Influence of Context Change on Spatial Updating in a Structured Real Environment

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Contents

1 Abstract

1.1 English Abstract

Navigational tasks can be reliably performed by humans even if there is no perceptual information available for a short amount of time. This is possible because of the cognitive process called *spatial updating*. An egocentric view of the position of an object near the observer can be held in spatial working memory after perceptual information ceases. This egocentric transient spatial representation (*spatial image*) can then be dynamically updated in relation to the observer's self-movement. Proprioceptive and vestibular information is utilized to update the object's location and thus enables appropriate navigation "in the dark". This process takes place in spatial working memory. Studies on working memory have found that a spatial context change (e.g. walking through a doorway) can cause a decline in working memory. The logical conclusion that a spatial context change may also have an influence on processes in spatial working memory (e.g. on spatial updating) has barely been studied thus far. This research paper seeks to fill this void by investigating whether a statistically significant influence of context change on spatial updating can be found. It was largely a replication study of Blessing's (2016) experiment. He had found a strong trend in his data, supporting the possible existence of such an influence of context change. Despite the trend, his results failed to show a statistical significance, which is why this study was conducted to validate or contradict the previous findings. The experiment was administered in the real structured environment of a testing room set-up. Fifteen participants each underwent two subsequent run-throughs of the experiment. Both times they learned the location of four picture cards in a circular arrangement in the testing room (a different picture set was used for each run-through). These run-throughs were differentiated by the walking phase following the picture card learning. In a condition without context change, the walkway remained within the testing room (*internal condition*). The other condition provided a context change in form of a walkway that lead out of the testing room, down a small hallway and back into the room through a second door (*external condition*). After both conditions, participants were blindfolded and given a virtual reality controller. The objects on the previously learned cards were named in a randomized order and the participants used the VR-controller to point at the position they believed the card to be in. This was done in two phases: Phase I didn't include rotations (minimal amount of spatial updating necessary). Phase II required the participants to rotate around their own axis in both directions (high amount of spatial updating necessary). The participant's angle deviation from the actual object location was calculated from participant's reported object location angle (captured by the controller). The hypothesis was that the context change condition would lead to an increase in *response time* and *pointing angle deviation*.

Against expectations no statistically significant influence or strong effect of condition was found on either of the variables. The data of both studies, primary literature and the experimental design itself were examined. The findings reveal that the conducted experiment is based on a plethora of vague assumptions, leading to the conclusion that the present experiment is not sufficient to exclude the possibility of an influence of context change on spatial updating. Possible optimizations are given and further research on the matter is imperative.

1.2 German Abstract

Menschen können Navigationsaufgaben auch dann zuverlässig ausführen, wenn kurzzeitig keine perzeptuellen Informationen vorliegen. Dies wird durch den kognitiven Prozess der *Positionsfortschreibung* (engl. *spatial updating*) ermöglicht. Die egozentrische Perspektive des Standortes eines Gegenstandes wird hierbei im Arbeitsgedächtnis des Beobachters gehalten. Diese egozentrische, transiente Repräsentation (engl. *spatial image*) kann dann in Relation zur Eigenbewegung des Beobachters dynamisch fortgeschrieben werden. Propriozeptive und vestibuläre Information wird genutzt, um den Standort des Objektes fortzuschreiben und so eine adäquate Bewegung „im Dunkeln" zu ermöglichen. Dieser Prozess findet im räumlichen Arbeitsgedächtnis statt. Studien zum Arbeitsgedächtnis zeigten, dass ein räumlicher Kontextwechsel (z.B. durch einen Türrahmen treten) ein Nachlassen des Arbeitsgedächtnisses zur Folge haben kann. Die logische Folgerung, dass ein räumlicher Kontextwechsel auch einen Einfluss auf Prozesse im räumlichen Arbeitsgedächtnis haben könnte ist bisher allerdings kaum untersucht worden. Die vorliegende Arbeit füllt diese Lücke nun durch die Untersuchung des Einflusses von Kontextwechsel auf Positionsfortschreibung. Es handelte sich hierbei vorwiegend um eine Replikation der Studie von Blessing (2016). Diese fand einen starken Trend, der für die Existenz eines solchen Einflusses sprach, doch trotz des Trends konnte sie keine statistische Signifikanz nachweisen. Die vorliegende Arbeit suchte also die vorangegangenen Ergebnisse zu validieren oder anzufechten. Das Experiment wurde in der realen, strukturierten Umgebung eines Versuchsraumes durch- geführt. Fünfzehn Teilnehmer nahmen jeweils an zwei Durchläufen teil. In beiden Durchläufen prägten sie sich den Standort der vier Bildkarten ein, die innerhalb des Raumes in einem Kreis angeordnet waren (unterschiedliche Bilder Sets). Die Durchläufe unterschieden sich voneinander durch eine Laufphase, die auf das einprägen der Karten folgte. In der Kondition ohne Kontextwechsel verblieb der Laufweg im Versuchsraum (*interne Kondition*). Die andere Kondition enthielt einen Kontextwechsel, da der Laufweg aus dem Versuchsraum hinaus, einen Gang entlang und durch eine zweite Türe wieder in den Raum führte (*externe Kondition*). Nach beiden Laufkonditionen wurden den Teilnehmern die Augen verbunden und ein virtual-reality-Kontroller gereicht. Die Objekte auf den zuvor gelernten Karten wurden in einer zufälligen Reihenfolge genannt und die Teilnehmer zeigten mit dem Kontroller auf die Position an der sie den genannten Gegenstand glaubten. Dies wurde in zwei Phasen gegliedert: Phase I beinhaltete keine Rotation (minimale Positionsfortschreibung). Phase II verlangte bidirektionale Rotation um die eigene Achse (erhöhte Positionsfortschreibung). Durch den angegebenen Winkel wurde die Winkelabweichung (Winkelfehler) zum realen Objektstandort berechnet. Es wurde postuliert, dass die Kondition mit Kontextwechsel zu einer Erhöhung in *Reaktionszeit* und *Winkelfehler* führen würde.

