a significant main effect for configuration, $F(3, 81) = 17.66$, $p < .001$, $\eta_p^2 = .40$. There was no significant interaction effect, $F(3, 81) = 0.18$, $p = .908$, $\eta_p^2 = .01$. We further used *t* tests to investigate the main effect of configuration (see Table 1).

The results of the *t* tests (see Table 1) indicate a configuration effect due to a higher location-detection performance for the complete configuration compared with no configuration. Most importantly, the results also indicate a reorganization effect during maintenance, as the complete and the congruent configurations are comparable, and there is a significant difference between the congruent configuration and no configuration.

First, we could replicate previous findings. When the cue appeared during encoding, we observed configuration effects of the cued partial configuration. More interestingly, presenting a cue during maintenance caused a pattern of results

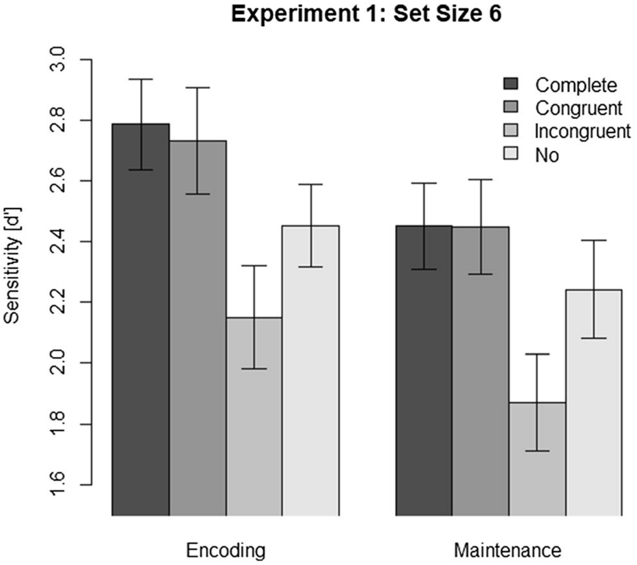

Fig. 2 Sensitivity (*d*′) across all participants for Experiment 1. Error bars indicate the standard error of the mean (*SEM*)

Table 1 The p values and t tests for configurations in Experiment 1

Configuration	Complete	Congruent	Incongruent
Congruent	.757		
Incongruent	<.001*	<.001*	
No	.012*	.019*	<.001*

*Statistically significant ($p < .05$)

similar to presenting the cue during encoding. Thus, we conclude that it is possible to reorganize spatial configurations to a subset of objects by shifting attention to these objects during maintenance. Although we had no specific predictions regarding the incongruent condition, one might have expected a performance similar to that in the no condition. However, location-change-detection performance was lower for the incongruent configurations than for the no configuration condition. This result will be discussed across all experiments in the General Discussion.

Experiment 2

In Experiment 1, participants showed very high sensitivity values across all conditions. Thus, we conclude that the location-change-detection task was rather easy with our set size of six objects. In order to further investigate the reorganization of spatial configurations under more challenging conditions, we conducted a second experiment with a doubled set size of 12 objects.

Method

We performed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on the Open Science Framework: https://osf.io/6mkft/.

Participants We used the same power analysis metrics (Papenmeier, 2016) as in Experiment 1. Subsequently, 28 participants were invited for this experiment and received course credit or monetary compensation. We applied the same exclusion criteria as in Experiment 1, and two participants had to be replaced because of a performance level that did not deviate from chance, leading to the participation of 30 participants but a final sample of 28, as previously appointed. Participants of the final sample had normal or corrected-to-normal vision, and their age ranged from 19 to 32 years (M = 23.4 years, SD = 3.0).

Stimuli and materials We used an experimental setup similar to that of Experiment 1, and thus there were also 10 trials per experimental condition (configuration, cue presentation, location, cue side). Because of the limited space, we reduced the dimension of the squares to 1° × 1° to ensure enough possible locations for all randomized objects. Furthermore, we used a minimum center-to-center distance of twice the square diameter.

Procedure and analysis We used the same procedure and analysis as in Experiment 1, except with 12 instead of six objects. The experiment duration was 1 hour.

Results and discussion

All analyses have been preregistered. We performed a repeated-measures ANOVA, with sensitivity (d') as the dependent variable and cue presentation and spatial configuration as the independent variables (see Fig. 3). There was a significant main effect for moment of cue presentation, $F(1, 27) = 38.78$, $p < .001$, $\eta_p^2 = .59$, and a significant main effect for configuration, $F(3, 81) = 23.38$, $p < .001$, $\eta_p^2 = .46$. There was also a significant interaction between moment of cue presentation and configuration, $F(3, 81) = 5.92$, $p = .001$, $\eta_p^2 = .18$. Because of the significant interaction effect, we further investigated the configuration effects with separate t tests for the two levels of moment of cue presentation (see Tables 2 and 3).

The results for the t tests (see Table 2) indicate a configuration effect during encoding due to a higher location-change-detection performance for the complete configuration compared with no configuration. Further, the results also indicate that observers used the cue during encoding, as the complete and the congruent configuration are comparable, and there is a significant difference between the congruent configuration and no configuration.

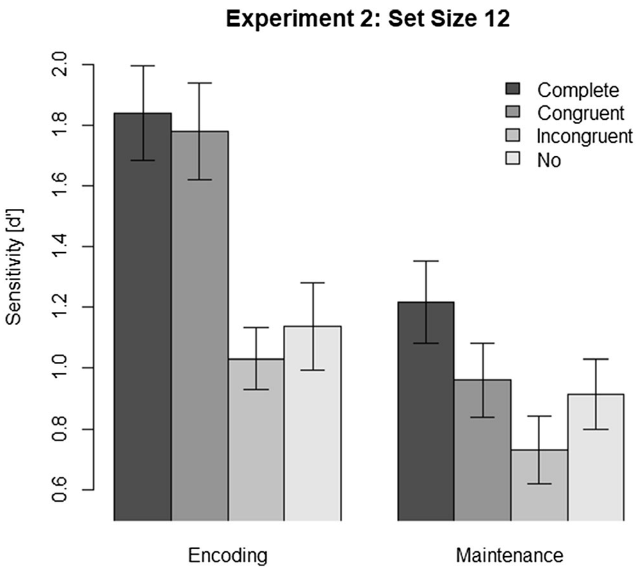

Fig. 3 Sensitivity (d') across all participants for Experiment 2. Error bars indicate the standard error of the mean (SEM)

Table 2 The p values and *t* tests for configurations in Experiment 2: Encoding

Configuration	Complete	Congruent	Incongruent
Congruent	.630		
Incongruent	<.001*	<.001*	
No	<.001*	<.001*	.400

*Statistically significant ($p < .05$)

The results for the *t* tests (see Table 3) also indicate a configuration effect during maintenance. As participants' location-change-detection performance was significantly lower with a single object compared with the complete condition, spatial configurations contributed to the memory representation. However, we did not observe a reorganization of spatial configurations during maintenance as indicated by the comparable performance in the congruent and the no condition, and the lower performance in the congruent than in the complete condition.

These results confirm previous findings that the formation of spatial configurations during encoding can include a subset of objects by shifting attention to these objects. However, in contrast to Experiment 1, reorganization was not possible during maintenance. Because of these differences, we ran a cross-experiment analysis.

Cross-experiment analysis

We compared location-change-detection performance as indicated by the sensitivity measure across conditions and experiments using a 2 (cue presentation: encoding, maintenance; within) × 4 (configuration: complete, congruent, incongruent, no; within) × 2 (set size: six, Experiment 1; 12, Experiment 2; between) mixed ANOVA. Most importantly, there was no significant three-way interaction of moment of cue presentation, configuration, and set size, $F(3,162) = 2.26$, $p = .083$, $\eta_p^2 = .04$. There were three significant main effects with $ps < .001$, η_p^2s between .42 and .49 for moment of cue presentation, configuration, and set size, as well as an interaction effect for moment of cue presentation and configuration, $F(3,162) = 3.59$, $p = .015$, $\eta_p^2 = .06$. All other effects were not significant.

Table 3 The p values and *t* tests for configurations in Experiment 2: Maintenance

Configuration	Complete	Congruent	Incongruent
Congruent	.013*		
Incongruent	<.001*	.083	
No	.012*	.687	.142

*Statistically significant ($p < .05$)

Taken the first two experiments into account, it was possible for participants to shift their attention to a relevant partial configuration during encoding with both six and 12 objects. During maintenance, a reorganization was possible with six objects, but not with 12 objects. However, we did not observe a significant three-way interaction of moment of cue presentation, configuration, and set size in our cross-experiment analysis. Thus, we cannot draw the clear conclusion that set size influences the reorganization process during maintenance based on our first two experiments. Therefore, we performed a third experiment that was specifically designed to investigate this influence.

Experiment 3

Because of the divergent results from the first two experiments and the cross-experiment analysis, we ran a third experiment that was designed to investigate the influence of set size on the reorganization of spatial configurations during maintenance. Because we were concerned that set size might be confounded with eye movements—larger set sizes elicit more eye movements (Zelinsky, 2001)—we introduced an additional condition with enforced fixations in Experiment 3.

Method

We performed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on the Open Science Framework: https://osf.io/738nh/.

Participants We doubled the number of participants due to the between design. Thus, 56 participants took part in this experiment in exchange for course credit or monetary compensation. We applied the same exclusion criteria as before, and, furthermore, participants had to have normal vision for a precise eye tracking. Moreover, participants that could not be calibrated by the eye tracker were removed and replaced by new participants. Fifteen participants had to be replaced, leading to the participation of 71 subjects, but a final sample of 56, as previously appointed. Nine participants had to be replaced because of a performance level that did not deviate from chance, and six participants could not be calibrated. Participants of the final sample had normal vision, and their age ranged from 18 to 30 years ($M = 22.5$ years, $SD = 2.8$).

Stimuli and materials We used an experimental setup similar to that of Experiment 2. In contrast to Experiments 1 and 2, we tested all Experiment 3 participants with a computer (Dell Precision M4800) that was accompanied by an SMI iView RED250 mobile eye tracker with a 250-Hz sampling rate to record eye movements, and we presented our stimuli on the corresponding 16-in. display. Six participants were tested with a sampling rate of 60 Hz instead of 250 Hz because of a software issue. The size of stimuli on the display was identical to Experiment 2. In the present experiment, we only varied the instructions between the groups (eye movements as usual vs. maintain fixation). Thus, participants saw the same material on the same equipment in both conditions. The only difference was the possibility of eye movements. Participants' heads were positioned in a chin rest.

Procedure We used the procedure of Experiment 2 with the following changes. First, cues were presented during maintenance only. Second, we manipulated set size (6/12) within participants. Third, we manipulated fixation enforcement between participants: One group had to fixate on the center of the screen throughout a trial, and the other group was allowed to move their eyes freely. For the first group, fixations were monitored throughout a trial, and a trial was aborted and repeated at the end of a block if a participant did not fixate on the center of the screen. A fixation cross was shown during the trial, and if gaze samples recorded were outside of an invisible surrounding circle with a radius of 1.5° for more than 250 ms, then a trial was aborted and repeated. Participants started each trial by looking at the fixation cross for 500 ms in both groups. Each condition occurred equally often within each block, and also within the whole experiment. Thus, we showed 10 trials per experimental condition (configuration, set size, location, cue side). The experiment duration was between 1 and 1.5 hours.

Design and analysis We compared location-change-detection performance as indicated by the sensitivity measure across conditions using a 2 (set size: 6, 12; within) × 4 (configuration: complete, congruent, incongruent, no; within) × 2 (fixation: enforced, free-view; between) mixed ANOVA. We manipulated fixation between participants in order to avoid potential carryover effects. In particular, we wanted to ensure that participants move their eyes freely when allowed to do so.

Results and discussion

All analyses have been preregistered. We performed a mixed ANOVA, with sensitivity (d') as the dependent variable and fixation, set size, and spatial configuration as the independent variables. There was a significant main effect for set size, $F(1, 54) = 164.16$, $p < .001$, $\eta_p^2 = .75$, and a significant main effect for configuration, $F(3, 162) = 16.96$, $p < .001$, $\eta_p^2 = .24$. There was no significant main effect for fixation, $F(1, 54) = 0.54$, $p = .464$, $\eta_p^2 = .01$. There was also a significant interaction effect for fixation and configuration, $F(3, 162) = 3.42$, $p = .019$, $\eta_p^2 = .06$, indicating that the location-change-detection performance in the two fixation groups was differentially affected by the presence of spatial configurations at retrieval. Because of the significant interaction effect of fixation and configuration, we further investigated the configuration effects with separate t tests for both experimental groups (see Tables 4 and 5).

We found no significant results for all remaining interaction effects of the mixed ANOVA. In detail, there were no significant effects for fixation and set size, $F(1, 54) = 0.47$, $p = .495$, $\eta_p^2 = .01$, configuration and set size, $F(3, 162) = 1.25$, $p = .294$, $\eta_p^2 = .02$. and for the three-way interaction of fixation, set size, and configuration, $F(3, 162) = 0.98$, $p = .404$, $\eta_p^2 = .02$.

In an exploratory analysis, we analyzed the eye-tracking data of the free-view group (see Table 6). We used the high-speed event-detection algorithm provided by the IDF Event Detector (SMI, Version 3.0.20) with the following detection parameters: minimum duration of 22 ms, peak velocity threshold of 40°/s, and a minimum fixation duration of 50 ms. This analysis included the 22 participants of the free-view group that we tracked with a sampling rate of 250 Hz. There were significant differences between the set sizes in number of saccades, $t(21) = -3.54$, $p = .002$, and saccade amplitudes, $t(21) = 3.21$, $p = .004$. That is, larger set sizes elicited more, but shorter, saccades. Despite this difference in eye movements in the free-view group, set size did not modulate the configuration effects on memory in Experiment 3. That is, we observed reduced contextual processing in the absence of eye movements only (enforced fixation).

In a nutshell, free-viewing participants could reorganize their spatial configurations, regardless of set size, during maintenance (see Figs. 4 and 5). Interestingly, the results of the enforced fixation do not show a configuration effect at all (see Fig. 4). Because of the fixation, eye movements were not possible, and it seems that this handicap interfered a configuration process in general. Previous research suggests that spatial representations are linked to eye movements (Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Berman & Colby, 2009; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kalogeropoulou, Jagadeesh, Ohl, & Rolfs, 2017; Ohl & Rolfs, 2017; Van der Stigchel & Hollingworth, 2018). In early studies using a dual-task paradigm, including a saccade assignment and a letter-discrimination task, it was discovered that saccade target selection and object recognition deploy a common attentional mechanism (Deubel & Schneider, 1996). Recent studies underline the theory that eye movements are needed for

Table 4 The p values and t tests for configurations in Experiment 3: Enforced fixation

Configuration	Complete	Congruent	Incongruent
Congruent	.823		
Incongruent	.007*	.021*	
No	.122	.252	.482

*Statistically significant ($p < .05$)

Table 5 The *p* values and *t* tests for configurations in Experiment 3: Free view

Configuration	Complete	Congruent	Incongruent
Congruent	.038*		
Incongruent	<.001*	<.001*	
No	<.001*	.014*	.015*

*Statistically significant ($p < .05$)

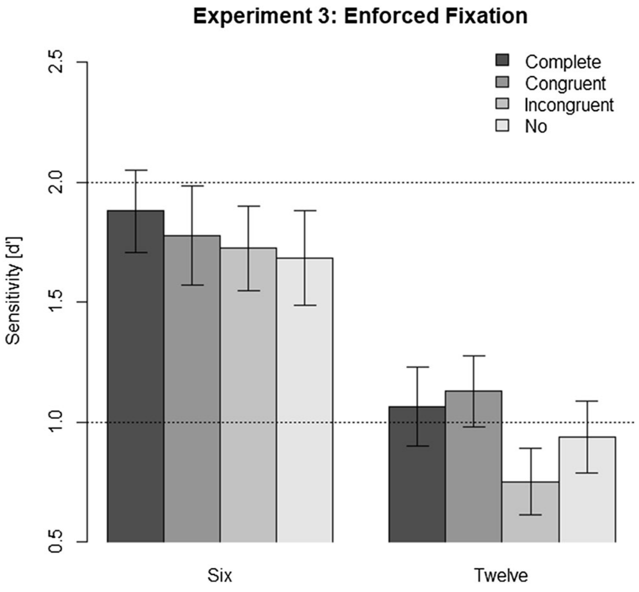

Fig. 4 Sensitivity (*d′*) across enforced fixation group for Experiment 3. Error bars indicate the standard error of the mean (*SEM*)

functioning working memory. That includes mechanisms such as target selection, maintenance, and feature conservation during and after a saccade as well as gaze correction during item search at retrieval (Van der Stigchel & Hollingworth, 2018). Our results provide evidence that there might also be the reverse relation between eye movements and working memory. That is, the construction of certain spatial representations in working memory—spatial configurations, in our study—might be needed for eye movements. This is in accordance with evidence showing that eye movements influence the process of spatial memory components and that the distances and relations to other objects are important for visual perception and subsequent memory processes (de Vito, Buonocore, Bonnefon, & Della Sala, 2014; Laeng & Teodorescu, 2002). We conclude that eye movements are necessary for the formation of spatial configurations in VWM that are a prerequisite for reorganization to occur. Thus, there might be a strong bidirectional relation of eye movements and working memory.

General discussion

We conducted three experiments investigating whether spatial configurations can be reorganized during maintenance. We focused on the comparison of encoding and maintenance, set size differences, and eye movements to better understand the underlying processes.

First, our results indicate that internal spatial configurations could be reorganized during maintenance with six objects. Second, we wanted to validate and better understand these findings by doubling the number of objects in the display. Although the results indicate no reorganization of spatial configurations during maintenance with 12 objects, there was no interaction of configurations and set size in a cross-experimental analysis. Finally, with our third experiment, it was shown that spatial configurations could be reorganized regardless of set size during maintenance, when people could move their eyes freely. Interestingly, there was no configuration effect at all when participants could not move their eyes.

By using a cue during encoding, we replicated previous findings that directing attention to a relevant subset of a global spatial configuration resulted in the

Table 6 Saccade parameters for Experiment 3 per trial, mean (*SD*): Free view

Set size	6	12
Number of saccades*	7.45 (3.51)	8.09 (3.45)
Saccade amplitude*[1]	279.67 (107.17)	259.40 (107.45)

* Statistically significant difference ($p < .01$)

[1] In pixels

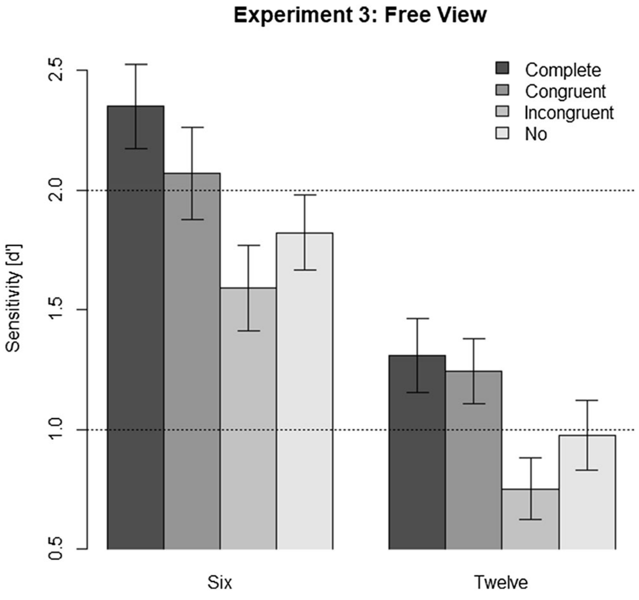

Fig. 5 Sensitivity (*d′*) across free-view group for Experiment 3. Error bars indicate the standard error of the mean (*SEM*)

representation of the relevant partial configuration (Jiang et al., 2000), irrespective of set size. However, the process leading to this effect might differ from previous research. In contrast to previous research, the relevant subset was not indicated right from the start of a trial but with a cue occurring 1 second after stimulus onset in our experiment. Thus, one cannot argue that participants looked at the relevant stimuli right from the start of trial in our experiments. Rather, it seems plausible that they first encoded the global configuration that was then updated based on the cue. This idea is further supported by the fact that the cue occurred in only 50 % of trials during encoding, such that participants could not wait for the cue to start encoding. Finally, in contrast to previous research (Jiang et al., 2000), the manipulation of the irrelevant objects affected memory performance in our experiments. That is, the presence of the incongruent configuration at retrieval led to a reduced memory performance compared with no configuration. If participants had just looked at or encoded the relevant stimuli, the incongruent configuration and no configuration conditions should be on the same level.

By using a cue during maintenance, we found that, in principle, spatial configurations can be reorganized during maintenance. Because there was no hint of the probed object's side before the occurrence of the retro cue, we argue for a reorganization of the global spatial configuration held in memory. As described in the beginning, we refer to reorganization as the process in which a global spatial configuration of objects is encoded in the beginning and the number of objects and their relations are updated into the cued partial configuration during maintenance. The pattern of our results indicate such a reorganization process. Although the performance with the congruent configuration was comparable to the complete configuration, the presence of the incongruent configuration at retrieval led to a reduced memory performance compared with no configuration. If participants were not reorganizing to the relevant stimuli, the congruent configuration, incongruent configuration, and no configuration conditions should be on the same level. However, we also observed some boundary conditions, such as reorganization not occurring with 12 objects in the second experiment or no configuration effects occurring with enforced fixation in the third experiment. Concluding, while showing that reorganization of spatial configurations during maintenance is possible, we also came across some boundary conditions that require future research. Moreover, future research should also investigate the process driving the reorganization of spatial configurations—that is, whether reorganization is caused by strengthening the representation of the attended objects, forgetting the unattended objects, or some other process. Furthermore, participants might have learned that we always cued one side of the screen across trials, resulting in the encoding of two separate configurations (left-hand vs. right-hand side) into VWM. The retro cue could then lead to the removal of the uncued configuration instead of a reorganization of the global spatial configuration. Investigating this idea further by future research would provide interesting insights because this would suggest that observers can maintain multiple separate spatial configurations concurrently in VWM instead of only one global spatial configuration, as previously proposed (e.g., Jiang et al., 2000; Papenmeier & Huff, 2014).

We used the dependent measure sensitivity (*d'*) as an indicator of memory performance. This procedure is well established in working-memory and change-detection-task paradigms (e.g., Boduroglu & Shah, 2009; Haatveit et al., 2010; Macmillan & Creelman, 2005; Stanislaw & Todorov, 1999; Turker & Swallow, 2019). Based on this measure, we conclude that the reorganization of spatial configurations is possible under certain conditions because the memory performance for the probed object was boosted if it was presented either within the complete or the congruent spatial configuration. In order to get a more detailed picture of the underlying mechanisms, we also provided hits, false alarms, and proportion correct for every configuration condition in each experiment (see Table 7 in the Appendix). This shows that the manipulation of spatial configurations had a greater influence on hits than false alarms. As hits refer to an "old" response on an "old" trial, participants particularly benefited from the presence of a meaningful configurational context if the object probed was presented at an old location. This stands in line with our results and conclusions that complete configurations as well as reorganized partial configurations are represented in VWM.

We varied set size in order to investigate its impact on reorganizing spatial configurations during maintenance. Location-change-detection performance dropped with increased set size in our experiments, replicating previous findings that sensitivity regarding location-change detection drops when more objects are present (Jiang et al., 2000; Luck & Vogel, 1997). Importantly, however, there was no significant interaction of spatial configuration and set size. Thus, it remains an open question whether there is a capacity limit for either spatial configurations in general or the reorganization of spatial configurations in particular. Especially when cued during encoding, it could be argued that the effective set sizes were three and six, not six and 12. Nonetheless, only 50% of the trials were cued during encoding, and the cue occurred 1 second after stimulus onset, so it seems plausible that participants encoded all stimuli before cueing, as they did not know the relevant stimuli until the (retro) cue occurred. Therefore, we defined set size as the number of objects visible at stimulus onset. In general, future research should still pay attention to set size when investigating potential capacity limits for reorganization effects.

We observed strong effects of the retro cue on the incongruent condition. The (retro) cue shifted the attention to one side of the whole configuration during encoding or maintenance. Based on previous findings that directing attention to a single object during maintenance eliminates configuration effects at retrieval (Sligte et al., 2008), one might have expected a similar location-change-detection performance with incongruent configurations and no configurations. However, when incongruent objects showed up at retrieval, we observed an interference, as people's location-change-detection performance was lower than in all other conditions. This corresponds to previous findings showing that cues and attention shifts influence the strength of interobject dependencies of working memory representations (Bae & Luck, 2017). Our findings led to similar assumptions, as it seems that a reorganization into the relevant partial configuration led to a disruption when the other objects reappeared. Thus, future research investigating the reorganization effect might benefit from not only focusing on congruent configurations but also from explicitly investigating the process underlying the interference caused by incongruent configurations.

The reliance of spatial configuration effects on eye movements was an interesting and unexpected finding of our third experiment. If spatial configurations in VWM were a rigid perceptual snapshot as proposed before (e.g., Higuchi & Saiki, 2017; Papenmeier & Huff, 2014; Wood, 2011), they should also have occurred with enforced fixation. However, configuration effects occurred only when people could move their eyes freely. Thus, spatial configurations required eye movements and exploration regarding the stimulus material. We will elaborate on this surprising finding by discussing literature on the relation between eye movements and VWM. One the one hand, eye movements are in the need of a functioning working memory. That includes mechanisms such as target selection, maintenance, and feature conservation during and after a saccade as well as gaze correction during item search at retrieval (Van der Stigchel & Hollingworth, 2018). This matches with neuroimaging outcomes, that visual processing parts of the brain are activated as well when it comes to spatial representations and selective attention (Berman & Colby, 2009). On the other hand, there is empirical evidence for the association of eye movements and VWM resources and processes (Bays et al., 2009; Bays & Husain, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kalogeropoulou et al., 2017; Ohl & Rolfs, 2017). Using a dual-task paradigm including a saccade assignment and a letter-discrimination task, it was discovered that saccade target selection and object recognition deploy a common attentional mechanism (Deubel & Schneider, 1996). In particular, there is also an association of eye movements with the capacity of the VWM resources, which are modified by selective attention as well as by visual direction (Bays & Husain, 2008). Some research even suggests that eye movements determine the content of VWM (Ohl & Rolfs, 2017). Summarizing, eye movements can both interrupt and stabilize working memory content. However, this previous research focused on VWM for single object features. Our results extend these findings by showing that eye movements are required for processing multi-object spatial configurations. Future research should further investigate the influence of eye movements on spatial configurations in VWM in order to elevate our understanding of the underlying processes.

Conclusion

The reorganization of spatial configurations is possible during maintenance. However, we also came across some boundary conditions that require future research. In particular, eye movements and their relation to spatial configurations and the reorganization process need further investigation. Our findings stand in contrast to the theory of a rigid memory representation, such as spatial configurations as perceptual snapshots (e.g., Higuchi & Saiki, 2017; Papenmeier & Huff, 2014; Wood, 2011). The multistore model of memory provided a first important step into the postulation of the memory's structure (Atkinson & Shiffrin, 1968). Their theory suggests that the short-term store consists of multiple substores, such as the auditory–verbal–linguistic store or the visual store. Our experiments were designed to investigate the latter one. By doing so, we provided evidence that the visual store does not consist of slots storing visual object locations independently. Instead, the global spatial configuration of memorized locations is also stored in visual short-term memory. With the retro-cue paradigm, we also investigated the processes operating on these configurations. In line with current interdisciplinary research, in which working memory can be described as the tool that you can use to access content of the short-term store (Diamond, 2013), we observed evidence for the reorganization of spatial configurations maintained in memory. Taken together, there is evidence that the original short-term store consists of different substores, and there are several ways to reorganize and update its contents.

Acknowledgments We would like to thank Selina Galefski, Eleni Sianni, and Chiara Winter for their help during data collection.

Funding This research project was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Project number 357136437.

Appendix

Table 7 Hit rates, false-alarm rates, proportions correct across all experiments (*SEM* in parentheses)

Condition	Spatial configuration	Hit rate	False-alarm rate	Proportion correct
Experiment 1 Encoding	Complete	.93 (.02)	.13 (.02)	.90 (.01)
	Congruent	.90 (.02)	.12 (.02)	.89 (.02)
	Incongruent	.80 (.03)	.15 (.03)	.83 (.02)
	No	.84 (.02)	.10 (.02)	.87 (.01)
Experiment 1 Maintenance	Complete	.88 (.02)	.15 (.02)	.87 (.01)
	Congruent	.86 (.03)	.13 (.02)	.87 (.02)
	Incongruent	.76 (.03)	.17 (.03)	.79 (.02)
	No	.78 (.03)	.11 (.02)	.84 (.02)
Experiment 2 Encoding	Complete	.85 (.02)	.28 (.02)	.79 (.02)
	Congruent	.84 (.03)	.28 (.03)	.78 (.02)
	Incongruent	.69 (.03)	.33 (.03)	.68 (.02)
	No	.65 (.03)	.27 (.03)	.69 (.02)
Experiment 2 Maintenance	Complete	.78 (.02)	.37 (.03)	.70 (.02)
	Congruent	.70 (.03)	.37 (.03)	.66 (.02)
	Incongruent	.64 (.03)	.38 (.02)	.63 (.02)
	No	.59 (.03)	.27 (.03)	.66 (.02)
Experiment 3 Enforced fixation	Complete	.76 (.02)	.29 (.02)	.74 (.02)
	Congruent	.75 (.02)	.28 (.02)	.73 (.02)
	Incongruent	.67 (.02)	.27 (.02)	.70 (.02)
	No	.68 (.02)	.26 (.02)	.71 (.02)
Experiment 3 Free view	Complete	.84 (.02)	.28 (.02)	.78 (.02)
	Congruent	.81 (.02)	.29 (.02)	.76 (.02)
	Incongruent	.70 (.02)	.32 (.03)	.69 (.02)
	No	.70 (.02)	.25 (.02)	.73 (.02)

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2. Timm, J.D. & Papenmeier, F. (2019). Reorganization of spatial configurations in visual working memory: A matter of set size? *PLOS ONE 14*(11): e0225068. doi.org/10.1371/journal.pone.0225068.

RESEARCH ARTICLE

Reorganization of spatial configurations in visual working memory: A matter of set size?

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Abstract

Humans process single objects in relation to other simultaneously maintained objects in visual working memory. This interdependence is called spatial configuration. Humans are able to reorganize global spatial configurations into relevant partial configurations. We conducted three experiments investigating the process underlying reorganization by manipulating memory set size and the presence of configurations at retrieval. Participants performed a location change detection task for a single object probed at retrieval. At the beginning of each trial, participants memorized the locations of all objects (set size: 4, 8, 12, or 16). During maintenance, a valid retro cue highlighted the side containing the object probed at retrieval, thus enabling participants to reorganize the memorized global spatial configuration to the partial cued configuration. At retrieval, the object probed was shown together with either all objects (complete configuration; Experiment 1a), the cued objects only (congruent configuration; all Experiments), the non-cued objects only (incongruent configuration, all Experiments) or alone (no configuration; Experiment 1b). We observed reorganization of spatial configurations as indicated by a superior location change detection performance with a congruent partial configuration than an incongruent partial configuration across all three experiments. We also observed an overall decrease in accuracy with increasing set size. Most importantly, however, we did not find evidence for a reliable impairment of reorganization with increasing set size. We discuss these findings with regard to the memory representation underlying spatial configurations.

OPEN ACCESS

Citation: Timm JD, Papenmeier F (2019) Reorganization of spatial configurations in visual working memory: A matter of set size? PLoS ONE 14(11): e0225068. https://doi.org/10.1371/journal.pone.0225068

Editor: Alessandra S. Souza, University of Zurich, SWITZERLAND

Received: June 7, 2019

Accepted: October 28, 2019

Published: November 13, 2019

Data Availability Statement: All data files are available from the OSF database. Links are included in the manuscript.

Funding: This research project was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project number 357136437 (https://www.dfg.de/) to FP. The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Background

In everyday life human beings encounter external stimuli, which are memorized as spatial configurations in visual working memory (VWM). In this process, single objects are held in VWM in relation to other simultaneously maintained objects. Examples include driving in traffic, playing video games, participating in sports or watching a movie. This process affects visual information processing and handling of information in VWM. In this study, we focused on the processing of relevant and irrelevant objects stored within a spatial configuration in VWM and the possibility to reorganize such information.

Regarding the organization of VWM, research focuses both on the representation of objects and features in VWM and on the influence of inter-object relations, such as spatial configurations or ensemble statistics, on memory representations. Whereas there is some debate as to whether features, such as color, shape, and location, are stored as integrated objects in VWM [1] or whether features are stored in separate layers and bound by attention [2], research agrees on VWM being a capacity-limited storage subject to narrow limits [3–11]. Further, there is considerable evidence demonstrating the influence of inter-object relations on memory representations, such as memory for single object locations being supported by the global spatial configuration of all objects [12,13] or memory for features of individual objects being biased towards the group mean [14,15]. Less is known, however, about the representation of inter-object relations in memory. In the present research, we investigated the influence of set size on participants' ability of manipulating the representation underlying inter-object relations during maintenance, more specifically the ability of participants to reorganize a spatial configuration during maintenance based on a retro cue. There are at least two plausible accounts of how inter-object relations might be represented in VWM: either in a manner that is inter-dependent on the objects that they are derived from [16,17] or in a separate and independent storage [18–20]. Those two accounts are particularly interesting, because different predictions regarding the capacity limited nature of the reorganization of inter-object relations can be derived.

If inter-object relations are represented in a manner that is inter-dependent on the objects that they are derived from, increasing set size should result in a reduced fidelity of individual object representations [14,19,21,22] or in the representation of only a subset of individual objects once a capacity limit is exceeded [1], thus also impairing participants ability of reorganizing inter-object relations during memorization with increasing set size. According to accounts suggesting a hierarchical organization of VWM, objects and features are not stored independently but as parts of higher-order representations [14,15,19,23,24]. For example, when observers are asked to memorize the sizes of multiple colored objects, they memorize not only the individual object sizes themselves but also cluster objects according to color, resulting in the recall of individual sizes being biased towards the group mean [14]. Similarly, effects like perceptual grouping influence the memory of single objects' locations [25]. While one might consider such hierarchical representations as being a case of inter-object relations being represented in a manner that is inter-dependent on the objects they are derived from, studies investigating hierarchical representations focused on the influence of ensembles or configurations on individual objects and leave open how ensembles or configurations might be represented in VWM [19].

If inter-object relations are represented in a separate and independent storage, however, the ability of reorganizing them during memorization might not be subject to set size per se but rather dependent on still to be defined properties of this storage. One account compatible with such a representation is the snapshot account that suggests that inter-object relations such as spatial configurations might be represented as global snapshots in VWM. The core knowledge architecture model of VWM [18], for example, suggests the existence of a specialized storage within VWM storing view-dependent snapshots. Because those snapshots retain the global scene rather than individual objects, they are not subject to the same tight capacity limitations. Previous research showing a viewpoint-dependence of contextual information in VWM supports the idea of view-dependent snapshots in VWM [26]. They found that whereas the manipulation of spatial configurations between encoding and retrieval influenced memory performance for single objects without viewpoint changes, this influence vanished if viewpoint changes were introduced. Further, there is evidence supporting the idea that the global spatial configuration of all encoded objects but not the partial configuration affects memory performance for single objects [12,27] and spatial configurations influence memory performance for single objects also at larger set sizes [12]. Finally, the detection of single object displacements is even impaired if task irrelevant perceptual grouping cues change between encoding and retrieval [25]. Thus, there is research suggesting that inter-object relations, particularly spatial configurations, might be encoded as a global snapshot in VWM.

In our present research, we studied inter-object relations using spatial configurations. In particular, we focused on the influence of set size on the reorganization of spatial configurations in VWM. Reorganization is defined as the process of updating a global spatial configuration into a partial configuration that is cued by a retro cue during maintenance [13]. Our previous results indicate that such a reorganization is possible. In the present study, we asked participants to encode the locations of multiple objects, to maintain those object locations throughout a blank and to detect location change for one probed object during the test. Replicating previous research, location change detection was better with the presence of the complete spatial configuration at retrieval than if no configuration was present [12]. Importantly, we added a retro cue during maintenance. This retro cue indicated the side containing the object for which participants had to perform the location change detection task. Thus, participants had the possibility of updating their memorized global spatial configuration to the configuration congruent to the cue during maintenance. Our results indicate that such a reorganization did occur because location change detection performance for the marked object was superior if the congruent spatial configuration was present than if the incongruent spatial configuration was present. Thus, although only global spatial configurations and not partial spatial configurations were found to support location change detection in previous research [12,27], using a retro cue and presenting the congruent spatial configuration also supported location change detection, indicating that participants reorganized their spatial configuration. This interpretation is also in line with recent research by Bae and Luck [23] who also used a retro cue in a task involving inter-object relations. In their task, participants memorized the orientation of two objects. Whereas they observed interactions between the object orientations (repulsion and attraction) without a cue, introducing a retro cue in their task resulted in the cued object being influenced less by the uncued object. Thus, manipulating attention by means of retro cues modulates the effects of inter-object relations in VWM.

Whereas our previous results showed that the reorganization of spatial configurations is possible, it was less conclusive regarding the influence of set size on this reorganization effect [13]. In particular, whereas the retro cue resulted in reorganization of spatial configurations with a memory set size of six objects in the first experiment, the reorganization effect was not significant with a memory set size of twelve objects in the second experiment. This indicates that the reorganization of spatial configurations might be limited by memory set size. However, the third experiment which was designed to investigate eye-movements, demonstrated reorganization in a free-view condition irrespective of set size.

In the present study, we conducted three new experiments systematically investigating the influence of set size on reorganization of spatial configurations. We hypothesized that reorganization of spatial configurations would be limited by set size. Thus, we predicted that the facilitation caused by the presence of congruent spatial configurations over the incongruent spatial configurations during the test should decrease with increasing memory set size.

Experiment 1a

With our first two experiments, we investigated the influence of set size on the reorganization of spatial configurations with the four conditions used in our previous research [13]: complete, congruent, incongruent, and no configuration. We split the four possible configurations up into two experiments (Experiment 1a and Experiment 1b) in order to keep the duration of each experiment within one hour per participant.

Method

We performed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on OSF: https://osf.io/r4zvu

Participants. We conducted a power analysis using the R-Package powerbydesign [28] with a critical power of .80 at the standard of .05 alpha error probability. The power analysis was designed for a 3 (configuration: complete, congruent, incongruent; within) x 4 (set size: 4, 8, 12, 16; within) repeated-measures ANOVA and we set the bootstrapping iterations to 3000. Based on data from a previous experiment [13], we set the within correlation to $r = 0.6$ and we set the full configuration effect to a difference in d' of 0.6 (*SD* for each condition: 0.8). Critical to the present manuscript, we ran two versions of the power analysis: one version assuming an interaction of set size and configuration and another version assuming only a main effect of configuration without the respective interaction effect. The critical sample size for observing the interaction in the first power analysis was 28 and for observing the main effect only in the second power analysis was 6. Thus, we recruited 28 participants in order to ensure a power of at least .8 for both possible outcomes, namely the interaction of configuration and set size or a main effect of configuration without the respective interaction. The R code and results for this power analysis are also available online in the OSF project (https://osf.io/tx4u3/).

We preregistered the following exclusion criteria: Participants identified as not performing the task correctly (always pressing the same button or performing at a level that does not deviate from chance) were removed from the data set and replaced by new participants, as well as any participants who did not complete the whole experiment. We had to replace three participants for this particular experiment. Eventually, 28 participants made the final sample in this experiment receiving course credit or monetary compensation of 2€ per 15 min. All of them had normal or corrected-to-normal vision and their age ranged from 19 to 36 years ($M = 24$, $SD = 3.5$). Up to six participants were tested at the same time on different computers. Simultaneous testing and monetary compensation were consistent throughout all experiments. The research was conducted in accordance with APA standards for ethical treatment of participants and with approval of the institutional review board of the University of Tübingen. All participants provided written informed consent.

Materials. We presented eight grey squares (RGB color hex code: #777777) on a 24" computer screen (Fujitsu Display B24-8 TE Pro) using PsychoPy 1.85.6 [29,30]. Each square measured 1° x 1° (degrees of visual angle). Participants were instructed to fixate a centric cross before each trial. The objects appeared in a 25° x 25° centered array. We did not enforce or measured viewing distance but adjusted the programming code for 40 cm. We generated random object locations for each trial with the same number of squares equally placed on each side, with a minimum center-to-center distance of twice the diameter of a square. Furthermore, this minimum distance was applied to the frame as well as to an invisible vertical center line (Fig 1).

Procedure. Participants performed a location change detection task (Fig 1). During encoding all objects were shown for 2000 ms. Afterwards a maintenance phase of 2000 ms followed with no objects shown. At retrieval objects reappeared either in a complete, congruent or incongruent configuration and one object was marked red (RGB color hex code: #FF0000). A grey cue (RGB color hex code: #E6E6E6) was shown 1000 ms into the maintenance period for 100 ms and highlighted the side of the object probed at retrieval. Participants had to press one of two keyboard buttons indicating whether the probed object changed its location or not. On change trials the probed object was presented at a random location within the cued area. It could not appear at a location which was taken by another object at encoding. Moreover, it had the same restrictions as the other objects, for example the minimum inter-object distance.