Entgegen der Erwartung wurde kein statistisch signifikanter Einfluss des Kontextwechsels auf die Variablen gefunden. Die Daten der Versuche, Primärliteratur und das experimentelle Design wurden untersucht. Das Untersuchungsergebnis offenbarte, dass das durchgeführte Experiment auf der Grundlage zahlreicher vager Annahmen beruhte und führte zur Schlussfolgerung, dass das vorliegende Experiment nicht ausreichte um einen möglichen Einflusses von Kontextwechsel auf die Positionsfortschreibung auszuschließen. Mögliche Verbesserungen werden vorgeschlagen und weitere Untersuchungen sind unabdingbar.

2 Introduction

Driving to work, weaving through store aisles, or finding home in the dark. Humans cannot survive without navigating and interacting with their environment, making functional spatial cognition essential. Especially on a larger spatial scale, the ability to find a way to an out-of-sight destination is a crucial aspect of sustaining human life. This is made possible by the ability to form, manipulate and recall spatial memories. However, not all processes of spatial cognition require memory formation and even within the processes that do, the underlying neural mechanisms are not defined as a singular process, but rather as the accumulation of several independent processes in various brain regions. These different processes require different types and amounts of memory performance (Mallot, 2012).

2.1 Processes in Spatial Cognition

Simple spatial processes, such as taxes, are an automatic like navigation of the environment. They are possible by solely using acute sensory information to adjust movement to maintain e.g. the balance of optical flow. This does not require the development or recruitment of a spatial memory (e.g. walking down a street "mindlessly") (Mallot, 2012).
More complex tasks of spatial cognition on the other hand require the formation and the access of a spatial working memory and/or spatial long-term memory. To navigate towards a distant destination, the recognition of beacons or guiding landmarks along the way or surrounding the destination is necessary. This demands the involvement of spatial long-term memory (Mallot, 2012). Other processes in spatial cognition that require the formation of a spatial long-term memory are *recognition-triggered response* behaviors (Trullier, Wiener, Berthoz, & Meyer, 1997) and the concept of *cognitive maps*. The former describes the process of route finding, where the recognition of a landmark is responded to by an appropriate movement. In this case both long-term and working-memory are involved in adding up a chain of landmarks and necessary movements to reach the destination. A *cognitive map* is a more complex form of spatial memory, where a network of locations is represented independently of one single location being the destination (Mallot, 2012).

2.2 Spatial Representation

The aforementioned processes are all crucial to a full functioning spatial cognition. However, the paper at hand is primarily concerned with the following processes which tend to rely more heavily on working memory formation. While a clear-cut distinction between long-term and working memory involvement in spatial processes is currently not possible, tendencies of involvement have been recognized and will be used with caution in this paper.

If an observer has to solve a navigational task but perceptual information is no longer available, mental spatial representation becomes pivotal. It enables coordination of an appropriate action to solve the task, by monitoring egocentric position. This egocentric transient spatial representation takes place in the working memory and is referred to as a *spatial image*. A spatial image is produced via input from the external surrounding, which can include auditory, visual, haptic or language stimuli, as well as recall from internal long-term memory. When stimulus and percept cease, the spatial image persists in working memory for a short amount of time. The spatial image corresponds to the percept, however, modality specific features (e.g. timbre in an auditory input) are transcended. After encoding, all following interactions with that image are independent of the source modality, suggesting a functional equivalence of all modalities. This leaves room for the discussion whether a spatial image is to be classified as multimodal or purely amodal. Regardless of one's position in the discussion, the modality most prevalent in spatial tasks is the visual one. Even advocates of functional equivalence have come to find that other modalities (e.g. auditory) lead to higher errors in spatial perception. Although visual input is the primary source of a spatial image, it is highly distinct from a *visual image*. A visual image is constantly fixed in the mind, irrespective of location, distance and locomotion of the imagining person (e.g. imagining a tree). Since visual images offer no information on the current surroundings of a person, this study focuses on spatial images. These images can be egocentrically updated with distance and direction information, causing different components of the spatial image to change according to relative parallax (e.g. imagining walking past a tree, including the accompanying changes in the image of the tree) (Loomis, Klatzky, & Giudice, 2013). A Spatial image is omnidirectional and can also be updated in all directions, even during rotations and translations (Farrell & Robertson, 1998). This spatial image makes appropriate motor action possible. It is independent of eye and head orientation, therefore it can operate without visual input for a short time period (Land, 2012).

2.3 Updating of Spatial Representations

Since spatial images are of a transient nature, transformation of the image is possible through four different processes. These are differentiated by the role of objects in the process as well as by the nature of the movement (actual physical movement versus imagined movement).

2.3.1 Path Integration

As an observer moves through a spatial environment a constant update of the observer's egocentric position information takes place. Facilitated by several sensory systems such as the vestibular, proprioceptive or optical system, all incoming information is integrated and stored in the working memory. Here it can be summed up over time to form a spatial image of the observer's location in reference to the starting point of the observer's journey. This process is called *path integration* (Figure 1). This spatial image update enables the observer to return to the starting point via the shortest way possible, independent of landmark ques. This process requires minimal memory effort, since only the one vector from current position to starting point (*home vector*) needs to be held in working memory (Mallot, 2012).

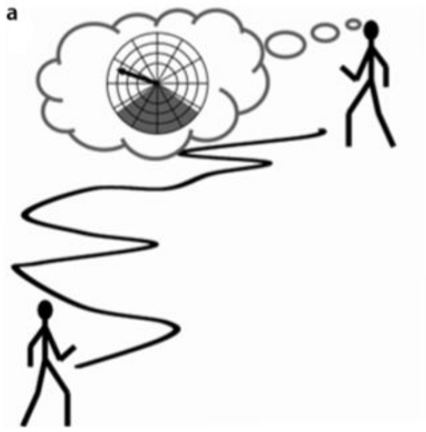

Figure 1: Working memory performance during path integration. The home vector is constantly updated in an egocentric coordinate system. The middle of the polar coordinate system represents the observer's position; The top represents the line of sight and the grey area the environment behind the observer (from Mallot, 2012).