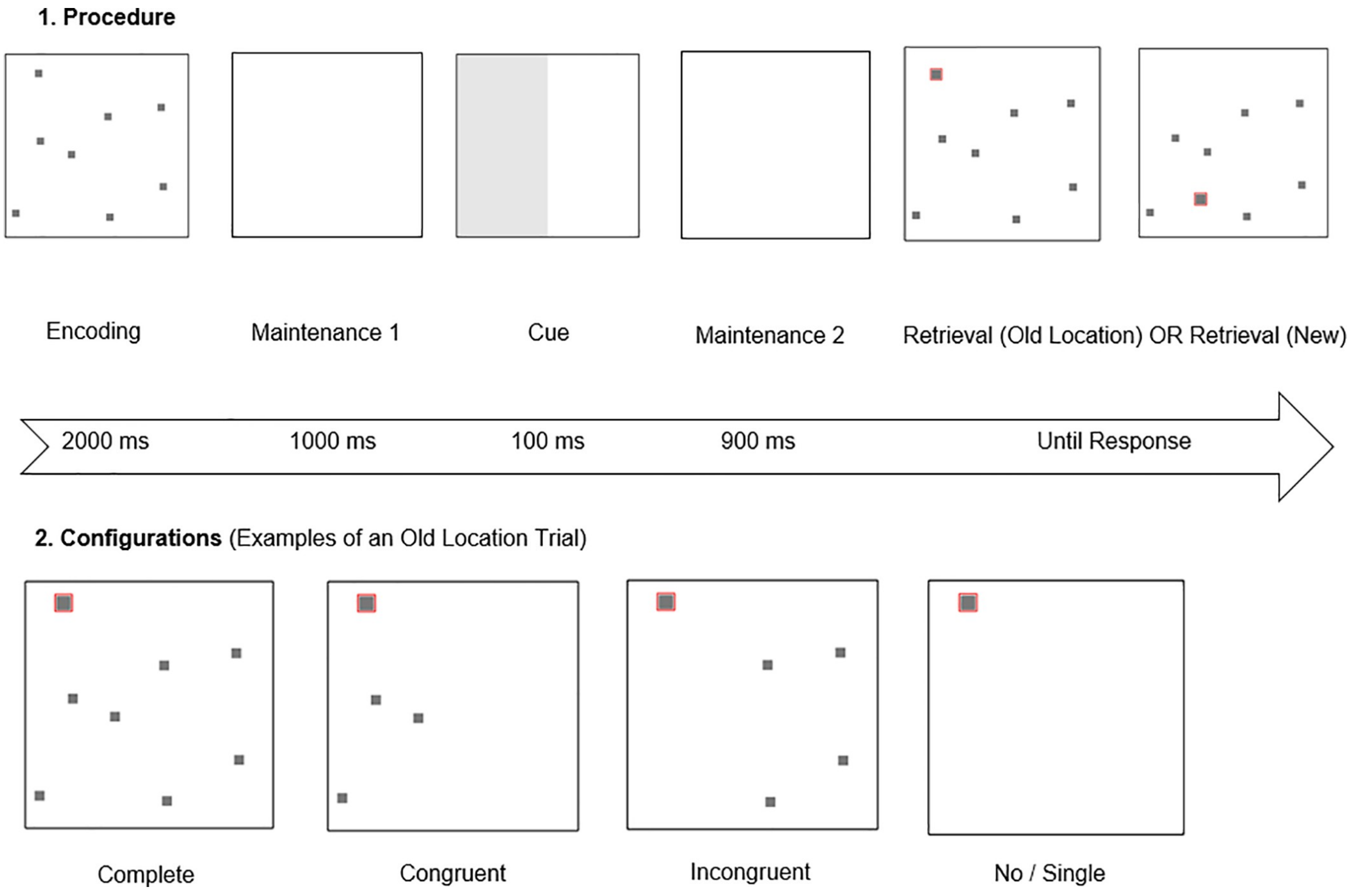

Fig 1. Procedure and manipulations across all experiments. (1) Example trial with all phases and eight objects. Last two panels were intermixed and were used in different trials in each case. (2) Configurations shown in E1a, E1b, or E2. Not every configuration was shown in all experiments. Configurations were intermixed and were used in different trials in each case.

https://doi.org/10.1371/journal.pone.0225068.g001

The timing used in our procedure, such as the 2000 ms for encoding, were set to be identical to our previous research [13] because our previous research demonstrated that free-viewing eye-movements might be necessary for configuration effects to occur, despite not yet disentangling during which phase of a trial eye-movements unfold their effect.

We manipulated the cue side (left/right), the set size (4/8/12/16) and the position of the object probed at retrieval (new/old). The cue was 100% valid, so the object probed was always one of the objects indicated by the cue. Moreover, we showed either a complete configuration (presence of object probed and all other objects that were present during encoding), a congruent configuration (presence of object probed and all other objects that were cued) or an incongruent configuration (presence of object probed and all other objects that were not cued) at retrieval.

Trials were presented in randomized order with the restriction that the experiment consisted of four blocks containing 96 trials each, leading to 384 trials in total. Each condition occurred equally often within each block and, thus, also within the whole experiment. Participants performed a practice block, containing one trial per possible condition. The experiment duration was one hour.

Analysis. We collapsed data across the factor cue side and compared location change detection performance as indicated by the sensitivity measure across conditions using a 3 (configuration: complete, congruent, incongruent; within) x 4 (set size: 4, 8, 12, 16; within) repeated-measures ANOVA. We calculated sensitivity (according to signal detection theory) as dependent measure across the responses to the old/new probe location trials. We used the sensitivity measurement of d', which is defined as $d' = \Phi^{-1}(phits) - \Phi^{-1}(pfa)$ with phits being the proportion of hits and pfa being the proportion of false alarms [31]. Hits refer to the accurate detection of old locations, and false alarms refer to responding "old" to a new location. We corrected phits or pfa having values of 0 and 1 with half a trial correct or half a trial incorrect respectively as sensitivity cannot be calculated for those values. Trials with response times exceeding 10 seconds were removed before the analysis (0.18%). When the assumption of sphericity was not met–as indicated by Mauchly's Test–we corrected the degrees of freedom and p-values with the Greenhouse-Geisser correction. Degrees of freedom accompanying corrected p-values are given with two decimal places. The same analysis was repeated for every experiment.

Results and discussion

All analyses have been preregistered. We hypothesized an interaction effects with the factors configuration and set size. We performed a repeated measures ANOVA with the dependent variable of sensitivity (d') and the independent variables of set size and spatial configuration. There was a significant main effect for set size, $F\ (2.29, 61.94) = 88.24\ p < .001$, $\eta_p^2 = .77$ and a significant main effect for configuration, $F\ (1.63, 43.92) = 26.49$, $p < .001$, $\eta_p^2 = .50$. There was a significant interaction effect, $F\ (6, 162) = 2.94$, $p = .010$, $\eta_p^2 = .10$ (Fig 2). We further investigated the interaction effect with t-tests (Table 1). Data and analysis script can be found on OSF: https://osf.io/tx4u3/

We predicted that the reorganization effect vanishes with an increase in set size. When considering set sizes eight, twelve and sixteen, we found evidence regarding this hypothesis: the difference of sensitivity between congruent and incongruent configuration conditions with eight and twelve objects was significant and the effect disappeared with sixteen objects, thus indicating that the reorganization of spatial configuration is affected by set size. This conclusion is further supported by the fact that location change detection performance with a complete configuration was better than the other two configuration conditions at set size sixteen. That is, configuration effects were possible to observe at set size sixteen, but participants did not successfully reorganize spatial configuration containing sixteen objects in VWM.

Surprisingly, we did not observe a significant reorganization effect at set size four. We can only speculate about the source of this unexpected finding. One the one hand, this might be caused by a cost-benefit consideration: four objects can be easily held in VWM such that participants might not invest the effort to reorganize the spatial configuration in VWM based on the cue given during maintenance. On the other hand, the congruent configuration consists of only two objects at set size four: the object probed and one other object on the same side of the display. Possibly, two objects do not form a spatial configuration that can draw on the memory representation used to represent spatial configurations, thus not enabling participants to reorganize the original configuration containing four objects to a congruent configuration containing only two objects.

Experiment 1b

This experiment was similar to Experiment 1a. We replaced the complete configuration condition with a no configuration condition.

Method

We performed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on OSF: https://osf.io/y4npj

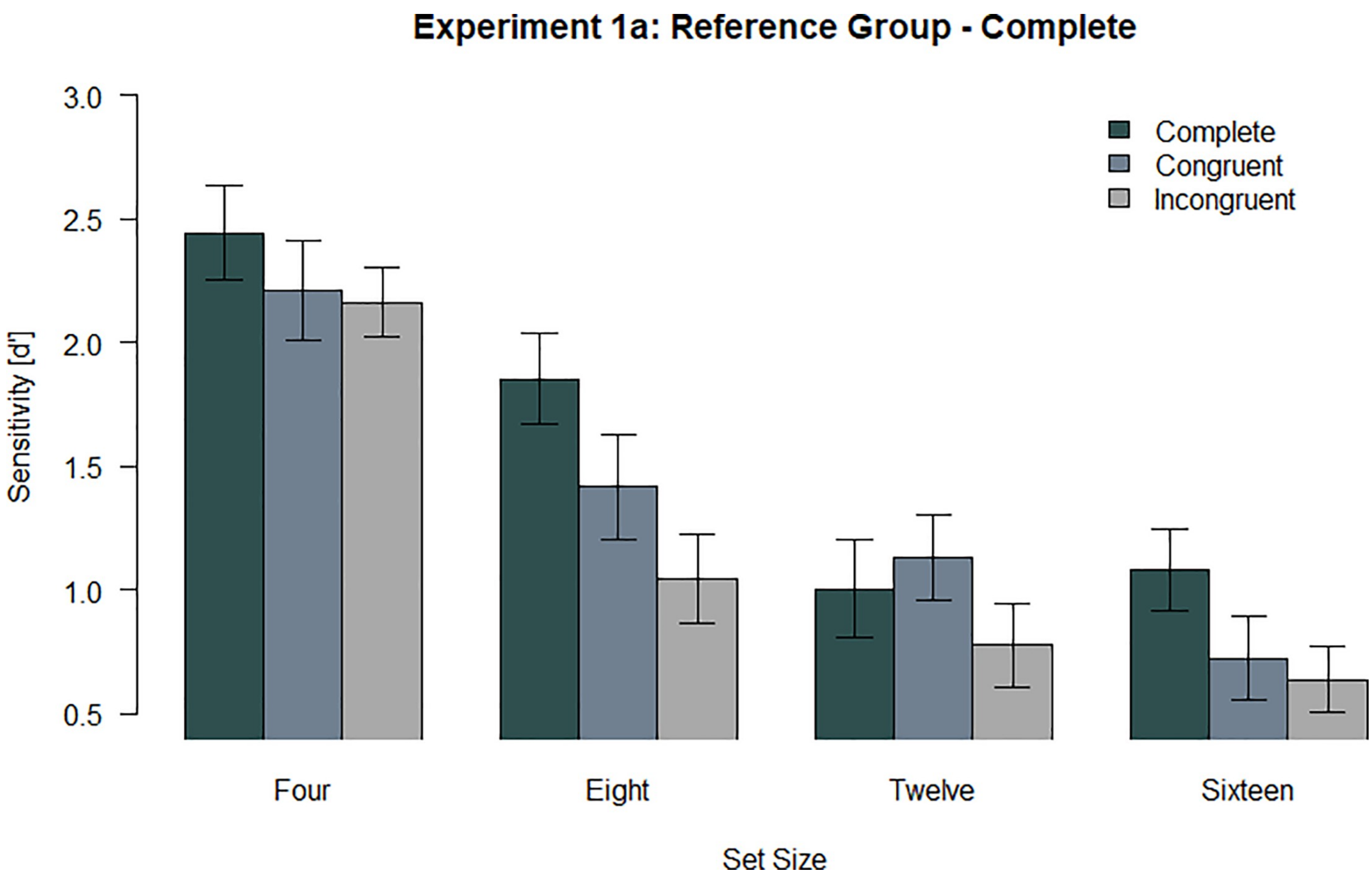

Fig 2. Sensitivity (d') across all participants for Experiment 1a. Error bars indicate the standard error of the mean (SEM).

https://doi.org/10.1371/journal.pone.0225068.g002

Participants. We used the same sample size metrics as in Experiment 1a. Subsequently, 28 participants were invited for this experiment receiving course credit or monetary compensation. We applied the same exclusion criteria and seven participants had to be replaced due to a performance level that did not deviate from chance leading to the participation of 35 subjects but a final sample of 28 as previously appointed. Participants of the final sample had normal or corrected-to-normal vision and their age ranged from 21 to 30 years (*M* = 24.5, *SD* = 2.1). All participants provided written informed consent.

Table 1. ***P-Values–t-tests for configurations in Experiment 1a.***

Set Size	Spatial Configuration	Complete	Congruent
Four	Congruent Incongruent	.062 .049*	.735
Eight	Congruent Incongruent	$<$ .001* $<$ .001*	.021*
Twelve	Congruent Incongruent	.247 .087	.013*
Sixteen	Congruent Incongruent	.013* .001*	.514

* statistically significant ($p < .05$)

https://doi.org/10.1371/journal.pone.0225068.t001

Materials. We used the same materials and setup as in Experiment 1a.

Procedure. We used a similar procedure as in Experiment 1a but replaced the complete configuration with the no configuration condition. In detail, we showed a single object condition (presence of object probed only) in this experiment, a congruent configuration (presence of object probed and all other objects that were cued) and an incongruent configuration (presence of object probed and all other objects that were not cued) at retrieval.

Analysis. The analyses were consistent with analyses described above. We collapsed data across the factor cue side and compared location change detection performance as indicated by the sensitivity measure across conditions using a 3 (configuration: single, congruent, incongruent; within) x 4 (set size: 4, 8, 12, 16; within) repeated-measures ANOVA. We calculated sensitivity (according to signal detection theory) as dependent measure across the responses to the old/new probe location trials. Trials with response times exceeding 10 seconds were removed before the analysis (0.03%).

Results and discussion

All analyses have been preregistered. We hypothesized an interaction effect of the factors configuration and set size. We performed a repeated measures ANOVA with the dependent variable of sensitivity (d') and the independent variables of set size and spatial configuration. There was a significant main effect for set size, $F\ (2.34, 63.18) = 112.77\ p < .001$, $\eta_p^2 = .81$ and a significant main effect for configuration, $F\ (2, 54) = 14.14$, $p < .001$, $\eta_p^2 = .34$. There was no significant interaction effect, $F\ (6, 162) = 0.68$, $p = .663$, $\eta_p^2 = .02$ (Fig 3). We further investigated the main effect of configuration with t-tests (Table 2). Data and analysis script can be found on OSF: https://osf.io/r2zah/

As in Experiment 1a, we again predicted that the reorganization effect vanishes with an increase in set size. Surprisingly, however, we did not observe the predicted interaction effect. Instead, there was a main effect of configuration indicating that the reorganization of spatial configuration in VWM was unaffected by set size. That is, the difference of sensitivity between congruent and incongruent configuration conditions was significant independent of set size. In order to further investigate this contradictory finding, we conducted Experiment 2.

Experiment 2

With our Experiments 1a and 1b, we investigated the influence of set size on the reorganization of spatial configurations in VWM. Whereas we observed the predicted interaction of set size and configuration in Experiment 1a, this interaction was not significant in Experiment 1b. We interpreted the difference in location change detection performance between the congruent and incongruent configuration conditions as the critical comparison indicating the occurrence of reorganization. We also presented two different reference conditions across Experiments 1a and 1b. The no configuration (Experiment 1b) served as reference condition indicating whether the configuration effect was present with the reorganized configuration leading to a superior location change detection performance with a congruent than no configuration. The complete configuration (Experiment 1a) served as reference condition indicating whether the reorganization occurred in full or not. This was shown with the difference in location change detection performance between the complete configuration condition and congruent configuration condition. With the present experiment, we wanted to further investigate the reorganization effect in terms of the capacity limit and as another measure regarding our contradictory findings in the previous two experiments. In particular, we were interested in the difference in performance between the congruent and incongruent conditions in the absence of reference conditions because their addition in Experiments 1a and 1b could have

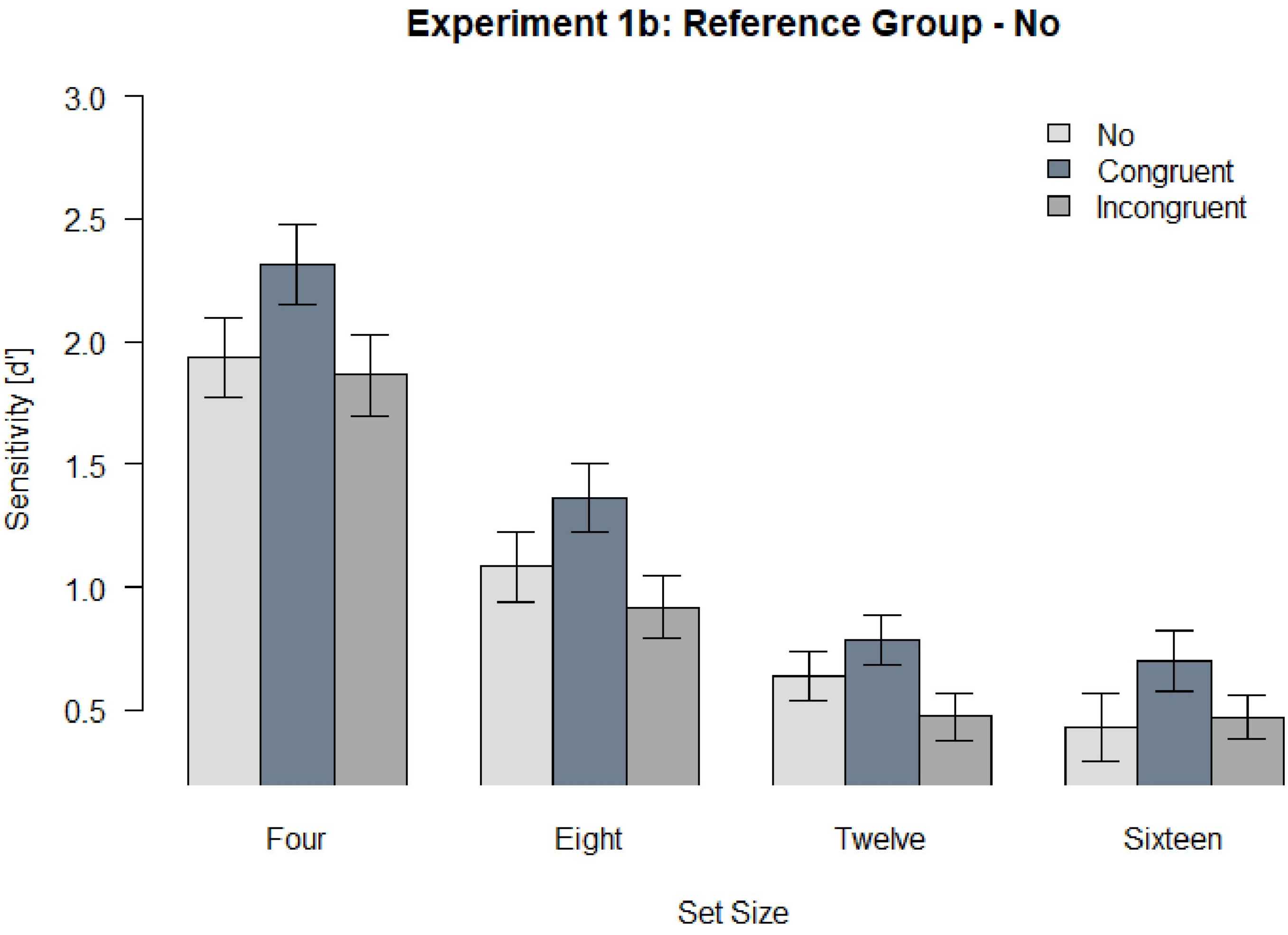

Fig 3. Sensitivity (d') across all participants for Experiment 1b. Error bars indicate the standard error of the mean (SEM).

https://doi.org/10.1371/journal.pone.0225068.g003

affected the processing of the displays, for example by implementing different encoding or maintenance strategies such as focusing more or less on configurational information due to the presence of the complete configuration in contrast to the single item condition. Thus, we abandoned both the complete configuration and the no configuration condition in this experiment and focused solely on the comparison of the congruent and incongruent configurations across set size.

Method

We performed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on OSF: https://osf.io/xndkc.

Table 2. ***P-Values–t-tests for configurations in Experiment 1b.***

Set Size	Spatial Configurations	No	Incongruent
Aggregated	Congruent	.002*	< .001*
	Incongruent	.217	

* statistically significant (p < .05)

https://doi.org/10.1371/journal.pone.0225068.t002

Participants. We used the same sample size metrics and exclusion criteria as before. Two participants had to be replaced due to a performance level that did not deviate from chance leading to the participation of 30 subjects but a final sample of 28 as previously appointed. Participants of the final sample had normal or corrected-to-normal vision and their age ranged from 20 to 34 years ($M = 24$, $SD = 3.2$). All participants provided written informed consent.

Materials. We used the same materials and setup as in Experiments 1a and 1b for the location change detection task.

Procedure. We used a similar procedure as in Experiments 1a and 1b. In contrast, we only showed a congruent configuration (presence of object probed and all other objects that were cued) or incongruent configuration (presence of object probed and all other objects that were not cued) at retrieval in this experiment.

Analysis. The analyses were consistent with analyses described above. We collapsed data across the factor cue side and compared location change detection performance as indicated by the sensitivity measure across conditions using a 2 (configuration: congruent, incongruent; within) x 4 (set size: 4, 8, 12, 16; within) repeated-measures ANOVA. We calculated sensitivity (according to signal detection theory) as dependent measure across the responses to the old/new probe location trials. Trials with response times exceeding 10 seconds were removed before the analysis (0.01%).

Results and discussion

All analyses have been preregistered. We performed a repeated measures ANOVA with the dependent variable of sensitivity (d') and the independent variables of set size and spatial configuration. There was a significant main effect for set size, $F\,(3, 81) = 79.15$ $p < .001$, $\eta_p^2 = .75$ and a significant main effect for configuration, $F\,(1,27) = 13.51$, $p = .001$, $\eta_p^2 = .33$. There was no significant interaction effect, $F\,(3, 81) = 2.26$, $p = .088$, $\eta_p^2 = .08$ (Fig 4). Data and analysis script can be found on OSF: https://osf.io/8ruxn/

Once again, we observed no significant interaction effect of set size and configuration but only the two main effects of set size and configuration. The location change detection performance was superior in the congruent configuration than in the incongruent configuration up to sixteen objects. Therefore, the results indicate that the reorganization effect is largely unaffected by set size and the reorganization effect did not vanish with an increase in set size. Despite the non-significant interaction, the descriptive results also indicate that the occurrence of reorganization at set size four might not be reliable, which is similar to what we observed in Experiment 1a.

Cross-experiment analysis

Whereas we found an interaction effect of set size and configuration in Experiment 1a as we had predicted beforehand, we could not find this interaction effect in Experiments 1b and 2. In order to further investigate the contradictory findings regarding the influence of set size on reorganization across our experiments, we calculated a cross-experiment analysis across our three experiments. For this analysis, we used the data of the congruent and incongruent configuration conditions as they occurred in all three experiments and calculated a 2 (configuration: congruent, incongruent; within) x 4 (set size: 4, 8, 12, 16; within) x 3 (experiment: 1a, 1b, 2; between) ANOVA. Similar to Experiments 1b and 2, there were significant main effects for set size and configuration, both $ps < .001$, and a non-significant interaction of set size and configuration, $F\,(3, 243) = 2.39$, $p = .069$, $\eta_p^2 = .03$. Importantly, neither the main effect for experiment nor connected interaction effects were statistically significant, ps between .277 and .556. In order to quantify the evidence for the absence of the interaction of set size and

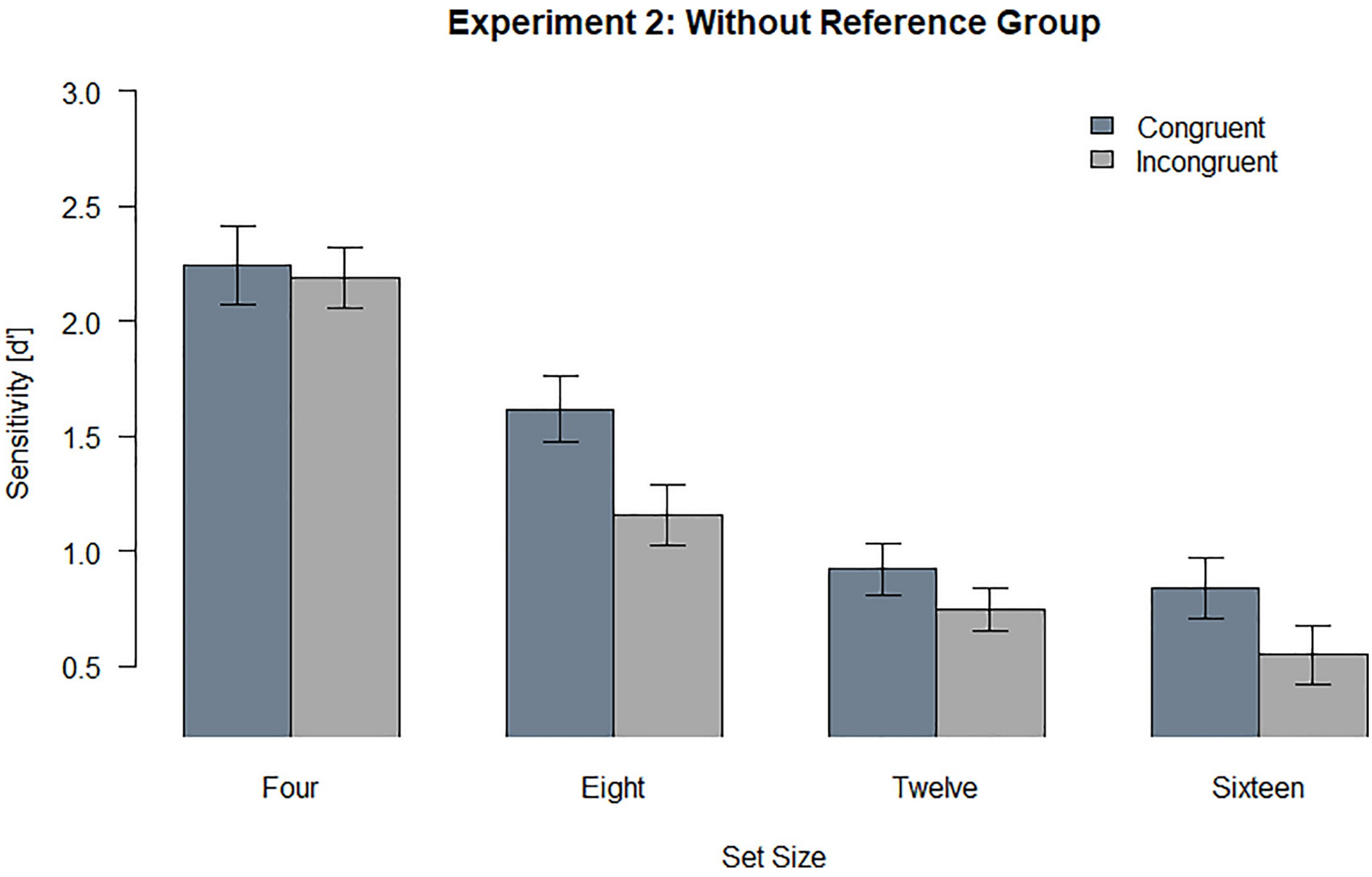

Fig 4. Sensitivity (d') across all participants for Experiment 2. Error bars indicate the standard error of the mean (SEM).

https://doi.org/10.1371/journal.pone.0225068.g004

configuration, we calculated the Bayes factor comparing a basic model (H0) including the main effects for set size and configuration only to a full model (H1) including both main effects and the corresponding interaction of set size and configuration. Both models included "participant" as a random effect. The Bayes factor was $BF10 = 0.13$ suggesting that our data provides evidence for the absence rather than presence of the interaction of set size and configuration, which is in accordance with our ANOVA results. Thus, there was no reliable influence of set size on the reorganization of spatial configurations in VWM across our experiments. The analysis script can be found on OSF: https://osf.io/8ruxn/

In a nutshell, two of our experiments (1b/2) and a cross-experiment analysis with a high number of participants could not provide evidence that the reorganization effect vanishes with an increase in set size. Thus, we conclude that reorganization of spatial configuration is largely unaffected by set size, at least within the range of set sizes investigated, that is up to sixteen objects.

General discussion

We conducted three experiments to investigate whether reorganization of spatial configurations in VWM is affected by set size. A valid retro cue presented during maintenance enabled participants to reorganize their spatial configuration to the cued side of the display. We measured reorganization by comparing location change detection performance of a single probed object under the presence of either the congruent (all cued objects) or incongruent (probed object and all not-cued objects) configuration. Whereas reorganization of configurations was affected by set size in Experiment 1a –reorganization of configurations at set sizes eight and twelve but not sixteen–no significant influence of set size on reorganization was found in Experiments 1b and 2 and in a cross-experiment analysis. We conclude that reorganization of spatial configurations is largely unaffected by set size.

Previous research suggested a slot model for VWM with a fixed maximum capacity threshold [1,3–11]. In the present research, we investigated the influence of set size on the participants' ability of manipulating the representation underlying inter-object relations during maintenance, more specific the ability of participants to reorganize a spatial configuration during maintenance based on a retro cue. There are at least two plausible accounts of how inter-object relations might be represented in VWM: either in a manner that is inter-dependent on the objects that they are derived from or in a separate and independent storage [18,19]. While one would expect a strong influence of set size on the reorganization of spatial configurations in VWM based on the former account, a much weaker influence of set size on the reorganization of spatial configurations would be expected based on the latter account. Our results speak in favor of the latter account and thus an independent storage for spatial configurations in VWM as set size did not lead to reliable reduction of the reorganization effect across the set sizes investigated in our experiments. One potential candidate for this independent storage is the view-dependent snapshot storage proposed by the core knowledge architecture model of VWM [18]. Given our general finding that reorganization is possible, however, this storage cannot be formalized as holding representations of spatial configurations as a frozen or rigid snapshot in VWM [18,26,32] but rather as a flexible storage within a global snapshot approach or alternatively as part of a flexible hierarchical representation. Future research could also establish whether there is a potential relation between this independent storage for configurations and the high-capacity fragile VWM store proposed by previous research [33], for example by manipulating the presence of backward-masks after encoding.

We concluded that set size does not affect reorganization of spatial configurations. This is limited in some points. For example, with four objects this effect was only shown in Experiment 1b. As already argued, reorganization might not be useful in this instance as the whole configuration of four objects is already easy to remember and reorganization seems ineffective. So that might be the threshold, where single objects relegate into a spatial configuration maintained in VWM caused by a cost-benefit consideration. Furthermore, the congruent configuration consists of only two objects at set size four: the object probed and one other object on the same side of the display. Possibly, two objects do not form a spatial configuration that can draw on the memory representation used to represent spatial configurations, thus not enabling participants to reorganize the original configuration containing four objects to a congruent configuration containing only two objects. Recent research suggested, that items were not bound to spatial configuration representations in VWM. Interestingly, the configurations in all these experiments consisted of no more than two items and no configuration effect was found [34]. This stands in line with the majority of our experimental results that too few objects might not form a stable spatial configuration. On the other hand, the reorganization of spatial configurations with four objects was observed in Experiment 1b. Therefore, the minimum threshold for the possibility of reorganization of spatial configurations cannot be established yet and should be investigated in future research.

We defined the partial configurations as congruent and incongruent, which apply to the relevant and irrelevant side of the screen. One might argue, that relevant and irrelevant items are also the objects near and far to the probed object. In our design, we randomized locations of the objects and therefore, also incongruent objects (e.g., next to the center) could be closer to the object probed than a congruent object (e.g., placed in the corner of the display). By analyzing a number of random locations generated by our location generation algorithm, we could confirm that the close items were not identical to the congruent configuration in our experiments. For example, with a set size of eight objects, we picked the three nearest objects (because a congruent configuration consisted of the object probed and three additional objects) and had a look if those three closest objects originated from the congruent configuration only or whether they also included objects from the incongruent configuration. Indeed, on about 2/3 of the trials at least one (and up to three) incongruent objects were part of the three objects closest to the object probed. Therefore, the objects closest to the probed object did not consist of the congruent objects only and thus, distance and congruence/relevance were not the same. Further, the ratio of the average distance between the target and the congruent items and the average distance between the target and the incongruent items was comparable across set size conditions. In previous studies, also the intact configuration rather than absolute location or distance of objects was shown to be important [12]. This is not to say that distance does not play a role for configurational processing at all. Importantly, however, we are confident that our congruent vs. incongruent findings cannot be explained by a pure distance account. Nevertheless, future research should systematically investigate the role of distance and object prioritization by cues on configurational processing and reorganization.

Another point to discuss are the configurations used as reference (complete & no) we used in our experiments. In Experiment 1a, the levels of location change detection performance in the complete configuration were better than the incongruent configuration. The performance levels in the complete configuration was superior than or equal to the congruent configuration levels. This also speaks for a successful reorganization as the location change detection performance level of the congruent configuration should be similar to the performance level in the complete configuration, while the level of the incongruent configuration should be inferior than the performance levels of the complete or congruent configuration to infer the reorganization effect. In Experiment 1b, the levels of location change detection performance in the no configuration condition were worse than in the congruent configuration. The performance level in the no configuration was equal to the incongruent configuration level. This favors a successfully evoked configuration effect. Location change detection should be higher with a surrounding configuration than with a single object only as a configuration supports memory representation–this was shown with the congruent vs. no comparison. Nevertheless, a configuration effect needs relevant objects, and irrelevant ones can impair memory recognition compared to congruent configurations–this was shown with the incongruent vs. no comparison, which were equal. So, with both experiments and reference conditions, we find support for both successful configuration memory advantages and the accompanying possibility of reorganization of spatial configurations. Nevertheless, we found different patterns of reorganization when we compared Experiments 1a and 1b using different reference conditions which might affected the extent of reorganization of spatial configurations. In Experiment 1a, we found a significant interaction effect while we did not find one in Experiment 1b. So, one might argue that the reference conditions might have affect the reorganization effect, but our cross-experiment analysis showed that across all three experiments there was no interaction effect regarding the reference conditions. So, reorganization as a difference of congruent and incongruent configuration memory performance was independent of reference conditions used. All in all, a conclusion of an effect of the reference conditions on the reorganization of spatial configurations cannot be drawn from our experimental results.

Concluding, reorganization of spatial configurations from a global and complete configuration into relevant (here congruent) and irrelevant (here incongruent) partial configurations was unaffected by set size. This speaks in favor of models suggesting the representation of configurations in a separate and independent storage, that is not subject to the same tight capacity limits suggested by classical VWM slot models. Future research can use our results as a starting point when the reorganization effect is investigated. There are several points that are still unclear, for example, if and how the cue and the different configurations are used. In a nutshell, we observed reorganization of spatial configurations as indicated by a superior location change detection performance with a congruent partial configuration than an incongruent partial configuration across all three experiments. We conclude that besides the overall decrease in accuracy the reorganization effect was stable across all experiments and that the reorganization effect itself was largely unaffected by any of the set sizes investigated.

Acknowledgments

We would like to thank Selina Galefski for her help during data collection and Maria Badanova for her help with proofreading.

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(Re-)Organization of Spatial Configurations in Visual Working Memory:
The Fate of Objects Rendered Relevant or Irrelevant by Selective Attention

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Abstract

People maintain object locations not as independent absolute positions but based on inter-object relations in the form of a spatial configuration in visual working memory (VWM). Initial evidence suggests that spatial configurations can be reorganized during maintenance; however, this mechanism is not well understood. We report three experiments investigating this reorganization process. First, we found that directing spatial attention with a retro cue triggers a reorganization of spatial configurations during maintenance (Experiment 1). Second, we investigated the role of contextual objects rendered either relevant or irrelevant through the retro cue by manipulating the locations of the context at retrieval both within a partial display (Experiment 2a) and a whole display (Experiment 2b). Whereas the similar impairment of memory performance by changing the relevant and global context suggests a complete reorganization of spatial configurations in VWM, this interpretation was challenged by the observation of impaired memory performance with changes of the irrelevant objects in a whole display that retains the relevant locations. Thus, we suggest that reorganization should be considered to be the formation of a partial configuration based on the objects rendered relevant by the retro cue in addition to the originally encoded global configuration, with both configurations affecting memory performance.

Background

While interacting with their environment, human beings regularly encode and retrieve object locations. When memorizing locations, they are usually not represented as independent object locations but rather in relation to one another, such as the keys lying to the left of the cup on the desk. The importance of inter-object relations for representations in visual working memory (VWM) was demonstrated by a great deal of research in the past years, both for locations in the form of spatial configurations (Jiang et al., 2000; Papenmeier et al., 2012) or object features such as color or shape (Blalock & Clegg, 2010; Boduroglu & Shah, 2009, 2014; Brady & Alvarez, 2011; Hollingworth, 2007; Lin & He, 2012; Papenmeier & Huff, 2014; Phillips, 1974; Wang et al., 2016, 2017; Woodman et al., 2012). Only recently, however, has research turned to investigating inter-object relations not only as a property of storage but also whether those relations can be flexibly adjusted during maintenance in VWM based on informative retro cues rendering a subset of encoded information as being relevant (Bae & Luck, 2017; Souza & Oberauer, 2016; Timm & Papenmeier, 2019a, 2019b). The initial results suggest that retro cues affect encoded inter-object relations, both by the reorganizations of spatial configurations (Timm & Papenmeier, 2019a, 2019b) or by influencing the strength of interference between object features (Bae & Luck, 2017). Reorganization refers to the process of restructuring a global spatial configuration into a partial spatial configuration based on a retro cue[1]. With our present work, we conducted three experiments tackling two important questions in advancing our understanding of the flexibility of inter-object relations in VWM, more specifically, regarding the reorganization of spatial configurations in VWM: First, does sole spatial attention like a retro cue induce a reorganization

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[1] Please note that we refer to the concept under investigation as reorganization similar to our earlier work. In our opinion, the advantage of using the term reorganization over another term such as updating is that reorganization refers to a restructuring of a mental representation whereas updating could either refer to the addition, removal or replacement of information in mental representations (Timm & Papenmeier, 2019a, 2019b).

of VWM? Importantly, previous research did not distinguish between the flexible reorganization based on the retro cue and a potential encoding of subsets of spatial configurations during encoding. Second, what is the fate of irrelevant items during the flexible reorganization of inter-object relations? In particular, we investigated whether changing context object locations during test affects memory of the probed information both within a whole-probe display and a partial display.

In contrast to a massive amount of research studying the representation of individual object location and features in VWM (Alvarez & Cavanagh, 2004; Bays et al., 2009; Luck & Vogel, 1997; Rouder et al., 2008; Wilken & Ma, 2004; Zhang & Luck, 2008), much of the past research has focused on the observation that objects are not represented independently in VWM but rather in relation to one another (Jiang et al., 2000, 2004; Papenmeier et al., 2012; Vidal et al., 2005). One central claim is that the organization of VWM is based on spatial configurations (Jiang et al., 2000). In their experiments, Jiang and colleagues (2000) had observers remember object locations and features. Importantly, the participants could detect changes of a single probed object more easily when the object appeared together with the global spatial configuration of all memorized objects than when it appeared by itself. While some follow-up research supported the idea that VWM for object locations is organized based on spatial configurations (Bateman et al., 2018; Boduroglu & Shah, 2009, 2014; Dent, 2009), the claim that object features such as color or shape are necessarily encoded based on the spatial configuration of the objects was challenged by some recent research (Udale et al., 2017, 2018a, 2018b). Nonetheless, the role of inter-object relations was demonstrated also within feature dimensions such as color or shape (Vidal et al., 2005), so that the representation of objects based on inter-object relations seems to be a general feature of VWM. For the present work, we focused on the representation of locations based on spatial configurations in VWM.

Whereas flexibility is a core property of VWM (Oberauer, 2009), previous research on the role of inter-object relations studied these relations as a property of storage of VWM rather than investigating their flexibility within existing representations of VWM. Recently, we provided some initial evidence that a reorganization of spatial configurations based on retro cues during maintenance might be possible (Timm & Papenmeier, 2019a, 2019b). Extending the paradigm of Jiang and colleagues (2000), we used a location change detection task and introduced retro cues during maintenance, following the rationale that informative retro cues cause a shift of attention. Thus, the retro cue divided the global spatial configuration into a relevant and irrelevant one. We reported two main findings. First, replicating the work of Jiang and colleagues (2000), location changes of the probed object were detected more easily with the presence of the global spatial configuration than without a configuration. Second, the presence of the relevant configuration supported location change detection to the same extent as the global spatial configuration. This latter finding was intriguing because partial spatial configurations do not usually support memory performance (Jiang et al., 2000; Papenmeier & Huff, 2014). Thus, we concluded that participants could update and reorganize their global spatial configuration VWM content into a relevant partial one (Timm & Papenmeier, 2019a). A potential limitation concerning this conclusion refers to the presentation of the cue in our previous research. More specifically, one might argue that the relevant partial configuration consisted of objects being closer to the probed object than the irrelevant ones. Because we presented an informative cue in each and every trial, the observed configuration effect might have also been triggered by distance rather than the cue (Timm & Papenmeier, 2019b). Thus, we found it important to investigate whether informative retro cues do indeed trigger a reorganization of spatial configurations in VWM, as this adds to the understanding of the flexibility of inter-object relations in VWM. We addressed this issue with Experiment

1 by manipulating the presence of the retro cue and investigating whether the pattern of results, previously interpreted as indicating a reorganization of VWM, occurs only if the cue is present.