2.3.2 Spatial Updating

A spatial image can also be updated in reference to the observer's environment. This is necessary to ensure that the perceived world remains consistent with the real world (Land, 2012). In this case, the location of objects is updated in relation to the observer's movement, even without visual input. This constant updating is based on the incoming proprioceptive and vestibular information caused by the observer's self-movement (Farrell & Robertson, 1998; Land,2012). This registered change in translational and/or rotational movement is then used to update the location and orientation of target locations surrounding the observer. This process is called *spatial updating* (Figure 2) (Loomis et al., 2013; Mallot, 2012). Just as spatial images are omnidirectional, spatial updating has been shown to be omnidirectional, allowing an updating of object locations in a 360° radius around the observer (Horn & Loomis, 2004). In case of spatial updating during rotational movement (Figure 3) the location of an object (big black dot) must be updated relative to the head. However, if only the relative position of object to head was considered, the position signal sent to the head would be wrong (Figure 3B, open circle). Therefore, the object representation onto E must counter-rotate to the head as the head rotates (Figure 3B) to maintain a consistent relationship with the environment (Land, 2012). Although special images are usually used in the context of working memory, bi-directional processing between working memory and long-term memory representations for spatial content have been found. A spatial representation can be transferred to long-term storage through spatial learning. This information can later be retrieved and help form a spatial image in working memory. That image can then be subject to spatial updating again. Therefore, spatial updating can indirectly influence information in long-term memory. Although the intermittent storage in long-term memory can cause a decline in precision of the memory of the target object location. Spatial images in the context of spatial updating seem to be unaffected by the number of locations saved in memory (Loomis et al., 2013).

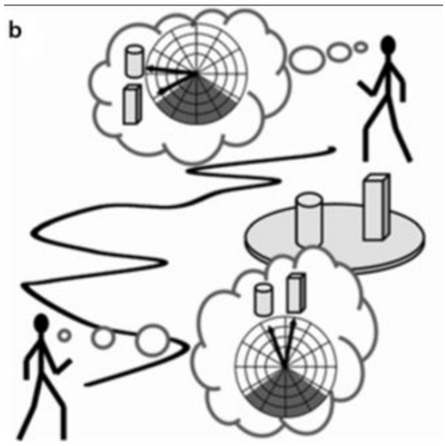

Figure 2: Working memory performance during spatial updating. The position of objects is updated in reference to the movement of the observer (from Mallot, 2012).

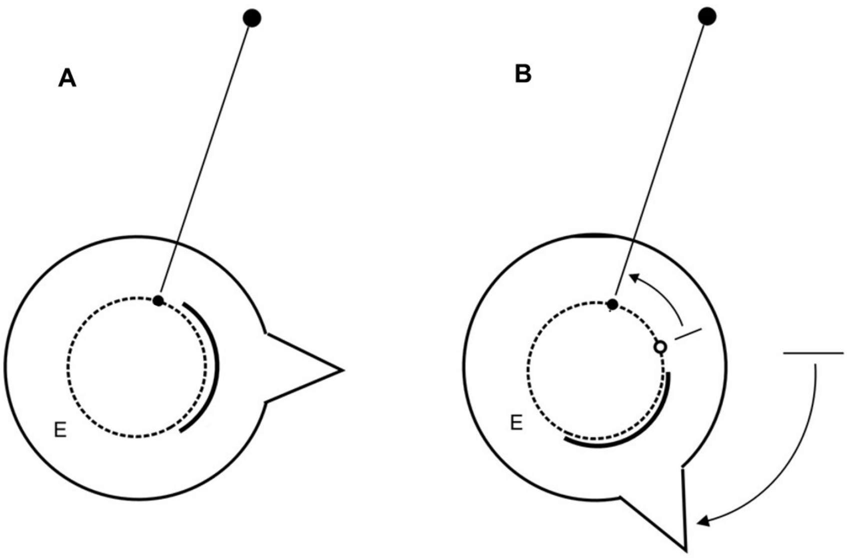

Figure 3: Representation of the location of a target object (black dot) in egocentric spatial memory (dotted line E). Original position in A and after rotation in B (Adapted and simplified from Land, 2012).

2.3.3 Perspective Taking and Mental Rotation

Spatial updating can also be self-induced on a mental basis by an observer. This can be done by either *perspective taking* (Figure 4) or *mental rotation* (Figure 5). Both exercises do not involve actual movement of the observer, but utilize imagined spatial transformations. During perspective taking the observer imagines his own physical movement and the resulting update of location and perspective of the objects relative to the new position. During mental rotation the object is mentally rotated and the update of object location and perspective relative to egocentric location is registered (Mallot, 2012).

Figure 4: Working memory performance during perspective taking. The observer imagines movement of self and the corresponding update of object location (from Mallot, 2012)

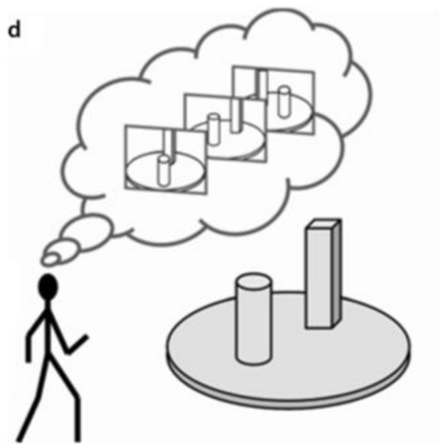

Figure 5: Working memory performance during mental rotation. The observer imagines movement of objects and the corresponding update of egocentric perspective change (from Mallot, 2012)

2.4 Previous Research on Spatial Updating

All four presented processes are important for the egocentric updating using a spatial image. The process of spatial updating, however, is of specific interest, since knowing the actual location of objects in the environment is key to survival (Land, 2012). Spatial updating thus enables actions to be in alignment with the environment (Farrell & Robertson, 1998).