Spatial information is maintained in VWM by binding elements into a coordinated relational system and improves performance at retrieval (Oberauer, 2009) since information is processed in chunks which can be stored parallel to each other (Cowan, 2001; Halford et al., 1998; Palmer, 1990; Palmer et al., 1993, 2015; Wilken & Ma, 2004). Souza and Oberauer proposed that “attended representations are strengthened in WM, […] not-attended representations are removed from WM, […] a retro-cue to the retrieval target provides a head start for its retrieval before decision making, and […] attention protects the selected representation from perceptual interference” (Souza & Oberauer, 2016, p. 1839). Thus, the understanding of the mechanism underlying the reorganization of spatial configurations requires the investigation not only of the fate of objects in the relevant configuration but also of the objects rendered irrelevant by the retro cue. This is particularly important as previous research found that even spatial configurations completely irrelevant to a feature change detection affect memory performance (Boduroglu & Shah, 2009). Whereas some previous research introduced explicit changes in categorical relations (Dent, 2009) or motion (Sun et al., 2015) to break global spatial configurations, more recent research investigated how displacements affect partial spatial configurations (Bateman et al., 2018). More precisely, it is not the displacement of a partial group that impairs memory performance but the change of relative locations between objects of the partial group. Thus, in order to extend our understanding of the reorganization of spatial configurations in VWM, we investigated the role of non-probed objects in both relevant and irrelevant configurations in Experiments 2a and 2b by not only manipulating the presence of the respective configurations but by also manipulating the locations of the non-probed objects. In particular, these displacements should impair the memory performance for the probed object only if the respective non-probed items are relationally connected to the memory representation of the probed object.

Experiment 1

With this experiment, we investigated the influence of spatial attention in the form of the retro cue on the reorganization of spatial configurations in VWM. More specifically, we manipulated the appearance of the cue. In 50% of the trials, there was an informative retro cue, and in the other half of the trials, there was no cue. We hypothesized that the informative retro cue triggers a reorganization of spatial configurations in VWM. Thus, a reorganization of spatial configurations in VWM should occur only in trials with a retro cue but not in trials without a retro cue. A successful reorganization is indicated by location change detection performance with the relevant configurations being higher than without configurations and being comparable to global configurations.

Additionally, we investigated whether the reorganization of spatial configurations in VWM is affected by the participants' working memory capacity. This research question was motivated by previous research providing evidence that the participants' working memory capacity has an effect on the (strategical) storage and utilization of (ir-)relevant spatial information (Boduroglu & Shah, 2009; Vogel et al., 2005; Vogel & Machizawa, 2004).

Method

We followed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on OSF:

https://osf.io/pe3bq/?view_only=ed18c09cc26f4842ac86c5fb63ce0445 *[This is a private link for the review process only. We will make the project public once the manuscript has been accepted for publication]*

Participants. We conducted a power analysis using the R-Package powerbydesign (Papenmeier, 2016) with a critical power of .80 at the standard of .05 alpha error probability. The power analysis was designed for a 2 (cue presence: yes, no; within) x 4 (configuration: global, relevant, irrelevant, no; within) repeated-measures ANOVA and we set the bootstrapping iterations to 3000. Based on data from a previous experiment (Timm & Papenmeier, 2019a), we set the within correlation to r = 0.67 and we set the full configuration effect to a difference in d’ of 0.35 (SD for each condition: 0.84). Critical to the present manuscript, we ran two versions of the power analysis: one version assuming an interaction of cue presence and configuration and another version assuming only a main effect of configuration without the respective interaction effect. The critical sample size for observing the interaction in the first power analysis was 56 and for observing the main effect only in the second power analysis was 16. Thus, we recruited 56 participants in order to ensure a power of at least .8 for both possible outcomes, namely the interaction of configuration and cue presence or a main effect of configuration without the respective interaction. Participants were invited for this experiment receiving course credit or monetary compensation. We paid 2€/15 min. We preregistered the following exclusion criteria: The participants identified as not doing the task (always pressing the same button or showing a performance level that does not deviate from chance) were to be removed from the data set and replaced by new participants - the same for any participants not completing the whole experiment. Nine participants had to be replaced due to a performance level that did not deviate from chance, leading to the participation of 65 subjects but a final sample of 56 as previously calculated. The participants of the final sample had normal or corrected-to-normal vision and their age ranged from 19 to 35 years (M = 22.9, SD = 3.4, 13 male participants). Up to six participants were tested at the same time on different computers. Simultaneous testing and monetary compensation were consistent throughout all experiments. The research was conducted in accordance with APA standards for ethical treatment of participants and with approval of the institutional review board of the University of Tübingen.

Materials. We presented eight grey squares (RGB color hex code: #777777) on a 24” computer screen (Fujitsu Display B24-8 TE Pro) with an unrestricted viewing distance of about 57 cm using PsychoPy 1.85.6 (Peirce et al., 2019). Each square measured 1° x 1° (degrees of visual angle). Participants were told to view a centric fixation cross before each trial. The objects could appear in a 25° x 25° centered array. Furthermore, we generated random object locations for each trial with the same number of squares equally placed on each side, with a minimum center-to-center distance of twice the diameter of a square, that was also applied to the border and an invisible center line.

Procedure. Participants performed a location change detection task (see Figure 1). During encoding, all objects were shown for 2000 ms. Then a maintenance phase of 2000 ms followed with no objects shown. At retrieval, objects reappeared either in a global configuration, in a relevant configuration, in an irrelevant configuration, or without configuration (no), and one object was marked red (RGB color hex code: #FF0000). In one half of the trials, a grey retro cue (RGB color hex code: #E6E6E6) was shown 1000 ms into the maintenance period for 100 ms and highlighted the side of the object probed at retrieval. The participants had to press a keyboard button, indicating whether the object marked changed its location or not.

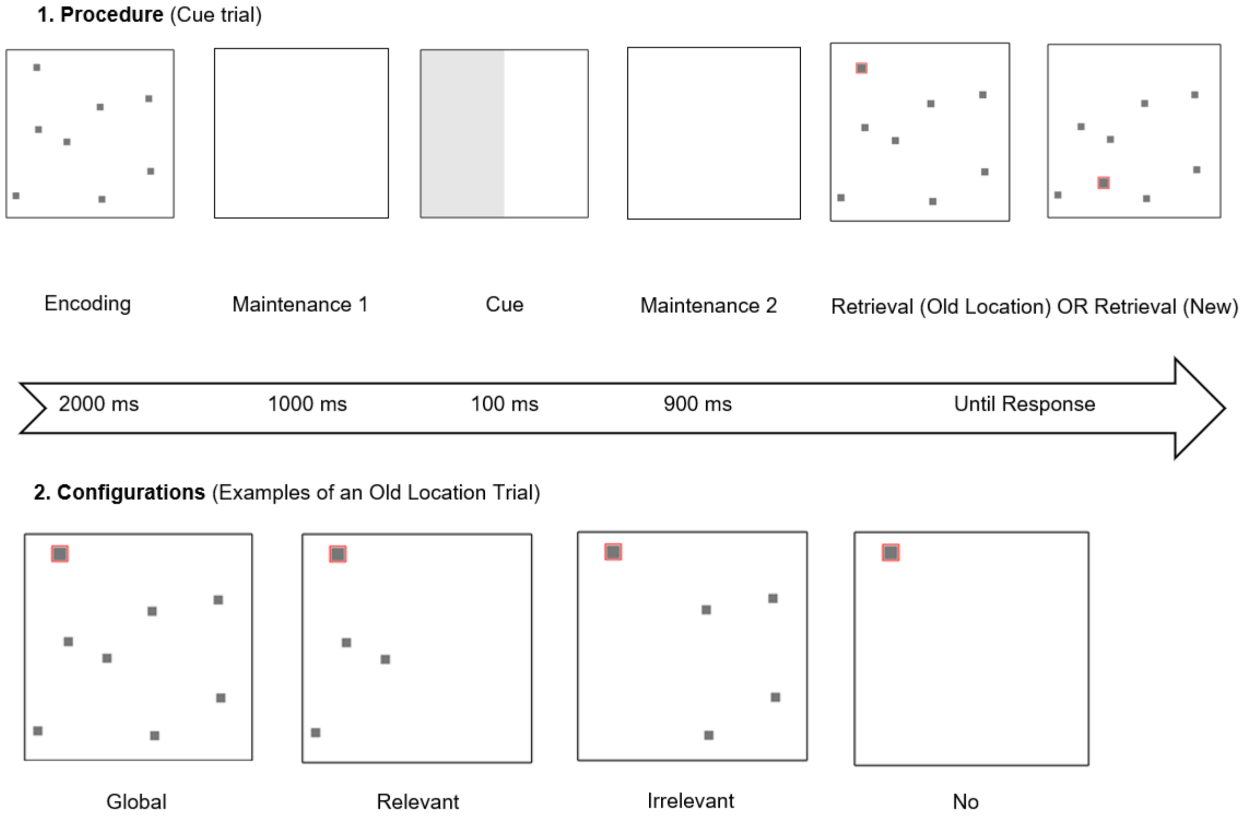


Figure 1 Procedure and Manipulations for Experiment 1

(1) Example cue trial with all phases and eight objects. Last two panels were intermixed and were used in different trials in each case. In 50% of the trials, a cue appeared during maintenance (as depicted here) and in 50% of the trials no cue was shown. (2) Configurations were intermixed and were used in different trials in each case. Figure adapted from Timm and Papenmeier (2019b).

We manipulated the cue presence (yes/no) and the position of the object probed at retrieval (new/old). The cue, when shown, was 100% informative and was presented either on the left-hand side or right-hand side of the display, intermixed within participants; that is, the probed object was always one of the objects indicated by the cue.

Trials were presented in randomized order with the restriction that the experiment consisted of two blocks containing 160 trials each leading to 320 trials in total. Each condition occurred equally often within each block and, thus, also within the whole experiment. One block contained a cue and the other block none. We counterbalanced the block order, leading to one group of participants with the cue presence block first and a subsequent block with no cue and vice versa for the other half of the participants. Participants performed a cue specific practice block containing one trial per possible condition (8 trials). In the beginning of each of the two blocks, there was a short practice block, depending on the cue condition (with/without). Hence, participants could not be aware of the different cue conditions until the second practice block. Following the location change detection task, participants performed 30 trials of an adaptive Corsi Blocks Task to estimate their VWM capacity (see next subsection). The whole experiment duration was approximately one hour.

Corsi Blocks Task. At the end of the experiment, we measured the participants' working memory capacity with a Corsi Blocks Task (CBT) on the same computer (Corsi, 1972; Kessels et al., 2000). In particular, we measured memory for spatial sequences with the length of sequence adaptively increasing or decreasing, depending on the performance of the participants. At encoding, participants saw a sequence of squares within a 5 x 5 grid with 1000 ms for every square. Then a blank of 300 ms followed and afterwards, participants had to replicate the sequence at retrieval by clicking the correct locations in the correct sequence. If the sequence was replicated correctly, the next sequence added one square. If the sequence was replicated wrongly, the next sequence included one square less. This task consisted of 30 trials per participant. The estimation of the participants' working memory capacity was based on the mean of the last ten correct trials of the CBT (adapted from Grinschgl et al., 2020).

Analysis. We performed two analyses in accordance with our preregistration. First, we collapsed data across the factor cue side and compared location change detection performance as indicated by the sensitivity measure across conditions using a 2 (cue presence: yes, no; within) x

4 (configuration: global, relevant, irrelevant, no; within) repeated-measures ANOVA. We calculated sensitivity (according to signal detection theory) as the dependent measure across the responses to the old/new probe location trials (Stanislaw & Todorov, 1999). Sensitivity d' is defined as $d' = \Phi^{-1}(phits) - \Phi^{-1}(pfa)$ with phits being the proportion of hits and pfa being the proportion of false alarms (Stanislaw & Todorov, 1999). Hits refer to the accurate detection of old locations, and false alarms refer to responding "old" to a new location. Note that sensitivity cannot be calculated for either phits or pfa having values of 0.0 and 1.0. Thus, we corrected such values to the respective proportions equaling half a trial correct or half a trial incorrect. Trials with response times exceeding 10 seconds were removed before the analysis (0.14%). Second, we performed an additional analysis investigating the potential influence of the participants' working memory capacity and block order on the reorganization of spatial configurations in VWM. Thus, we performed a mixed ANOVA with the same factors used before (cue presence & configuration; within) as well as with the factor block order (cue/no cue vs. no cue/cue; between) and a continuous measure of the participants' working memory capacity. When the assumption of sphericity was harmed – indicated by Mauchly's Test – we corrected the statistical values with the Greenhouse-Geisser correction. Corrected p-values are stated with degrees of freedom with two decimal places. This was applied to all experiment analyses.

Results and Discussion

All analyses had been preregistered. We performed a repeated measures ANOVA with the dependent variable of sensitivity (d') and the independent variables of cue presence and spatial configuration (see Figure 2). There were significant main effects for cue presence *F* (1, 55) = 10.19 *p* = .002, η_p^2 = .16 and for configuration, *F* (3, 165) = 36.77, *p* < .001, η_p^2 = .40 as well as a significant interaction effect, *F* (3, 165) = 2.73, *p* = .046, η_p^2 = .05. We further investigated the main effect of configuration and interaction effect with t-tests (see Tables 2 & 3), showing that the reorganization of spatial configurations in VWM was indeed triggered by the informative retro cue; that is, location change detection performance with the relevant configuration was higher than without a configuration and comparable to the global configuration only in the block with the informative retro cue but not in the block without the informative retro cue.

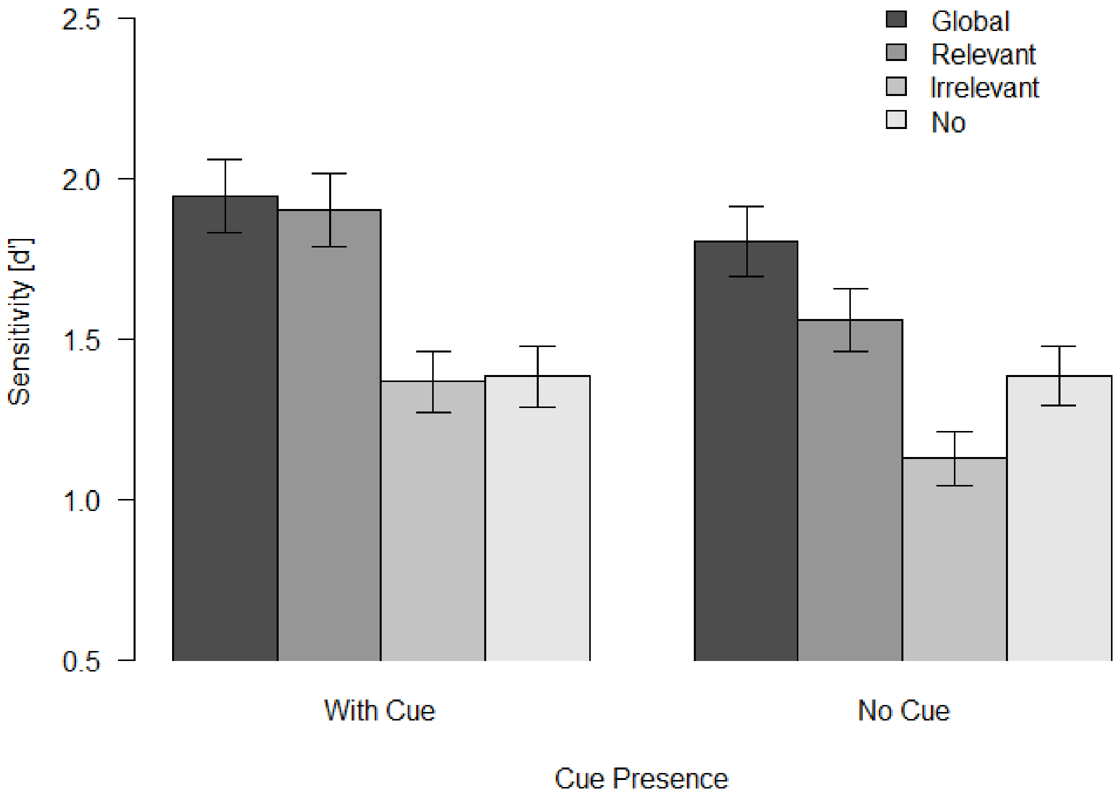


Figure 2 Sensitivity (d') Across All Participants for Experiment 1

Error bars indicate the standard error of the mean (SEM)

Table 2

P-Values – T-Tests for Configurations in Experiment 1 With Cue Presence

Spatial Configuration	Global	Relevant	Irrelevant
Relevant	.629		
Irrelevant	<.001*	<.001*	
No	<.001*	<.001*	.837

* statistically significant (*p* < .05)

Table 3

P-Values – T-Tests for Configurations in Experiment 1 Without Cue Presence

Spatial Configuration	Global	Relevant	Irrelevant
Relevant	.010*		
Irrelevant	<.001*	<.001*	
No	<.001*	.073	.009*

* statistically significant (*p* < .05)

We also ran a mixed ANOVA, additionally including the between-factor of block order and the continuous measure of the participants' working memory capacity. Importantly, there were no significant interaction effects regarding block order and working memory capacity, *p*s between .107 and .955, indicating that neither block order nor working memory capacity influenced the reorganization of spatial configurations in VWM. Further, there was a significant main effect for working memory capacity, F (1, 52) = 12.55, $p < .001$, $\eta_p^2 = .19$, with location change detection being lower the lower working memory capacity was, but no significant main effect for block order, F (1, 52) = 0.20, $p = .653$, $\eta_p^2 = .00$. In addition, the pattern of main effects and the interaction of configuration and cue presence were comparable to the results reported above.

In a nutshell, the participants reorganized the global configuration into a relevant configuration with the help of a retro cue but not without a retro cue; that is, location change detection performance with the relevant configuration was higher than without a configuration and comparable to the global configuration only with the presence of the informative retro cue but not without the informative retro cue (see Figure 2). As participants were not aware of the probed object's side at retrieval without a retro cue, the relevant objects could not be reorganized into a relevant configuration. Furthermore, there was no interaction with block order, suggesting that without a cue – even after practicing with a cue – the reorganization did not take place. Thus, the reorganization of spatial configurations was indeed triggered by the informative retro cue and not caused by participants adopting some kind of strategies, such as trying to utilize distances between objects or trying to encode two partial configurations upfront during encoding. Additionally, we only found a main effect but no interaction effects including the participants' working memory capacity. This speaks against the influence of the participants' working memory capacity on the reorganization of spatial configuration in VWM. Unexpectedly, performance with the uncued irrelevant configuration was lower than without a configuration in the block without a retro cue, although we expected both conditions to result in a similar performance level. We can only speculate about the source of this finding. Potentially, the irrelevant objects grabbed attention on test onset in the absence of the retro cue, thus impairing location change detection performance for the probed object. Importantly, however, we replicated previous findings suggesting that the organization of VWM is based on spatial configurations because the advantage of a global spatial configuration over no configuration occurred in both experimental blocks irrespective the presence of the retro cue.

Experiment 2a

With Experiment 2a, we intended to further investigate the process underlying the reorganization of spatial configurations following retro cues. Thus, we investigated the role of contextual objects in reorganized spatial configurations by manipulating the locations of the context at retrieval. To be more specific, whereas previous research on the reorganization of spatial configurations in VWM manipulated only the presence or absence of respective configurations, with the present experiment, we also manipulated the locations of the non-probed objects at retrieval. These displacements should impair memory performance for the probed object only if the respective non-probed items are relationally connected to the memory representation of the probed object. Thus, this manipulation allows for the investigation of the fate of objects in the relevant configuration but also of the objects rendered irrelevant by the retro cue following the reorganization of spatial configurations in VWM.

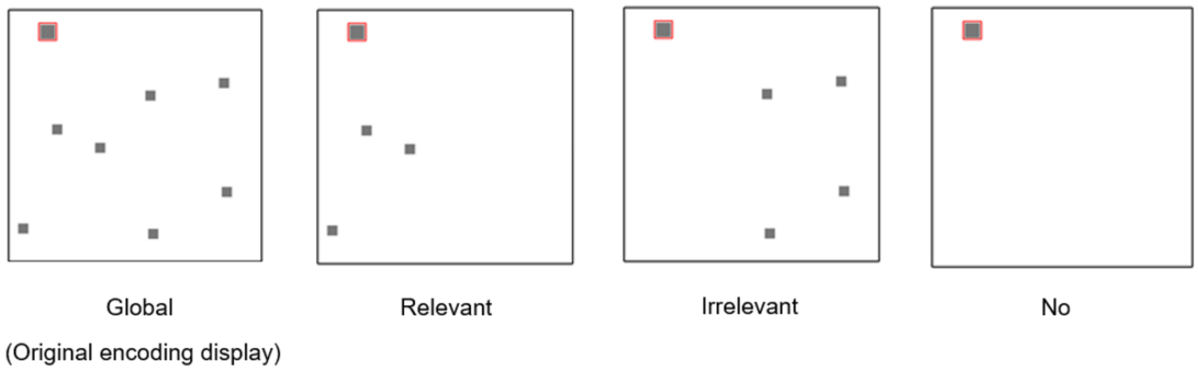
Method

We followed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on OSF:

https://osf.io/fg4sd/?view_only=f7838d8b3796447e894482524d07803c *[This is a private link for the review process only. We will make the project public once the manuscript has been accepted for publication]*

Participants. We used the same sample size as in Experiment 1. Three participants had to be replaced due to a performance level that did not deviate from chance, leading to the participation of 59 subjects but a final sample of 56 as previously appointed. The participants of the final sample had normal or corrected-to-normal vision and their age ranged from 19 to 45 years (M = 24.1, SD = 4.2, 10 male participants).

1. Configurations (Same context)



2. Configurations (Changed context)

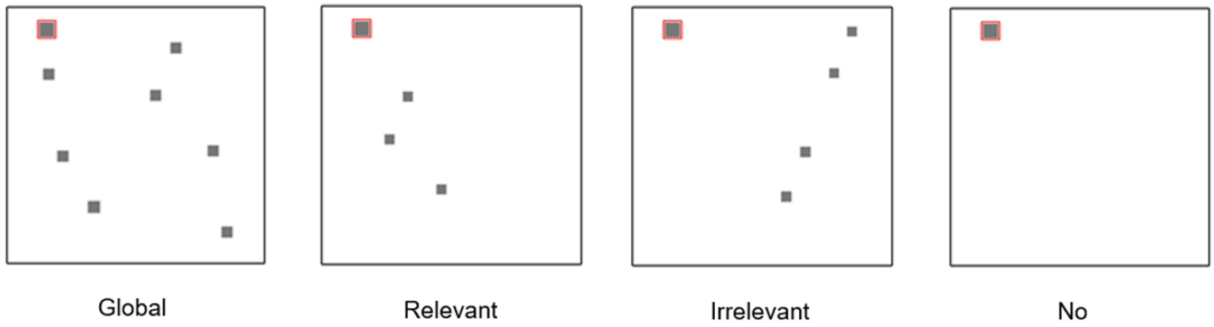


Figure 3 Manipulations at Retrieval for Experiment 2a (Example of an old location trial)

(1) Configurations with same context locations compared to the original encoding display.

(2) Configurations with changed context locations compared to the original encoding display.

Materials. We used the same material as in Experiment 1 but no CBT.

Procedure. Participants performed a location change detection task as in Experiment 1. This time, we manipulated the following variables: context locations (same/change), the position of the object probed (new/old) and the configuration of the objects (global/relevant/irrelevant/no). The cue appeared in every trial (left/right) and was always informative. In trials with changed context locations, the contextual objects at retrieval were located on a new location on the same side of the display that were not occupied during encoding with the restriction of the applied minimum distance parameters (see Figure 3).

Trials were presented in randomized order with the restriction that the experiment consisted of five blocks containing 64 trials each, leading to 320 trials in total. Each condition occurred equally often within each block and, thus, also within the whole experiment. Participants performed a practice block, containing one trial per possible condition, in the beginning of the experiment (16 trials). The whole experiment duration was approximately one hour.

Analysis. We performed two analyses in agreement with our preregistration. For the purpose of analysis, we collapsed data across the factor cue side and analyzed sensitivity as the dependent measure. This resulted in a 2 (context locations: same, change) x 4 (configuration: global, relevant, irrelevant, no) repeated-measures ANOVA with the dependent measure sensitivity.

Second, we calculated a reduced 2 (context locations: same & change) x 2 (configuration: relevant & irrelevant) repeated-measures ANOVA with the dependent measure sensitivity. We compared location change detection performance to investigate the role of contextual objects in relevant and irrelevant configurations. Trials with response times exceeding 10 seconds were removed before the analysis (0.29%).

Results and Discussion

All of the analyses had been preregistered. We performed a repeated measures ANOVA with the dependent variable sensitivity (d’) and the independent variables context locations and spatial configuration. There was a significant main effect for context locations, F (1, 55) = 39.79, $p < .001$, $\eta_p^2 = .42$ and no significant main effect for configuration, F (3, 165) = 1.59, $p = .194$, $\eta_p^2 = .03$. There was a significant interaction effect, F (3, 165) = 26.17, $p < .001$, $\eta_p^2 = .32$. We further investigated the interaction effect with t-tests. This revealed that the context location changes strongly influenced the result pattern. Whereas we replicated the reorganization of spatial configurations based on the retro cue without changes to the context locations (see Figure 4 and Table 4), changing the context locations reduced location change detection performance (see Figure 4 and Table 5). Thus, we further analyzed the influence of context location change on memory performance within each configuration condition. This revealed that presenting changed instead of the same context locations led to a lower memory performance for both the global configuration, t (55) = 9.42, $p < .001$, d = 1.26, and the relevant configuration, t (55) = 6.56, $p < .001$, d = 0.88. Manipulating the locations of the context did not affect location change detection performance for the irrelevant configurations, t (55) = 1.52, $p = .134$, d = 0.20. This is an interesting finding because it indicates that the spatial relations between the probed object and the non-probed objects rendered irrelevant by the retro cue were weakened to such a degree that they did not influence the memory performance for the probed object at all. In contrast, the manipulation of the context had similar effects for the global configuration and relevant configuration, indicating that the importance of the spatial relations between the probed object and the non-probed objects rendered relevant by the retro cue were strengthened to such a degree that they seemed to be the only inter-object relations affecting the memory performance for the probed object. Surprisingly, we observed a significant difference between the same and the changed context locations for the no configuration condition, t (55) = 2.37, $p = .021$, d = 0.32, despite them being identical to the observer (see Figure 3). Thus, this is likely a chance finding.

Table 4

P-Values – T-Tests for Configurations in Experiment 2a With Same Context Locations

Spatial Configuration	Global	Relevant	Irrelevant
Relevant	.291		
Irrelevant	<.001*	.002*	
No	<.001*	<.001*	.568

* statistically significant (*p* < .05)

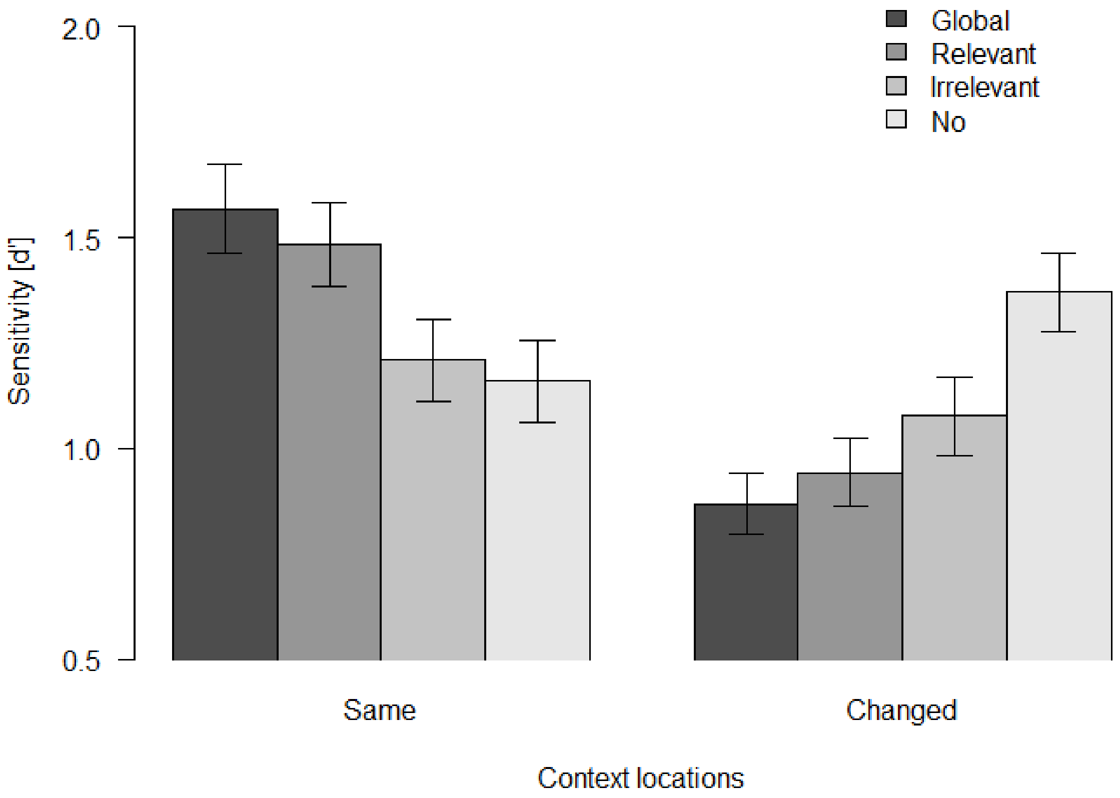


Figure 4 Sensitivity (d') Across All Participants for Experiment 2a

Error bars indicate the standard error of the mean (SEM)

Table 5

P-Values – T-Tests for Configurations in Experiment 2a With Changed Context Locations

Spatial Configuration	Global	Relevant	Irrelevant
Relevant	.323		
Irrelevant	.016*	.116	
No	<.001*	<.001*	<.001*

* statistically significant ($p < .05$)

We also performed the preregistered reduced repeated measures ANOVA with the dependent variable sensitivity (d') and the independent variables context locations (same/change) and spatial configuration (relevant/irrelevant). There was a significant main effect for context locations, F (1, 55) = 30.98, $p < .001$, $\eta_p^2 = .36$ and no significant main effect for configuration, F (1, 55) = 1.52, $p = .222$, $\eta_p^2 = .03$. There was a significant interaction effect, F (1, 55) = 11.77, $p = .001$, $\eta_p^2 = .18$. Thus, this reduced ANOVA delivered the same pattern of results and interpretation as the whole ANOVA reported above.

Experiment 2b

The results of Experiment 2a suggest that spatial inter-object relations are completely reorganized following a retro cue. While this was applied to displays only presenting the partially visible configurations, it is also important to understand how reorganization works within a global spatial configuration because relevant and irrelevant objects are normally still part of the configuration and do not disappear all of a sudden. Previous research has already pointed out that the number of objects visible at retrieval might in itself affect relational processing (Udale et al., 2018b). Thus, we investigated the role of contextual objects in a whole display by manipulating the locations of contextual objects at retrieval within the global configuration. Accordingly, the test displays either showed all of the objects or no configuration. When all objects were shown, we manipulated the locations of the contextual object within the global relevant or irrelevant configuration in order to deepen the understanding of the (re)organization of spatial configurations.

Method

We followed the method including sample size, experimental procedure, stimuli characteristics as well as the analysis as we had preregistered on OSF:

https://osf.io/496z5/?view_only=e14e4aee2279415baa09c1e7e2160a79 *[This is a private link for the review process only. We will make the project public once the manuscript has been accepted for publication]*

Participants. We used the same sample size as in Experiments 1 and 2a. Thirteen participants had to be replaced due to a performance level that did not deviate from chance, leading to the participation of 69 subjects but a final sample of 56 as previously appointed. The participants of the final sample had normal or corrected-to-normal vision and their age ranged from 19 to 34 years (M = 23.8, SD = 2.9, 8 male participants).

Materials. We used the same material as in Experiment 2a.

Procedure. Participants performed a location change detection task as in Experiment 2a. This time we manipulated context locations and configurations within a global configuration. We tested the five following test displays: (Global-) Same, Global-Change, Relevant-Change, Irrelevant-Change, no configuration (see Figure 5). As before, the cue was 100% informative; that is, the object probed at retrieval was always one of the objects indicated by the cue. Contextual objects with changed locations were presented in a new location on the same side of the display that was not occupied during encoding. We defined the configurations in the test display as follows:

- Same: All items from the encoding display were re-presented in the test display, with no changes of location for contextual items.

- Global-Change: All items from the encoding display were re-presented in the test display, with changes of location for all contextual items.

- Relevant-Change: All items from the encoding display were re-presented in the test display, with changes of location for the relevant contextual items.

- Irrelevant-Change: All items from the encoding display were re-presented in the test display, with changes of location for the irrelevant contextual items.

- No: Only the object probed was re-presented in the test display.

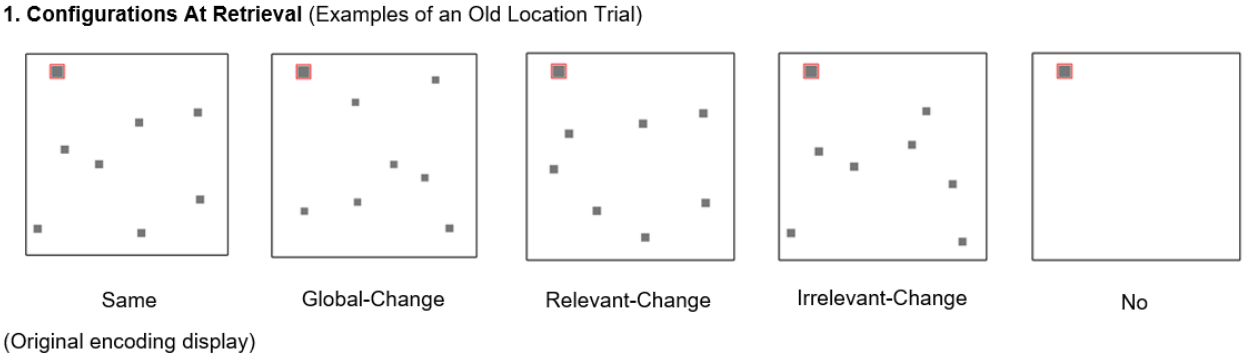


Figure 5 Manipulations at Retrieval for Experiment 2b (Example of an old location trial)

Trials were presented in randomized order with the restriction that the experiment consisted of five blocks containing 40 trials each leading to 200 trials in total. Each condition occurred equally often within each block and, thus, also within the whole experiment. Participants performed a practice block, containing four trials in randomized order (same/old, same/new, no/old, no/new), in the beginning of the experiment. The whole experiment duration was approximately 45 minutes.

Analysis. We followed the analysis in agreement with our preregistration. For the purpose of analysis, we collapsed the data across the factor cue side and analyzed sensitivity as the dependent measure. This resulted in a one-factorial (configuration: same, global-change, relevant-change, irrelevant-change, no) repeated-measures ANOVA with the dependent measure sensitivity. Trials with response times exceeding 10 seconds were removed before the analysis (0.06%).

Results and Discussion

All of the analyses had been preregistered. We performed a repeated measures ANOVA with the dependent variable sensitivity (d') and the independent variable spatial configurations. There was a significant main effect for configuration, *F* (4, 220) = 25.71, $p < .001$, $\eta_p^2 = .32$. We further investigated this main effect with t-tests (see Table 6).

Table 6

P-Values – T-Tests for Configurations in Experiment 2b

Spatial Config.	Same	Global-Change	Relevant-Change	Irrelevant-Change
Global-C	<.001*			
Relevant-C	<.001*	.753		
Irrelevant-C	<.001*	<.001*	<.001*	
No	<.001*	<.001*	<.001*	.608

* statistically significant ($p < .05$)

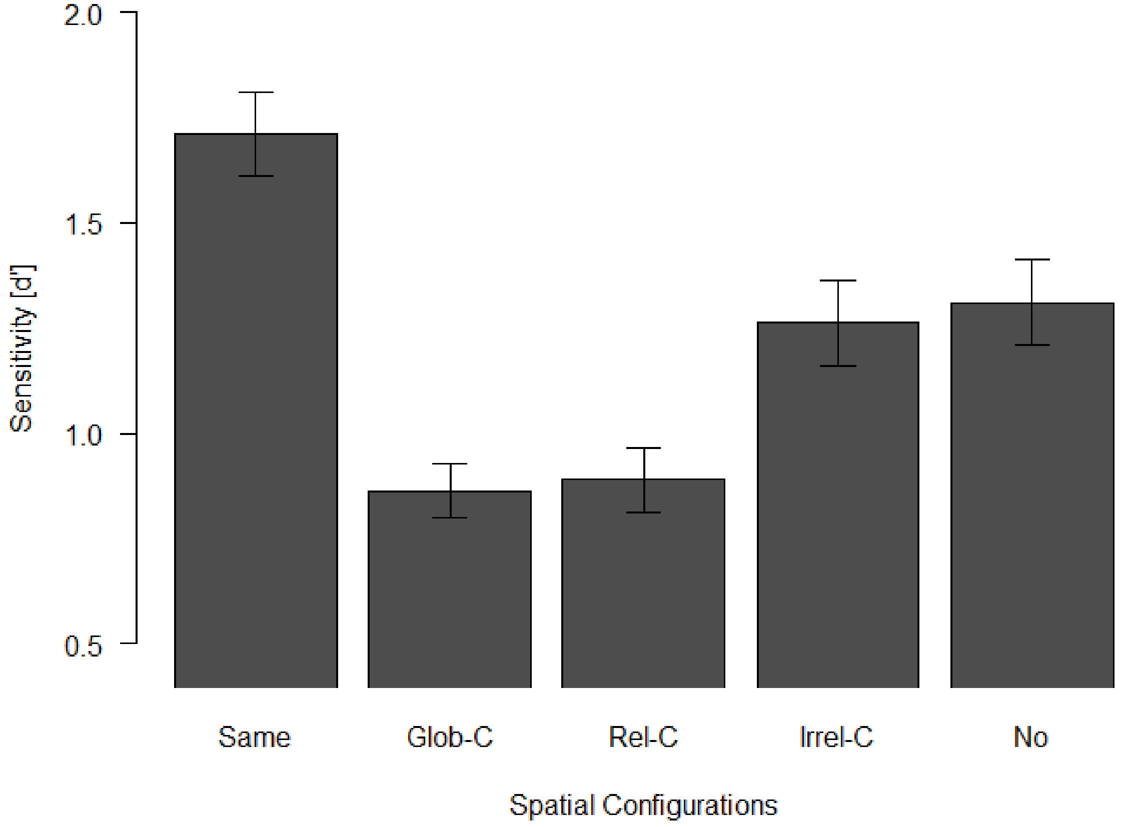


Figure 6 Sensitivity (d') Across All Participants for Experiment 2b

Error bars indicate the standard error of the mean (SEM)

In accordance with the assumption of VWM being organized based on spatial configurations, we again observed a global configuration effect (see Figure 6), namely, a higher memory performance with the global same configuration (same) than without a configuration (no). Importantly, changing all of the contextual objects (global-change) impaired memory performance to a similar degree as changing only the relevant objects within the global configuration (relevant-change). This is in line with our previous conclusion suggesting a complete reorganization of the relevant objects following a retro cue. Unexpectedly, changing the locations of the irrelevant objects within the global configuration (irrelevant-change) also impaired memory performance compared to the same global configuration condition, although the relevant objects as indicated by the retro cue remained on their same locations. If there was truly a complete reorganization, changing the irrelevant objects should not have impaired memory performance. Nonetheless, the memory performance for the irrelevant-change condition was still better than for the global-change and relevant-change conditions. We will further discuss the potential implications of this result pattern for the reorganization process in the General Discussion.

General Discussion

In the present paper, we performed three experiments investigating the reorganization of spatial configurations. First, we found that a retro cue is necessary to induce a reorganization of spatial configurations. Second, we investigated the role of contextual objects in reorganized spatial configurations by manipulating the locations of contextual objects at retrieval. This revealed two main findings. On the one hand, it seems that only the spatial relations between the relevant objects are retained following a reorganization of spatial configurations based on a retro cue in a partial display (Experiment 2a). This suggests a complete reorganization of the encoded global spatial configurations to the then relevant partial configuration in VWM. This was further supported by our finding that changing only the relevant objects within a global configuration impaired memory performance to the same degree as changing all objects within a global configuration (Experiment 2b). On the other hand, however, retaining the locations of the relevant objects and changing the locations of the irrelevant objects within the global configuration still impaired memory performance to a certain degree.

With this set of experiments, we intended to extend our understanding of the (re)organization of spatial configurations. A number of previous research studies indicates that VWM is organized based on spatial configuration both for basic objects and features (e.g. Jiang et al., 2000; Papenmeier et al., 2012; Papenmeier & Huff, 2014) as well as scene perception (Hollingworth, 2007; Klinghammer et al., 2015, 2017). We have added to this research by showing a stable memory advantage based on global spatial configurations across all our three experiments. More recent research has provided initial evidence that a reorganization of inter-object relations in VWM can occur for both locations and features (Bae & Luck, 2017; Timm & Papenmeier, 2019a, 2019b). Experiment 1 extends those findings by showing that reorganization is indeed triggered by the retro cue and not by an artifact of other influence factors such as distance. With Experiments 2a and 2b, we contribute to the understanding of how reorganization in VWM might occur by explicitly manipulating the locations of the contextual objects.