Several spatial updating studies (eg. Rieser, 1989) operate on the premise that even with lack of visual input, the connection between spatial updating and the motor system for pointing remains functional during full-body rotation (Land, 2012). One such study conducted by Farrell and Robertson in 1998 represents a classical research paradigm for a spatial updating study and is of special interest to the paper at hand for two reasons:
i) The results show that the observer's egocentric reference frame is automatically aligned with their new position. This indicates that spatial updating is an automatically occurring

process. ii) The basic methodology and procedure are a useful basis for spatial updating paradigms and can be adapted according to modern technology and research standards.
The basic principle of such experiments is the following. In a testing room subjects were seated on a rotating chair in the middle of a circular arrangement of e.g. seven common objects. They underwent a training period, in which they learned the location of the objects from their central position. This learning was controlled by blindfolding the participant while facing one of the seven possible directions. The participant was then asked to point to a target-object's location and the response (pointing) accuracy was revealed. This was repeated for all possible directions. In the following actual testing phase four conditions were introduced. All conditions take place after facing the participants toward one of the objects and blindfolding them:
Updating: The participant was rotated to face a different object and then asked to point to the location of a target-object from this new orientation.
Imagination: The participant wasn't moved, but instead instructed to imagine facing a new object. Then he was asked to point to a target-object from the new, imagined orientation.
Ignoring: The participant was rotated to face a different direction, but asked to ignore the movement and point to a target-object as if he hadn't been moved.
Control: The participant was rotated in one direction and then back to their original starting orientation. He was then asked to point to a target object location from this orientation.
Comparisons were made to identify an effect of the conditions on an angular error. Such an error indicates how far the participant's guess of a target-object location was off from the true target-object location. Furthermore, the effect of each condition on response latency was measured. The relevant results and their interpretation are summarized as follows.
Effect of conditions on angular error: Angular errors were higher in imagination and ignoring tasks than in control and updating conditions. Therefore, the participants must have had difficulties in discerning the actual location of the target-object, if they had to imagine the movement. This indicates, that an update of the spatial image automatically takes place as the participant is turning, explaining why the updating task showed a low angular error.
Effect of rotation magnitude on angular error for different conditions: In line with previous findings of a similar paradigm (Rieser, 1989), no correlation between rotation magnitude and angular error was found for control and updating conditions. Since spatial updating is not influenced by rotation magnitude, it appears to be occurring instantaneously and not post-hoc to the movement. In contrast, rotation magnitude caused higher angular error in imagination and ignoring conditions. This is indicative of a need to actively induce spatial updating in those conditions.
Effect of conditions on response latency: Response latency was significantly higher after the imagination and ignoring tasks, while there was no significant difference in latency between updating and control. This means that the test subjects required additional time to actively override or induce spatial updating when their actual orientation didn't coincide with the orientation they were supposed to make a location judgment from. All these findings indicate, that spatial updating is an automatically occurring process (Farrell & Robertson, 1998).

Current studies on spatial and location updating still utilize similar paradigms of circular object arrangement around a study subject usually in combination with pointing and angle error as an indicator of the degree of object location memory (eg. Avraamides, Galati, & Papadopoulou, 2013). Hereby updating performance is not dependent on whether the observer rotates actively by self-initiated motion or is passively rotated. The vestibular and proprioceptive input, which are the same in both conditions, appear to be of higher relevancy for spatial updating than outgoing motor commands or a lack thereof (Wraga, Creem-Regehr, & Proffitt, 2004).

Beyond studying the observable effects of spatial updating, one study focused on the underlying spatial representation systems. Two different spatial representations have been identified: the online, transient and dynamic spatial representation system and the offline and enduring memory representation system. Waller and Hodgson (2006) compared the two systems and examined the circumstances under which one system is employed over the other. They used the previously discovered disorientation effect in their study. This effect states that an increase in disorientation of a study subject results in an increase of angular error when the subject is then asked to estimate the direction of a target without visual input. The underlying idea was that disorientation may cause "a switch from a relatively precise online representation to a relatively coarse enduring one" (Waller & Hodgson, 2006, p.867). They conducted four experiments which yielded results supporting their hypothesis. They first confirmed that both representations systems participate in mediating the interaction with the environment in a disorientation situation. They then showed that the enduring spatial representation system is less precise than the transient, online one. They tested and confirmed that self-rotation of the observer, of as small as 135 degrees, could lead to a similar switch between the two systems as disorientation. Lastly, they focused on the type of change from one system to the other, deeming it a discrete "switch", not a gradual transition. Overall, their results indicate that the egocentric, dynamic spatial representation system takes effect in regulating orientation in situations where the observer is well oriented and in interaction with the surroundings. This system operates in real-time and is largely reliant on visual input and self-motion registration. Yet, it can remain intact without visual input for a short time period by utilizing other modalities, which makes it important in situations employing working memory. In light of spatial updating, this is the system that tracks the updating of spatial relations between observer and objects in the surrounding environment. Therefore, this system has been the focus of most of the previous research on spatial updating. Waller and Hodgson (2006) call this the "online" form of spatial updating. The second spatial representation system is also viewed in light of spatial updating. Experiments show that a switch is made to the second, offline and enduring memory representation system, if no current information about the environment is available or is unreliable, for example due to disorientation or self-motion (self-rotation). This system is anchored in long-term memory and remains stable over time while offline, at the cost of precision. Assuming this "switch" actually takes place would have major implications on the idea of spatial updating. It would indicate that a second form of spatial updating, an "offline" form, exists. It would be responsible for enduring representations, causing spatial reconstruction processes when disorientation sets in. A switch back to the online system seems possible, if visual input is restored and an interaction with the environment is required again. In summary, "an egocentric system tracks relationships in one's immediate environment, and an enduring memory system enables retrieval of spatial relations offline" (Waller & Hodgson, 2006, p.22).

Looking at the interaction between the two systems, the study offered indications for both a seamless hand-off as well as for an interference of the egocentric system on judgments mediated by the enduring system. Whereby this influence was only observed in context of perspective taking, spatial updating tasks showed a pattern of distinct switching between the two systems (Waller & Hodgson, 2006).

2.5 Influence of Spatial Context Change on Memory for Objects

The importance of spatial updating has been discussed, which is largely associated with working memory, where the spatial relation of objects to an observer is held and updated. These spatial relations aren't the only influencing factor on (spatial) memory however. One of the most important influencing factors is the movement of the observer through space, whereby this movement can be seen as a continuum of spatial events or contexts which the observer changes or instantly shifts into by e.g. going into a new room. Several studies have shown a relationship between such a spatial shift (*context change*) of an observer in experienced space and a decrease in performance ability (e.g. speaking and reading slower; slower information retrieval). In 2006, a study was conducted to determine the influence of such a spatial shift on the ability to access information about objects the test subjects had recently encountered. A series of experiments was conducted on participants moving through rooms in a virtual environment. In Experiment 1, participants moved from one room to the next while carrying a (virtual) object. This object was to be set down on a table and replaced by a new object which was then to be carried to the next room and so on. When an object was picked up, it disappeared, leaving no visual reminder. At different points in time, the participants were probed via appearance of an object on screen. They were asked to respond "yes" if this was an object they were currently carrying (associated), or had just set down (disassociated) or "no" for other objects (negative probes). Results showed a quicker response time and less error when the object was associated than when it was disassociated. A correlation analysis linked the effect to difficulties in retrieving information about disassociated objects and not to problems in retaining information about the associated object. The error in retrieving information about associated object was significantly higher, if the participants had undergone a spatial shift. The cause of this effect couldn't conclusively be explained by this experiment alone. It was either due to the degree of association of an object or a spatial shift. Experiment 2 offers answers for this uncertainty. The same paradigm was used, specifically probing the participants either after undergoing a spatial shift (going into another room) or after walking across a large room (no spatial shift). The spatial distance travelled was the same in both scenarios (although spatial distance has been shown to play a minimal role compared to spatial shifts). The same effect of association/disassociation as in Experiment 1 was seen. More importantly, there was a significantly longer response time in recognizing associated objects after spatial shift conditions than after no-shift conditions. The average error rate for associated objects was also significantly increased after spatial shifts versus non-shift situations.

In general, the results of the study show that the spatial and relational characteristics of a dynamic situation are continuously registered by humans and that this in turn influences the availability of information in memory. Memory of an object with which an observer has a functional interaction is more easily retrieved than of non-associated objects. Especially for those associated objects, they repeatedly found a significant influence of spatial shifts on information retrieval and cognitive processing (Radvansky & Copeland, 2006).

The observed compromise in memory for associated objects due to location change is referred to as *location updating effect*. It is believed that this effect is indirectly due to the observer moving through doorways, since this causes an update of the spatial relations of entities in the new location (context). Information that is still relevant for the new context is retained while information that seems to only be relevant to the previous context is removed. Yet, it is to be noted that the memory of associated objects is not fixed to a specific context, since reentering the context the object was last seen/learned in doesn't enhance performance (Radvansky & Copeland, 2006; Radvansky, Krawietz, & Tamplin, 2011; Radvansky, Tamplin, & Krawietz, 2010). This is consistent with the idea of movement along a continuum of context or event changes, rather than just being tied to time-locked locations. Previous findings on the effect of context change (often referred to as *event boundaries*) on memory in non-spatial contexts seem to support the theory of the locations updating effect (eg. Speer & Zacks, 2005; Swallow, Zacks, & Abrams, 2009). However, some findings raise concern that results of studies on the effect could be falsified, if the nature of the probe task is different from the nature of the task context (Swallow et al., 2009). This discrepancy is present when probe task instructions focus on conceptual qualities (e.g. verbal labels of objects), while the actual task concentrates on perceptual qualities (e.g. pictures of the objects). To clarify, it was investigated how dependent the location updating effect is on the degree to which the information in the memory probe is integrated into the environmental context. A very similar paradigm to Radvansky and Copeland (2006) was used, also featuring *no-shift* and *shift* conditions and probing on associated, disassociated and negative objects. Two experiments were aimed to either increase or decrease the degree to which the probed-for information was embedded in the context of the situation the observer was in. In Experiment 1, the information of the probes was more (visual) or less (verbal) embedded in the ongoing event. The results yielded no significant difference in error rate for either type of probe task, meaning the nature of the cue was irrelevant to how well it was remembered by the participants. Consistent with previous findings, they found a significant increase in error rate and response latency in spatial shift conditions compared to non-shift conditions. In Experiment 2, participants were given information with a lower degree of environmental integration alongside the formerly used objects and verbal memory cues. This was done in the form of nonsensical word pairs (e.g. ethnic cake), which were also probed for after shift or no-shift scenarios. The word pairs were contextually not embedded in the situation. Results showed that the error rate, indicative of forgetting, was significantly increased in context change conditions for both word pairs and objects.

It can be concluded, that an increase in forgetting as a result of context change (location updating effect) is independent of the information's degree of embedment in the situational environment (Radvansky et al., 2010).

The effect has also been deemed independent of the observer's immersion in the environment. This was tested by reducing the observer's immersion (smaller display) and then by increasing it via immersing participants in a real-world environment instead of a virtual one. The location updating effect on memory has thus been validated both in real-world and virtual-world conditions (Radvansky et al., 2011).

2.6 Influence of Spatial Context Change on Spatial Updating

Spatial context change appears to be a major influence in the retrieval of information from working memory. While this is true for several memory tasks, the location updating effect has been reliably observed as the decreased ability to remember objects one has recently interacted with, after undergoing a context shift (e.g. walking through a doorway). Remembering or forgetting of an object last seen in another room cannot be detached of a spatial component. If an object is forgotten, the memory for the object-location will most likely also be decreased. Therefore, location updating must in some form influence spatial memory, particularly in a situation where visual input of the object is unobtainable. Following this logic, a spatial context change should therefore also affect the mental spatial representation which has previously been referred to as *spatial image*. One must be reminded that the process responsible for updating the spatial image in reference to the location of objects in the observer's environment was introduced as *spatial updating*. To close the circle of logic, one must therefore assume that a context change, in form of walking through a doorway, has an influence on spatial updating.
Despite the important implications for spatial updating posed by the location updating effect, surprisingly, only very little research has been done on the matter.
Blessing (2016) tested this hypothesis in a paradigm similar to Farrell and Robertson's (1998) and despite not finding a statistically significant effect of context change on spatial updating in a structured environment, he found a strong trend indicating the existance of such an effect. More specifically, he found that participants that had left the testing room by walking through a doorway (so had undergone a context change) and then reentered the room were significantly worse at remembering the location of the objects than those that had remained in the testing room. He tested this by analyzing the angular errors of participant's guesses of target-object location versus actual target-object location. As objects he used picture cards which and he determined the angular error by having the participants point at the objects with a virtual reality controller. To produce both within and between subject data two testing conditions were determined: in the *internal* condition the study participants would undergo the entire experiment and a walking phase in the testing room. The *external* condition differed in the walking phase, in which the participants would briefly leave the testing room.