The participants could reorganize a global configuration into a relevant partial one (see Experiment 1) and changing the relevant objects but not the irrelevant objects at retrieval disrupted memory performance (see Experiment 2a). In Experiment 2b, changing the locations of the relevant context within a global configuration impaired performance to the same degree as changing the locations of all contextual items within the global configuration. This indicates that a global configuration is completely reorganized into the relevant configuration in VWM based on the retro cue. Therefore, one could have expected that a change of the irrelevant objects within a global configuration would not disrupt memory performance because the relevant objects still hold their positions. However, memory performance was impaired and rather comparable to the level of the no configuration condition. Nonetheless, performance in the irrelevant change condition was still higher than for the global change and relevant change conditions. This result pattern challenges a complete reorganization account. Retro cueing relevant and irrelevant objects leads to a change in attention, thus influencing memory representations and shielding cued objects against interference (Astle et al., 2012; Bae & Luck, 2017; Griffin & Nobre, 2003; Jiang et al., 2000; Kalogeropoulou et al., 2017; Makovski & Jiang, 2007; Timm & Papenmeier, 2019a, 2019b). Therefore, instead of removing the originally encoded global configuration from VWM due to reorganization, it might also be possible that the retro cue results in the formation of an additional spatial configuration based on the cued items in VWM. Explaining the results of Experiment 2b based on the existence of two configurations - namely, the originally encoded global spatial configuration and the relevant spatial configuration based on the retro cue - would then suggest that changing the global configuration or relevant configuration impaired performance to a larger degree than changing only the irrelevant configuration. This is because the former change provided contextual information disagreeing with both represented configurations, while the latter change provided contextual information disagreeing with only one represented configuration. Indeed, the idea that VWM could store two spatial configurations in parallel to each other is supported by previous research employing a modified object-reviewing paradigm (Hollingworth & Rasmussen, 2010). In their experiments, performance was supported not only by the spatial configuration updated through object motion but also the spatial configuration that was visible at object onset.

There are at least two ways in which directing attention with retro cues can influence memory performance. They can either result in the restructuring of memory representations by enhancing the cued objects and shielding them against interference (Astle et al., 2012; Griffin & Nobre, 2003; Makovski et al., 2008) or they can serve as a pre cue on where to direct attention on test display onset. Despite our experiments were not designed to distinguish between the two approaches, we discuss our results in the light of both approaches in the following. We designed our experiments in order to test the first approach, namely the reorganization of spatial configurations based on the retro cue. As is in line with this approach, we observed that a partial configuration consisting of relevant objects only supported memory performance only in the presence of the retro cue (Experiment 1) and that changing the cued contextual information impaired memory performance to the same extent as changing the complete configuration (Experiments 2a and 2b). We thus consider the reorganization of spatial configurations based on the retro cue as a plausible candidate for the explanation of our findings, in particular when considering that the originally encoded global spatial configuration is not replaced but rather supplemented by the cued partial configuration as we discussed in the previous paragraph. This idea is also in line with previous research because informative retro cues were already linked to the phenomenon that irrelevant objects remain a part of the memory representation because when former irrelevant configuration became unexpectedly relevant, it still benefitted memory performance (Kalogeropoulou et al., 2017). The second approach, namely that the retro cue acts as a pre cue for directing attention in the test display, can also explain some of our findings. That is, the uncued irrelevant configuration interfered with performance in the absence but not presence of a cue (Experiment 1). Further, changes to the uncued irrelevant configuration had a more limited effect on performance than changes in cued relevant or global configuration (Experiments 2a and 2b). However, this second approach cannot explain other findings. For example, performance in the no configuration condition was similar for both the presence and absence of the cue despite directing attention to the probed object should result in an increased performance following the pre cue account (Experiment 1). Further, changes to the uncued irrelevant configuration still led to a worse performance than the unchanged complete context in Experiment 2b. Thus, based on our present data we consider the reorganization account more likely than the pre cue account. Nonetheless, we urge for future research directly testing both accounts against each other in order to gain further insights in the representation (and flexibility) of spatial configurations in VWM.

We also investigated the influence of the participants' working memory capacity on the reorganization of spatial configuration in VWM. Several theories were proposed that include the dependency of VWM capacity and load on memory performance (Alvarez & Cavanagh, 2004; Dempere-Marco et al., 2012; Engle, 2002; Gurariy et al., 2016; Matsukura & Hollingworth, 2011; Öğmen et al., 2013; Palmer, 1990; Rolls et al., 2013; Turner & Engle, 1989; Udale et al., 2018a, 2018b; Vogel & Machizawa, 2004; Wilken & Ma, 2004). Our findings support these theories in general because there was a main effect of VWM capacity; thus, a reduced overall performance was linked to a lower VWM capacity. In contrast, the participants' working memory capacity did not interact with any of our manipulations, suggesting that VWM capacity influences neither the organization of VWM based on spatial configurations in general nor the reorganization of VWM based on the retro cue. This is also in line with previous research conducted in our lab (Timm & Papenmeier, 2019a, 2019b), in which we found that the reorganization of spatial configurations in VWM is unaffected by set size.

Whereas our present findings as well as a number of previous research studies have consistently reported that the representation of object location is based on spatial configurations in VWM (Jiang et al., 2000, 2004; Papenmeier et al., 2012; Papenmeier & Huff, 2014), there is still a debate being conducted to what degree and under which conditions object features such as color, orientation, or shapes are also represented based on the spatial layout of the respective objects (Udale et al., 2017, 2018a, 2018b). Irrespective the question whether features are bound to locations, there is evidence that inter-object relations are important for the representation of object features, for example, in the form of the representation of a structural gist (Vidal et al., 2005). According to the structural gist account, the concept of VWM being organized into multiple parallel feature stores (Wheeler & Treisman, 2002) should be extended to include the representation of relational information within each feature dimension, such as information about all colors or all shapes being visible in a display. If VWM is indeed organized to store not only object locations based on spatial configurations but also object features based on respective feature configurations, this raises the important questions as to whether both the organization of inter-object relations and the reorganization of inter-object relations as triggered by a retro cue is governed by similar or even a common mechanism(s) for locations and features. On the one hand, there might indeed be similar mechanisms involved because manipulating contextual information within the same dimension causes similar impairments for feature change detection (Vidal et al., 2005) and location change detection (Jiang et al., 2000). Further, for both features (Udale et al., 2017, 2018a, 2018b; Vidal et al., 2005) and locations (Bateman et al., 2018), reduced memory performance cannot be explained by an increase in decision noise due to changed contextual information. On the other hand, selective attention during encoding seems to have different effects on both the formation of spatial configuration and the formation of feature relations; that is, whereas directing selective attention to a subset of relevant objects during encoding results in the formation of a spatial configuration including only the attended objects (Timm & Papenmeier, 2019a), all features within a display seem to enter the relational information within the respective feature dimension irrespective of selective attention during encoding (Vidal et al., 2005). Further, studies from the related research area on ensemble perception demonstrated the existence of separate and independent high-level (such as average facial expression) and low-level (such as color) ensemble representations (Haberman et al., 2015). Thus, it is certainly possible that also spatial relations and feature relations are governed by separate mechanisms.

Conclusion

In the present paper, we have reported three experiments investigating the reorganization of spatial configurations in VWM. In the first experiment, we demonstrated that participants reorganized a global configuration into a relevant partial one only if a spatial retro cue shifted attention to the relevant part during maintenance. By manipulating the locations of the contextual objects at retrieval for both partial displays (Experiment 2a) and whole displays (Experiment 2b), we demonstrated a strong influence of the contextual objects rendered relevant by the retro cue on location change performance. Interestingly, when we changed the locations of the irrelevant objects within a whole display, thus retaining the locations of the relevant objects, location change detection performance was also impaired, however, to a lesser degree. Based on these results, we suggest that the reorganization of spatial configurations based on a retro cue should not be considered as a complete reorganization rendering the originally encoded spatial configuration ineffective. Rather, we suggest the alternative view that the retro cues cause the formation of a new partial spatial configuration based on the objects that became relevant by the retro cue in addition to the originally encoded global spatial configuration with both configurations affecting memory performance at retrieval.

Acknowledgments

We would like to thank Selina Galefski and Nele Vagt for their help during data collection.

Funding

This research project was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project number 357136437

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Appendix

Table A1

Proportion correct across all experiments

Condition	Spatial Configuration	Proportion correct *M (SE)*
Experiment 1	Global	.80 (.01)
With Cue	Relevant	.80 (.01)
	Irrelevant	.73 (.01)
	No	.73 (.01)
Experiment 1	Global	.78 (.01)
Without Cue	Relevant	.76 (.01)
	Irrelevant	.69 (.01)
	No	.73 (.01)
Experiment 2a	Global	.75 (.01)
Same Context	Relevant	.74 (.01)
	Irrelevant	.71 (.01)
	No	.70 (.02)
Experiment 2a	Global	.65 (.01)
Changed Context	Relevant	.66 (.01)
	Irrelevant	.68 (.01)
	No	.73 (.01)
Experiment 2b	Same	.77 (.01)
	Global-Change	.65 (.01)
	Relevant-Change	.66 (.01)
	Irrelevant-Change	.71 (.01)
	No	.72 (.01)

Proportion correct results. In the following, we report the analysis of our data with proportion correct (see Table A1) instead of sensitivity as dependent variable. This analysis was not preregistered and is thus exploratory. For Experiment 1, there was a significant main effect for cue presence, F (1, 55) = 10.69, p = .002, η_p^2 = .16, a significant main effect for configuration, F (3, 165) = 31.73, p < .001, η_p^2 = .37, and a non-significant interaction effect, F (3, 165) = 1.71, p = .168, η_p^2 = .03. For Experiment 2a, there was a significant main effect for context locations, F (1, 55) = 35.66, p < .001, η_p^2 = .39, a non-significant main effect for configuration, F (3, 165) = 2.07, p = .106, η_p^2 = .04, and a significant interaction effect, F (3, 165) = 21.69, p < .001, η_p^2 = .28. For Experiment 2b, there was a significant main effect for configuration, F (4, 220) = 22.47, p < .001, η_p^2 = .29.

4. Timm, J.D. & Papenmeier, F. (under review). *Processing spatial configurations in visual working memory is boosted by shifts of overt visual attention.*

Processing spatial configurations in visual working memory
is boosted by shifts of overt visual attention

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Word count abstract: 235/250

Word count text: 4505

Abstract

When memorizing multiple objects, humans process them in relation to each other, proposing a configuration benefit. Shifts in overt visual attention through eye movements might influence the processing of spatial configurations. Whereas some research suggests that overt visual attention aids the processing of spatial representations, other research suggests a snapshot-like processing of spatial configurations, thus likely not relying on eye movements. In the first experiment, we focused on the comparison between an enforced fixation and a free view condition regarding configurational effects. Participants encoded objects' locations and were asked for changes at retrieval. One object was displaced in half of the trials and was either accompanied by a configuration or was displayed alone. In the second experiment, we expanded this idea by enforcing fixation during different task phases, namely encoding, maintenance and retrieval. We investigated if a fixed gaze during one specific phase drives the influence of eye movements when processing spatial configurations. We observed reliable configuration benefits for the free view conditions. Whereas a fixed gaze throughout the whole trial reduced the effect, enforced fixations during the task phases did not break the configuration benefit. Our findings suggest that whereas the processing of spatial configurations in memory is boosted by the ability of performing shifts of overt visual attention, configurational processing does not rely on these shifts occurring throughout the task. Our results indicate a reciprocal relationship of visual working memory and eye movements.

Keywords: Eye movements, spatial configurations, visual working memory, overt visual attention, trans-saccadic memory

Introduction

Single objects are remembered together with their surrounding objects in visual working memory (VWM), which is called a spatial configuration benefit (Jiang et al., 2000). Thus, a change of an object location is detected more easily, when the probed object is accompanied by the objects maintained in parallel than when the probed objects is shown alone at retrieval. Even when participants are instructed to memorize multiple single objects individually, the global spatial configuration of all encoded objects is processed automatically (Jiang et al., 2000; Papenmeier et al., 2012). Rendering a part of this global configuration relevant by a retro cue during maintenance results in similar configuration benefits for the relevant partial configurations (Timm & Papenmeier, 2019a, 2019b, 2020). Configuration benefits are not only limited to featureless objects (Jiang et al., 2000; Papenmeier et al., 2012) but also arise with natural stimuli (Hollingworth, 2007; Papenmeier & Huff, 2014). While it is well established that spatial configurations are represented in VWM, the conditions causing their representation are still not well understood. With the present research, we addressed this issue by studying the influence of eye-movements on the representation of spatial configurations in VWM.

The performance and programming of saccadic eye-movements is strongly interconnected with visual attention and visual working memory. For example, performing a saccadic eye-movement to one location inevitably causes the direction of covert visual attention to the very same location making it impossible to saccade to one target but to attend to another target (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). In a similar manner, limited working memory resources are directed towards saccade targets improving the precision of their representation in VWM (Bays & Husain, 2008), with some research postulating that shifts in overt visual attention determine the composition of VWM contents (Ohl & Rolfs, 2017). Vice versa, shifts of overt visual attention by means of saccadic eye-movements require an operating memory store for target selection, the maintenance of information across saccades, object correspondence, or gaze correction (Van der Stigchel & Hollingworth, 2018). While the strong interconnection between saccadic eye-movements and VWM has been shown for the representation of single objects, we extend this research by focusing on the relation between eye-movements and the representation of spatial configurations.

Regarding the representation of inter-object relations in VWM, two competing accounts explaining the storage and processing of spatial configurations in VWM can be identified in the literature. One account assumes a rather rigid, snapshot-like, representation of spatial configurations in VWM whereas the other account assumes a more flexible representation.

The snapshot account is based on the observation that only the global spatial configuration of all encoded objects but not a partial spatial configuration of a subset of encoded objects results in a memory benefit (Jiang et al., 2000; Papenmeier et al., 2012) and this snapshot might be represented in a separate view-dependent snapshot store in VWM that is also used for spatial navigation (Papenmeier et al., 2012; Wood, 2011). This idea fits with the finding that spatial configurations are represented in a view-dependent manner with configuration benefits disappearing when viewpoint changes of 30 or 60 degrees between encoding and retrieval are introduced (Papenmeier & Huff, 2014). Further, location change detection is impaired by changes to task-irrelevant features that destroy the perceptual grouping of the memorized objects (Jiang et al., 2004).

The flexible account suggests that spatial configurations are stored interdependently in VWM. It is based on the idea that the representation of inter-object relations such as summary statistics (mean color or location across individual object representations) might result from a hierarchical representation of features in VWM with individual objects being organized in higher order hierarchical clusters (Brady & Alvarez, 2011; Brady & Tenenbaum, 2013; Orhan & Jacobs, 2013; Papenmeier & Timm, 2020). This more flexible account is in accordance with recent findings showing that the influence of inter-objects relations on memory representations can be manipulated by shifting visual attention with retro cues during maintenance and thus after encoding has already been completed. This accounts for both the representation of object features such as orientation (Bae & Luck, 2017) and object locations as represented in spatial configurations (Timm & Papenmeier, 2019a, 2019b, 2020). Regarding the latter, it was shown that the presentation of valid retro cues during encoding caused a reorganization of spatial configurations to the relevant probed one (Timm & Papenmeier, 2019a, 2019b, 2020).

Whereas the snapshot account suggests a rather holistic representation of spatial configurations, the flexible account emphasizes the role of individual objects as nodes for the higher-order representations. Applying both accounts to the potential role of eye-movements on the representation of spatial configurations in VWM, on might predict that eye-movements are rather unimportant or even harmful for the representation of spatial configurations based on the snapshot account. Based on the flexible account, in contrast, one might predict that eye-movements and thus the shift of overt (and covert) attention might have a strong influence on the representation of individual objects and thus potentially also their inter-object relations. There is some initial evidence supporting both views. In accordance with the former view, the implicit learning of spatial configurations within the contextual cueing paradigm is not only possible but even superior without eye-movements than with eye-movements (Higuchi & Saiki, 2017). In support of the latter view, an experiment that was designed to test the influence of retro cues and set-size on the reorganization of spatial configurations but that also manipulated eye-movements observed a configuration benefit for the group of participants allowed to perform eye-movements freely but not for the other group of participants being enforced to maintain fixation (Timm & Papenmeier, 2019a).

With the present set of two experiments we aimed at further investigating the role of eye-movements for the encoding of spatial configurations in VWM. We did so by manipulating eye-movements within-participants rather than between-participants (Timm & Papenmeier, 2019a) providing a stronger test of whether eye-movements rather than other random cognitive differences across groups of participants drive the encoding of spatial configurations. Further, we manipulated eye-movements in a fine-grained manner such as the encoding, maintenance and retrieval phase in Experiment 2 in order to shed light on the interrelation of eye-movement performance and the representation of spatial configurations in VWM.

Experiment 1

With this experiment, we investigated the influence of shifts of overt visual attention on the processing of spatial configurations in VWM. Therefore, we manipulated whether participants had to maintain fixation or whether there were allowed to perform eye-movements freely and measured the benefit of the presence of configurational information during retrieval on memory performance in a location change detection task.

Method

We performed the method including sample size and analyses as we had preregistered on OSF: https://osf.io/gw7v5.

Participants. We used the R-Package powerbydesign (Papenmeier, 2016) to conduct a power analysis based on our previous experiments (Timm & Papenmeier, 2019a, 2019b). Our goal was to obtain at least a power of .90 at the standard of .05 alpha error probability. This led to a sample size of 56. Participants were invited for this experiment receiving course credit or monetary compensation. We paid 2€/15 min. We preregistered the following exclusion criteria: Participants identified as not doing the task (pressing always the same button or a performance level that does not deviate from chance) were supposed to be removed from the data set and replaced by new participants as well as any participants not completing the whole experiment. Eight participants had to be replaced due to a performance level that did not deviate from chance. Participants had normal or corrected-to-normal vision and their age ranged from 18 to 31 years (*M* = 23.9 years, *SD* = 3.3 years). Up to two participants were tested at the same time on different laptop computers. Simultaneous testing and monetary compensation were consistent throughout all experiments. The research was conducted in accordance with APA standards for ethical treatment of participants and with approval of the institutional review board of the University of Tübingen. All participants provided written informed consent.

Materials. We presented eight grey squares (RGB color hex code: #777777) on a 15.6” computer screen (Dell Precision M4800) using an SMI iView RED250 mobile eye tracker to record eye movements with a sampling rate of 250 Hz. The experiment was programmed with PsychoPy 1.85.6 (Peirce et al., 2019). Each square measured 0.8° x 0.8° (degrees of visual angle). The objects could appear in a 18° x 18° centered array. A fixation cross (0.5° x 0.5°) was presented in the center of this array. We generated random object locations for each trial with a minimum center-to-center distance of twice the diameter of a square and with a minimum distance to the center of the array of once the diameter of a square. Participants’ heads were positioned in a chin rest.

Procedure. Participants performed a location change detection task (see Figure 1). During encoding all objects were shown for 2000 ms. Then a maintenance phase of 2000 ms followed with no objects visible. At retrieval objects reappeared either with a configuration (complete) or without configuration (single) and one object was marked by a red outline (RGB color hex code: #FF0000). We manipulated the position of the object probed at retrieval (new/old). Participants had to press the respective keyboard button (1/9) to indicate whether the object probed changed its location or not.

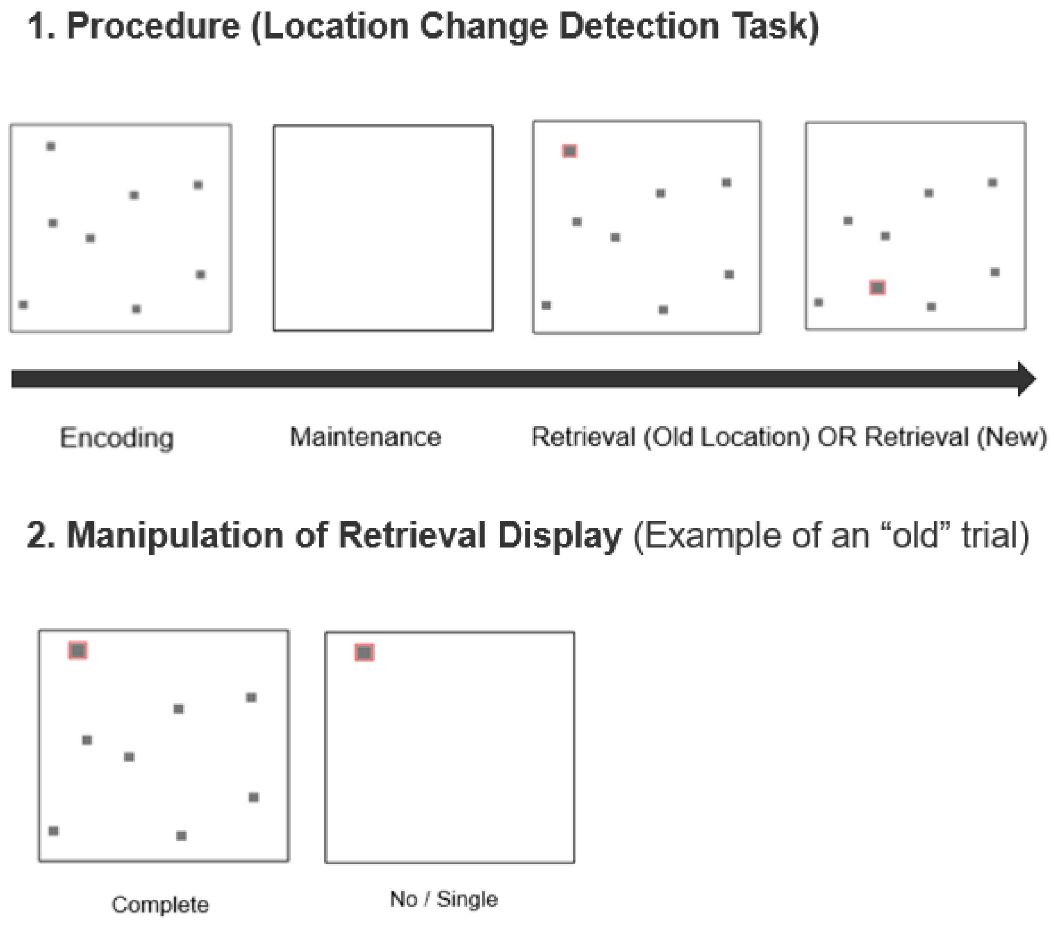

Figure 1 Location Change Detection Task

Note that the fixation cross is not displayed in this figure for illustrative purposes.