The goal of the study at hand is to further investigate Blessing's findings with a higher number of participants to validate or contradict a statistically significant influence of context change in a structured environment on spatial updating.

3 Materials and Methods

3.1 Participants

A total of 15 participants took part in the experiment, six males and nine females. All participants were students of the University of Tübingen or nursing students of the University Hospital Tübingen (UKT). All participants were between 19 and 25 years old and had naturally good or corrected vision. All participants were right handed, spoke German fluently (minimum C1 Level) and had no hearing impairments or other physical or ocular disabilities.

3.2 Experimental Set-up

The experiment was conducted in a windowless testing room with the scale of 6 m x 8.4 m. The room was left as bare as possible, eliminating any reflective surfaces and obstacles in the immediate testing space.
The visual images (i.e., pointing targets) chosen for this experiment were two picture sets of each four colored picture cards. According to the images used by Blessing (2016), two sets (set A and set B)) of four cards each were used (Figure 6). Each card was printed on thick square paper and had an edge length of 15.35 cm. The German object name was printed on the top center of each card. A red dot marked the center of each picture, indicating where the study participants should point. All selected object names had two syllables and were of similar semantic awareness, spatial dimension, perspective and art style (Clipart). Furthermore, the words were chosen to be semantically as far apart as possible, reducing the possibility of confusion during memorization.
The four cards of one picture set were each placed on a 1 m high post and arranged circularly in the testing room (Figure 7). The radius measured 2 m and the central point of the circle was marked. It was made sure that there was only one picture of each set per quadrant for maximum separation of the pictures. The positions of the picture sets mirrored each other to maintain a similar level of pointing difficulty and angle measurements for each set. The placement was set to avoid the four cardinal direction angles (0°, 90°, 180°, 270°) relative to the facing direction of the participants starting positions, since these pointing angles might be more easily recalled. Only one set of picture cards was set up at a time and randomly assigned to each participant (in the end, each set was used equally often within and between the two experimental conditions; see Attached Table 4).
The participants were directed to point at the objects using a hand-held wireless virtual reality controller (Figure 8: Flystick 2 by A.R.T. GmbH, Weilheim i.OB, Germany). The VR-controller was detected by six ceiling mounted motion tracking cameras in the testing room. The pointer position (3 degrees of freedom) and orientation (9 degrees of freedom) was recorded with 60 Hz by a tracking system (ART-track DTrack Recorder Version 1.24.7 by A.R.T. GmbH, Weilheim i.OB, Germany) and finally reported to a personal computer (Intel inside; operating system: Windows XP).
The participants were verbally instructed by the researcher which object to point at next. For the duration of the experiment the researcher always stood at the same spot while giving instructions verbally. Two of the six buttons on the pointer were used during the experiement

(Figure 8). The participants were asked to press Button 1 immediately upon hearing the instructions for the next pointing object, to measure response time. Button 2 functioned as the trigger and was pressed by participants when they had reached the pointing position they assumed the target object to be located in. The response time was defined as time between the two button-presses.

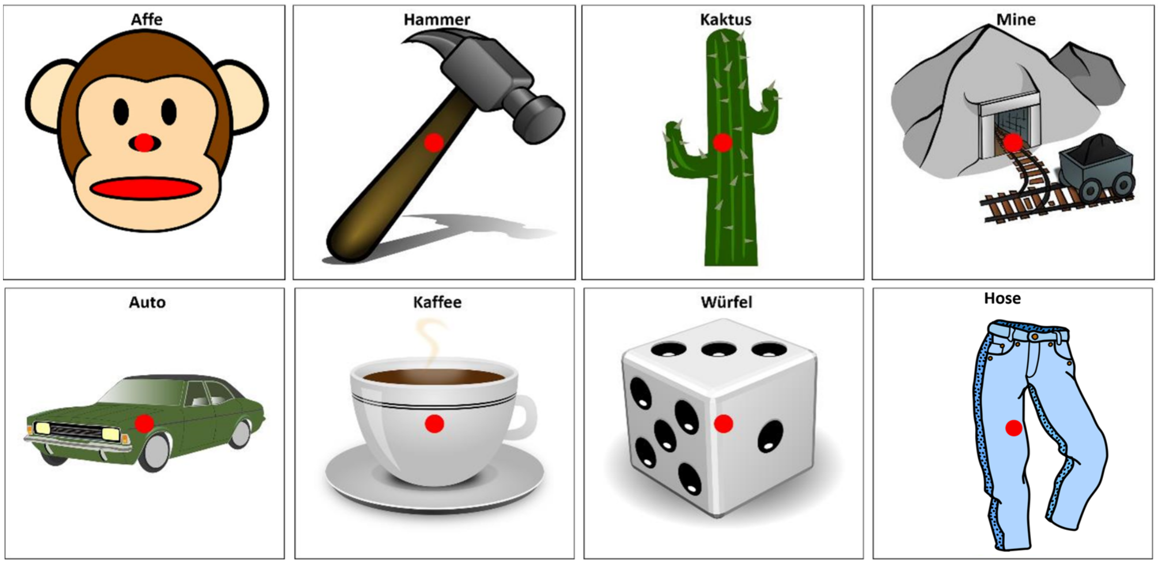

Figure 6: The square picture cards of set A (top) and set B (bottom) used in the experiment.