Trials were presented in randomized order with the restriction that the experiment consisted of two blocks containing 80 trials each leading to 160 trials in total. One block was performed without any restrictions regarding eye movements while the other block was performed with a fixed gaze. Participants started each trial with fixating the centric cross for 250 ms, which was visible across the whole trial. If participants did not hold the fixation throughout the trial in the enforced fixation condition, the trial was aborted and repeated at the end of the block. In detail, if gaze samples were recorded outside of an invisible surrounding circle with a radius of 1.5° around the centric cross for more than 250 ms, the respective enforced fixation trial was aborted and repeated at the end of the block. We counterbalanced the block order leading to one group of participants with a first block of free view and a subsequent block with a fixed gaze and vice versa for the other half of the participants. Each other condition occurred equally often within each block and, thus, also within the whole experiment. Participants performed an eye movement specific practice block, containing one trial per possible condition (4 trials), in the beginning of the experiment depending on the eye movement condition (with/without). In the beginning of the second block, another practice block was done, containing the other eye movement condition. Participants were not aware of a change in the possibility of shifting overt visual attention until that second practice block occurred. The whole experiment duration was approximately 45 minutes.

Results and Discussion

The data and the analysis can be obtained from https://osf.io/rqejx/. We performed the analyses in accordance with our preregistration. We calculated sensitivity (according to signal detection theory) as dependent measure across the responses to the old and new probe location trials (Stanislaw & Todorov, 1999). Sensitivity d' is defined as $d' = \Phi^{-1}(phits) - \Phi^{-1}(pfa)$ with phits being the proportion of hits and pfa being the proportion of false alarms (Stanislaw & Todorov, 1999). Hits refer to the accurate detection of old locations, and false alarms refer to responding “old” to a new location. Note that sensitivity cannot be calculated for either phits or pfa having values of 0.0 and 1.0. Thus, we corrected such values to the proportions equaling half a trial correct or half a trial incorrect respectively. Trials with response times exceeding 10 seconds were removed before the analysis (0.08%).

First, we compared location change detection performance as indicated by the sensitivity measure across conditions using a 2 (eye movements: free view, fixation; within) x 2 (configuration: global, single; within) repeated-measures ANOVA (see Figure 2). Importantly, there was a significant interaction effect of eye movements and spatial configuration, F (1, 55) = 7.32, p = .009, η_p^2 = .12. That is, the configuration benefit was stronger for the free view trials than for the trials with enforced fixation. This suggests that the ability of planning and performing shifts of overt visual attention by eye movements boosts the processing of spatial configurations. Furthermore, there was a significant main effect for eye movements F (1, 55) = 15.75, p < .001, η_p^2 = .22 and a significant main effect for configuration, F (1, 55) = 44.25, p < .001, η_p^2 = .45. Due to the interaction effect, we further investigated the conditions with t-tests (see Table 1). Second, in order to investigate the influence of block order, we performed an additional exploratory mixed ANOVA with the factors eye movements (free view, fixation; within), configuration (global, single; within) as well as the group factor block order (fixation/free view, free view/fixation; between). The main effects of spatial configuration, F (1, 54) = 43.92, p < .001, η_p^2 = .45, and eye movements, F (1, 54) = 15.66, p < .001, η_p^2 = .22, as well as their interaction, F (1, 54) = 7.41, p = .009, η_p^2 = .12, remained significant. Importantly, neither the main effect of block order, F (1, 54) = 0.51, p = .479, η_p^2 = .01, nor any interaction effect including block order, all F (1, 54)s ≤ 1.68, ps ≥ .201, were significant. Therefore, block order did not influence our results.

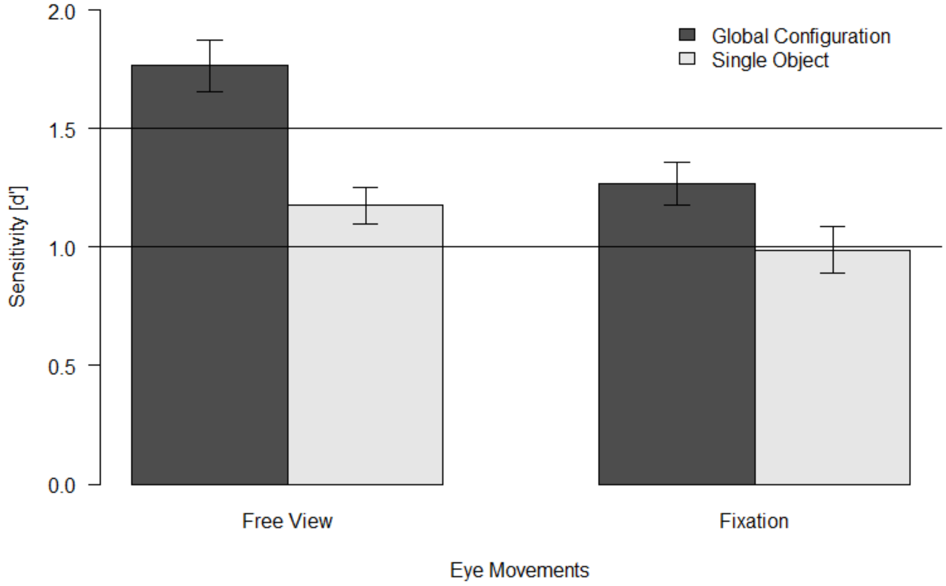

Figure 2 Sensitivity (d’) across conditions for Experiment 1

Error bars indicate the standard error of the mean (SEM)

Table 1

p-values – t-tests for configurations in Experiment 1 across conditions

Eye Movements		Free View		Fixed Gaze
		Global	Single	Global
Free View	Single	< .001*	---	---
Fixed Gaze	Global	< .001*	. 364	---
	Single	< .001*	.088	.003*

* statistically significant (p < .05)

Third, we compared fixation and saccade parameters between hit and false alarm trials in the free view condition (see Table 2 in the Appendix). We used the high-speed event-detection algorithm provided by the IDF Event Detector (SMI, Version 3.0.20) with the following detection parameters: minimum duration of 22 ms, peak velocity threshold of 40°/s, and a minimum fixation duration of 50 ms. This analysis included all trials for which a maximum of 20% of the gaze samples were flagged as invalid by the eye-tracker and also all trials with a response time lower than 10 s (93.39% of all trials included in this analysis). There was no significant difference between hit and false alarm trials in the number of fixations, *t*(55) = -0.63, *p* = .530, the frequency of fixations (number of fixations divided by trial duration), *t*(54) = 0.82, *p* = .417, saccade amplitudes, *t*(54) = 0.44, *p* = .661, nor the number of saccades, *t*(55) = -0.16, *p* = .873.

To summarize, while there were no significant differences in the eye-movement parameters in the free view condition, the overall ability in performing eye-movements (as compared with enforced fixations) had a significant effect on the processing of spatial configuration. Thus, the ability of performing eye movements boosted the processing of spatial configurations in VWM.

Experiment 2

With our first experiment, we investigated the influence of overt visual attention on the processing of spatial configurations in VWM. As predicted, the configuration benefit was stronger in the free view trials than with enforced fixation. What remained unresolved, however, was whether it was the general ability in performing free shifts of overt visual attention or rather the free distribution of overt visual attention during specific task phase, such as during encoding, maintenance, or retrieval, that boosted the processing of spatial configurations. Previous research suggests that eye-movements during specific phases, such as during maintenance (Williams et al., 2013), might aid memory performance. That is, participants tend to move their eye to previously encoded locations during maintenance, and holding attention on the fixation cross during maintenance reduces memory performance (Williams et al., 2013). Therefore, in contrast to Experiment 1, we did not enforce fixation throughout the whole trial in our Experiment 2, but we rather enforced fixation only during specific phase (i.e. encoding, maintenance, retrieval). By doing so, we investigated whether enforcing fixation in just one of the three phases might be enough to reduce the configuration benefit as compared with a free view condition.

Method

We performed the method including sample size and analyses as we had preregistered on OSF: https://osf.io/vsfzk.

Participants. We increased the desired sample size to 60 participants, because this allowed us to counterbalance block order across participants. We preregistered the following exclusion criteria: Participants identified as not doing the task (pressing always the same button or a performance level that does not deviate from chance) were supposed to be removed from the data set and replaced by new participants as well as any participants not completing the whole experiment. Nine participants had to be replaced due to a performance level that did not deviate from chance in the baseline condition. Participants had normal or corrected-to-normal vision and their age ranged from 19 to 36 years (*M* = 24.2 years, *SD* = 4.0 years). All participants provided written informed consent.

Materials. We used the same materials with a 15.6” computer screen (Dell Precision M4800) and an SMI iView RED250 mobile eye tracker to record eye movements with a sampling rate of 250 Hz.

Procedure. Participants performed the same location change detection task as in Experiment 1. Thus, participants again started each trial with fixating the centric cross for 250 ms, which was visible across the whole trial. We manipulated the possibility of performing eye movements. Participants performed a free view condition as in Experiment 1 (baseline) as well as three conditions in which they had to maintain fixation in one of the three task phases (encoding, maintenance, retrieval). For example, participants had to fixate the center of the screen during encoding and then had to free view during maintenance and retrieval. All participants performed the baseline condition as the first experimental block. The three fixation conditions were presented counterbalanced across participants. We controlled that participants fixated the centric cross in the respective phase and that they looked away from the fixation cross at least once for each free view phase forcing a saccade. If participants did not hold the fixation throughout the specific fixation phase, the trial was paused, and the screen turned black with a red cross (#FF0000). Participants were instructed that a red color of the cross indicates they had to regain the fixation and if executed, the trial was continued. The trial was paused when the fixation loss exceeded 100 ms. To avoid that participants fixated the center throughout the whole trial, we applied the same logic the other way around to the respective free view phases. If participants fixated the centric cross at the beginning of each free view phase for longer than 300 ms, the trial was paused, and the screen turned black with a blue cross (#0000FF). Participants were instructed that a blue color of the cross indicates they had to move their eyes away from the cross and if executed, the trial was continued. The whole experiment duration was approximately 60 minutes.

Results and Discussion

The data and the analysis can be obtained from https://osf.io/h5yng/. We performed the analyses in accordance with our preregistration. We calculated sensitivity (according to signal detection theory) as in Experiment 1. Trials with response times exceeding 10 seconds were removed before the analysis (1.77%).

First, we compared location change detection performance as indicated by the sensitivity measure across conditions using a 2 (configuration: global, single; within) x 4 (fixation phase: baseline, encoding, maintenance, retrieval; within) repeated-measures ANOVA. Strikingly, we did not observe a significant interaction of eye movement condition and configuration, F (3, 177) = 1.26, p = .288, η_p^2 = .02 (see Figure 3). Thus, enforcing fixation during specific task phases was not enough to reduce the configuration benefit as compared with the free view condition. This suggests that it is rather the general ability of planning and performing shifts of overt visual attention by eye movements that boosts the processing of spatial configurations in VWM (see Experiment 1) than the performance of eye movements during specific task phases (present experiment). Furthermore, there were significant main effects for fixation phase, F (3, 177) = 25.91, p < .001, η_p^2 = .31, and configuration, F (1, 59) = 94.24, p < .001, η_p^2 = .61.

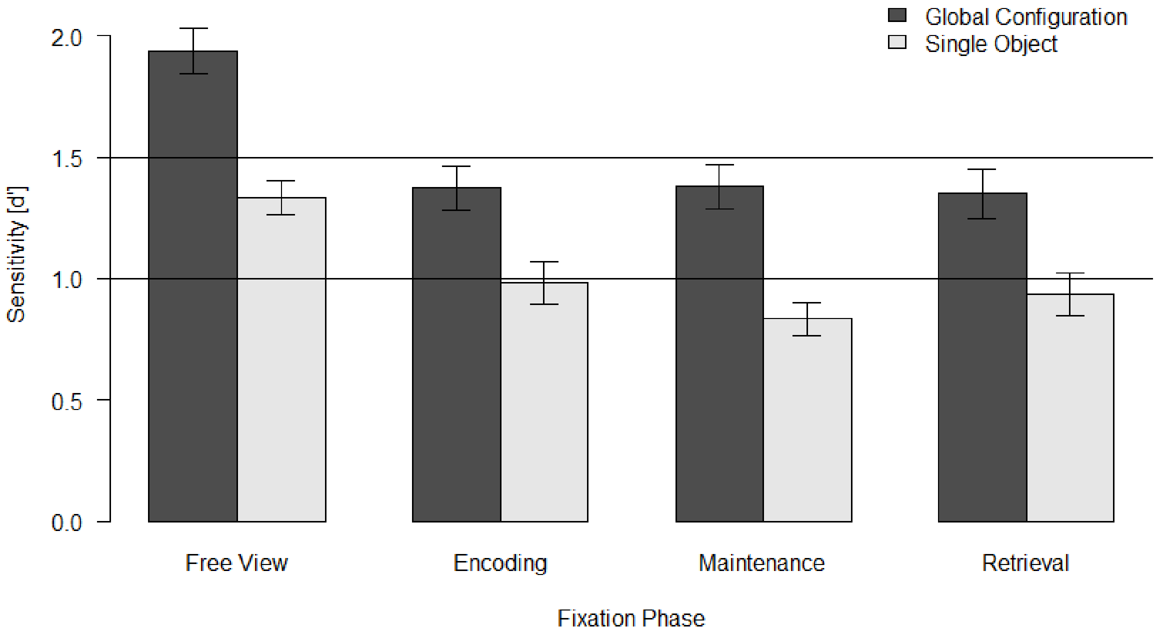

Figure 3 Sensitivity (d’) across conditions for Experiment 2

Error bars indicate the standard error of the mean (SEM)

Second, we compared fixation and saccade parameters between hit and false alarm trials in the free view condition (see Table 2 in the Appendix). This analysis included all trials for which a maximum of 20% of the gaze samples were flagged as invalid by the eye-tracker and also all trials with a response time lower than 10 s (93.31% of all trials included in this analysis). There was no significant difference between hit and false alarm trials in the number of fixations, $t(59) = -1.16$, $p = .252$, the frequency of fixations (number of fixations divided by trial duration), $t(59) = 1.12$, $p = .265$, saccade amplitudes, $t(58) = -1.41$, $p = .163$, nor the number of saccades, $t(59) = -0.87$, $p = .386$.

General discussion

We conducted two experiments investigating the influence of overt visual attention on the processing of spatial configurations in VWM. As a proxy for the processing of spatial configurations, we used the well-documented configuration benefit, namely the higher performance in the detection of location changes of single objects under the presence of all encoded objects (i.e. spatial configuration) than the object probed alone (Jiang et al., 2000; Papenmeier et al., 2012; Timm & Papenmeier, 2019a). We implemented three eye-movement conditions: free view, enforced fixation throughout the trial, and enforced fixation during specific task phases (i.e. encoding, maintenance, retrieval). In our experiments, we observed that the possibility of performing eye movements boosted the configuration benefit. Interestingly, the processing of spatial configurations was reduced only in the condition that enforced fixation throughout the whole trial but not in conditions enforcing fixation during specific phases. That is, whereas configurational processing is boosted by the performance of eye-movements, it does not rely on eye-movements occurring throughout a trial.

We identified two competing accounts regarding the processing of spatial configurations in VWM in the literature, namely the snapshot account, which assumes a rather rigid, snapshot-like, representation of spatial configurations in VWM (Papenmeier & Huff, 2014; Wood, 2011), and the flexible account, which focuses on hierarchical representations in VWM with objects being organized in higher order hierarchical clusters (Brady & Alvarez, 2011; Brady & Tenenbaum, 2013; Orhan & Jacobs, 2013). Whereas shifting overt visual attention with eye-movements should impair the processing of spatial configurations based on the snapshot account (Higuchi & Saiki, 2017; Papenmeier & Huff, 2014), the performance of eye-movements might support the representation of individual objects (Bays & Husain, 2008; Deubel & Schneider, 1996; Hoffman

& Subramaniam, 1995), and as a consequence also inter-object relations and spatial configurations based on the flexible account. Our results support the latter view, namely that eye-movements boost rather than hinder the processing of spatial configurations. Thereby, our results support the flexible account, namely that spatial configurations are represented rather in the form of hierarchical representations based on the individual object representations than within a separate snapshot storage. The conclusion that spatial configurations are represented in a flexible form rather than as a rigid snapshot is also in line with recent evidence demonstrating that the representation of spatial configurations in VWM can be updated based on retro cues and thus after encoding has already been completed (Timm & Papenmeier, 2019a, 2019b, 2020).

For individual objects, previous research suggests a strong relationship between overt visual attention, covert visual attention, and VWM (Bays et al., 2009; Bays & Husain, 2008; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kalogeropoulou et al., 2017; Ohl & Rolfs, 2017). More specific, the performance of eye movements towards objects is associated with respective shifts in covered visual attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995) as well as the allocation of VWM resources (Bays & Husain, 2008). Vice versa, VWM is an important component of the eye movement system (Van der Stigchel & Hollingworth, 2018). While most of the previous research investigated VWM processes of single objects and their features, our results provide evidence for the role of eye-movements when processing inter-object relations in the form of spatial configurations in VWM.

To our knowledge, this is the first study, which shows that limited non-availability of overt visual attention with regard to processing spatial configurations can be compensated via VWM. That is, only enforcing fixation throughout a trial caused a significant reduction in the processing of spatial configurations. If the eyes were enforced to fixate during specific phases (i.e. encoding, maintenance, retrieval) only and free to move during the rest of a trial, no reduction in the configuration benefit was observed. Thus, eye movements do not boost the processing of spatial configuration during either encoding, maintenance, or retrieval. Rather, it seems that single movements of the eyes might be sufficient to trigger the observed boost in configurational processing. While it is up to future research to identify the specific process underlying this boost, we speculate that processes related to trans-saccadic memory (TSM) and its interplay with VWM might be involved. Based on TSM, observers establish correspondence between pre-saccadic and post-saccadic information, and TSM capacity is larger than or equal to VWM capacity (Kleene & Michel, 2018). Therefore, it seems possible that TSM draws on inter-object relations such as spatial configurations, thereby also informing VWM representations.

Our results are also consistent with previous research that demonstrated decreased change detection performance when participants were prevented from executing saccades to the object locations of interest due to enforced fixation (Williams et al., 2013). That is, we also observed that overall change detection performance decreased in all conditions that introduced enforced fixations, no matter whether fixation was enforced throughout a trial or at specific task phases. Importantly however, only the complete enforcement but not partial enforcement of fixations caused a reduction in the processing of spatial configurations. Thus, being able to perform eye movements during at least some phases of a trial boosts the processing of spatial configurations. It is important to note, however, that we observed a configuration benefit in all conditions. That is, even in conditions with enforced fixation throughout a trial, location change detection performance for single objects did benefit from the presence of the global spatial configuration of all encoded objects during retrieval. That is, despite this configuration benefit being lower with enforced fixations, it was still present. This suggests that observers also process spatial configurations without eye movements. This configurational processing is, thus, boosted by eye movements but it does not depend on eye movements.

Conclusion

Participants utilized the ability of performing shifts of overt visual attention by eye movements to increase their memory performance. Experiment 1 demonstrated that eye movements boost the configurational processing of object locations in memory. Whereas participants in Experiment 2 showed a lower overall performance in the conditions containing phases of enforced fixation, the size of the configuration benefit was similar across conditions. Thus, whereas the ability of performing shifts of overt visual attention by eye movements boosts the processing of spatial configurations, this configurational processing does not rely on these shifts occurring throughout the task.

Acknowledgments

The Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) funded this research project, project number 357136437. We would like to thank Selina Galefski and Nele Vagt for their help during data collection and Lisa Widmayer for contributing further data preparation.

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Appendix

Table 2

Eye movement parameter means (SD) of the free view conditions for Experiments 1 and 2

Visual parameter	Hit trials	False alarm trials
Number of fixations (E1)	8.56 (4.21)	8.70 (4.17)
Frequency of fixations (E1)	1.54 (0.69)	1.51 (0.68)
Number of saccades (E1)	7.44 (4.52)	7.47 (4.33)
Saccade amplitude* (E1)	258.82 (71.34)	255.58 (77.57)
Number of fixations (E2)	9.16 (3.99)	9.42 (4.57)
Frequency of fixations (E2)	1.63 (0.68)	1.60 (0.72)
Number of saccades (E2)	8.00 (3.80)	8.18 (4.37)
Saccade amplitude* (E2)	199.88 (39.60)	204.38 (36.51)

* in pixel