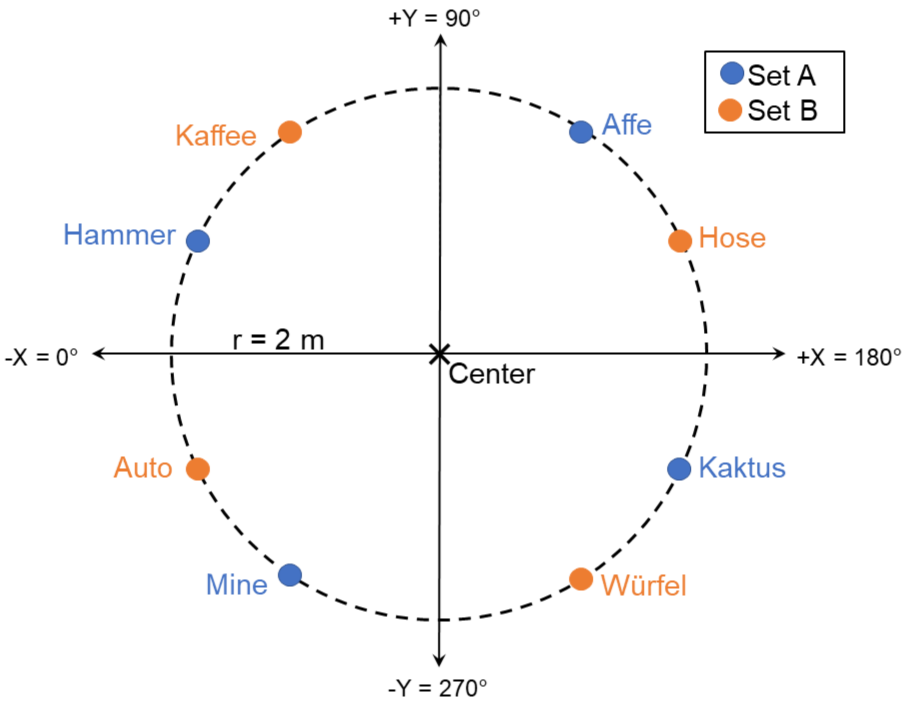

Figure 7: Top-down view of the circular arrangement and position of the picture cards used as pointing targets in the experiment (set A blue circles, set B orange circles). The radius of the circle was 2 m. The arrows indicate the circle's coordinate sys coordinate system in the testing room.

Figure 8: Flystick 2 hand held virtual reality controller to measure pointing accuracy and response time. Relevant buttons: Button 1 (*response time*) and Button 2 (*trigger*).

3.3 Experimental Design

To obtain a within-subject comparison, all participants underwent two different conditions (*internal* or *external*). Per condition each participant was shown a different one of the picture sets (set A or B). The conditions, the order of conditions, and the picture sets were the independent variables of the experiment and were randomly assigned to participants depending on their arrival in the testing lab (Attachment Table 4). This repetition of orders with different subjects also made a between-subject comparison possible. The two conditions were differentiated by the walkways. The internal and external walkway had the same walking distance and were matched for turning angle numbers and sizes (Figure 9). The internal walkway was entirely within the testing room, while the external walkway led out of the room via one door, along a short hallway and back into the room via a second door (doors were only openend for entering and exiting). To match the time of the two conditions, two 3 second breaks were taken during the walking phase of the ineternal condition (the first break was taken infront of the door, which remained closed. The second break was taken before the last bend of the walkway). Per condition the participants always underwent a learning, a testing and two experimenal phases (Figure 10) which followed each other without interruption of measurement. After completing all phases for the first condition the second condition followed, with the other picture set and walkway. After the second run-through the experiement was completed.
For every participant the pointer position and orientation aswell as the button pressing was recorded during phase I and II of each condition. From the measurements per participant and condition the angle deviation between actual object positions and the reported object positions were determined (Figure 11). Additionally, the response time was determined. Pointing angle and response time are the two dependant variables of the experiment.

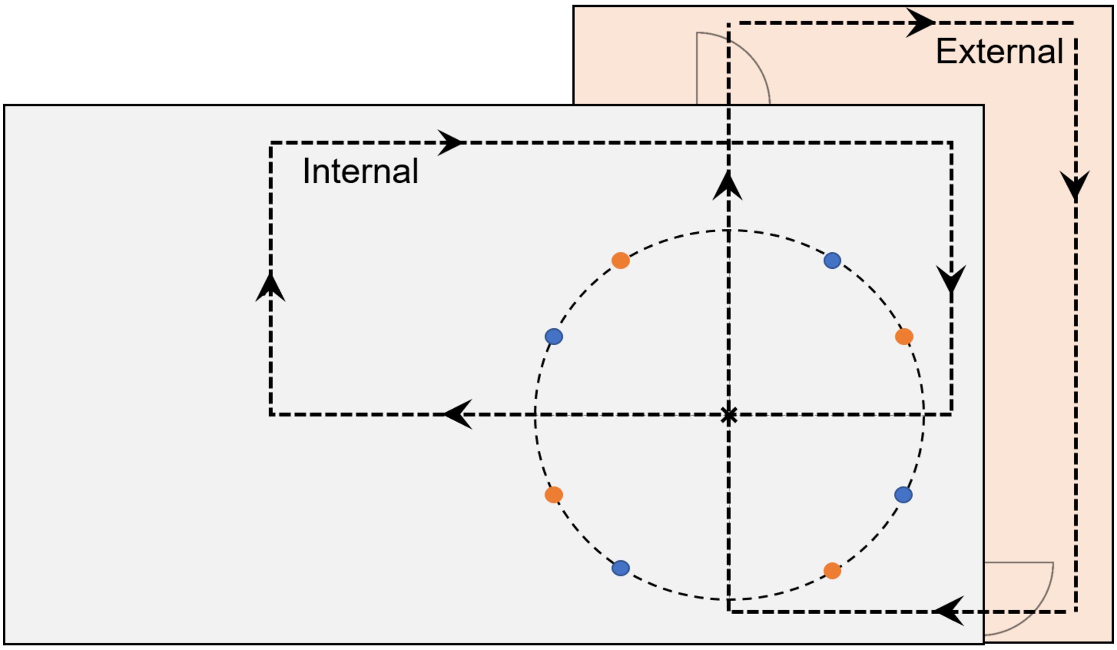

Figure 9: Schematic top-down view of the two walkways used for the internal and external condition. Also depicted: the testing room (grey area) with circular arrangement of cards and the hallway (orange area). During the internal walkway the participants would not leave the testing room. The external walkway led participants out of the room onto the hallway for a short distance and then back into the testing room via a second door. In both cases the participants were blindfolded at the last bend before being led back to the center of the circle.

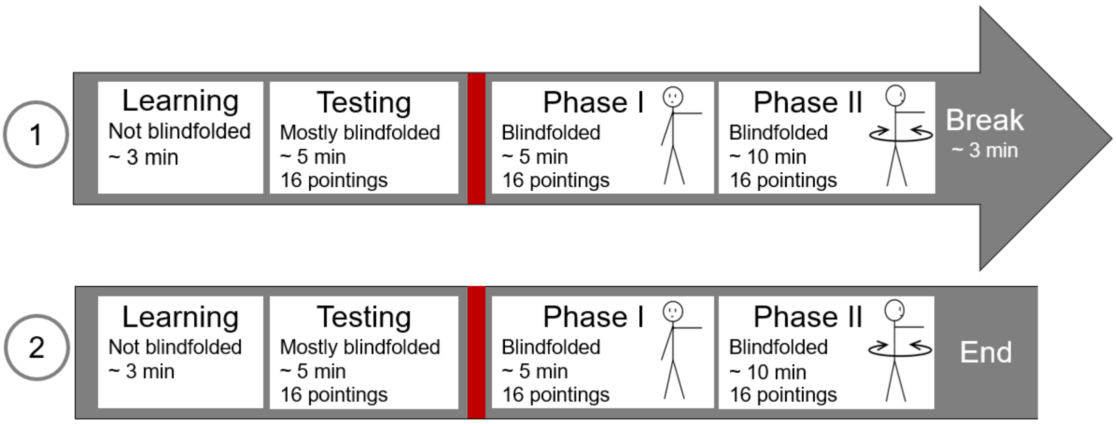

Figure 10: : Visualization of the experimental design and timeline. In the first run-through (1) the condition was either internal or external and either set A or B was used. The second run-through (2) was then conducted with the other condition and set. The walking phase (red line) was either internal or external and determined the condition. Measurements were taken during the two pointing phases after the walking. A short break separates the run-throughs, during which the second picture set was set up.

3.4 Procedure

First, the participants received written and verbal instructions on the experiment and signed an informed consent form. They were then led to the testing room, where the VR-pointer and relevant buttons as well as the pointing procedure were explained. They were asked to steadily hold the pointer in their right hand with an extended arm and aim for the red dots on the picture cards. The experimenter took position on the sideline and would remain there for the duration of the experimental procedures. The experimental design and timeline is depicted in Figure 10.

During the **learning phase** the participants were free to move around and learn the position of the picture cards. The learning phase was ended when the participant reported feeling confident of the object locations.

In the following **testing phase** participants were oriented according to the starting position of the condition they were about to undergo (Figure 9). The blindfold was added, and the experimenter named the four images in a randomized order. The participants pointed at the presumed object location. After four images the participants could take the blindfold off and were given feedback on performance accuracy. This was repeated four times. Continuous crude angle deviations would have called for additional testing run throughs, which wasn't necessary for any of the participants. After completion of tests the images and posts were removed while participants were still blindfolded.

The non-blindfolded **walking phase** followed, which was the condition-manipulation. The participants walked behind the experimenter, who slowly walked ahead. During the external walkway as little distraction as possible was allowed on the hallway e.g. through people walking by. For each walkway the participants were stopped and blindfolded before the last turn and led to the circle's center (Figure 9). This was a safety measure to exclude the possibility of landmark recognition by the participants before returning to the center that would aid them in their guesses of object location. They remained in this final position for the following phase I.

At this time the measurement was started. In **phase I** participants were asked to keep their feet planted while pointing at the images named by the experimenter. The order of objects was randomized, but the same for all participants. Each image was named four times in a randomized order (total of 16 pointings). They were allowed to turn their upper body or bend their arm if the image was located behind them.

Phase II followed subsequently, the blindfold remained on and at first the participant remained in the same position. In this phase the experimenter slightly touched the participants on the left or right shoulder. This was the indicator to slowly rotate in the applicable direction on the spot until the experimenter said "stop", which ment they had reached the next orientation. The speed of rotation was comfortably left up to the participants. This was repeated four times, facing each of the four cards in a randomized order. In each orientation they pointed at all four objects (total of 16 pointings). The turning angles were matched for the first and second run-through to not cause a higher disorietation in either.

After Phase II the measurement was interrupted and a three minute **break** follwed. The participants left the room and the experimenter set up the other picture card set. Then the participants re-entered the room and a second run-through with the other set and condition was conducted. The measurement was fully stopped after the second run-through, as the particpants had completed the experiment.

3.5 Analysis Methods

The initial data analysis was done with Matlab (Version 2017b). The participants' pointing angle was extracted from the recorded data and graphically vizualised (example in Attachment Figure 22). Measurements were considered "problematic" if there had been a double measurement, if a participant had accidentally pressed one of the buttons or the tracking system was unable to track the pointer position. These problematic measurements were individually removed by the experimenter (via Microsoft Office Excel 2016). The remaining data was then further analyzed in Matlab.

The **response time** was calculated by the number of recorded framenumbers between the last pressing of button (1) (*button 16*) and the first pressing of button (2) (*trigger*).

The **angle deviation** was defined as the difference between the reported object location angle *(RLA)* and the actual object location angle *(ALA): RLA - ALA* (Figure 11).

The **reported object location angle** *(RLA)* (Figure 11) was determined by reshaping the rotationmatrix of the VR-pointer at the time of trigger pressing:
1. Extract rotationmatrix of mean frame number during trigger pressing
2. Rotationmatrix * [-1;0;0] = reported object loctation vector
3. Reported object location vector * (-1)
4. Use function: *RLA(°) = atan2d(Y,X) + 360 * (Y>0)*
(After personally provided manuscript, Hardieß & Blessing, 2017)

The **actual object location angle** *(ALA)* (Figure 11) was definied by:
1. The straight line running from the controller to the actual object location (*distance x*)
2. The straight line running through the controller and parallel to one of the room's coordinate axes (*distance y*)
3. For the calculation: *ALA(°) = (atand2(distance x, distance y))*.

Per participant the angle deviation was determined for every measurement and sorted by condition (internal or external) and pointing phase (phase I or phase II). From this, two dependent variables were derived (via Microsoft Office Excel 2016):
1) **RFE** = Global Reference Frame Shift Error. This variable describes an overall shift in the participants reference frame. It's indicated by a consistent shift of pointing angles throughout all images. It was defined as the absolute of the mean angle deviation over all 16 measurements of each condition and phase.
2) **RE** = Residual Error. This is a measure for a participant's angle deviation that goes beyond the global reference frame shift error (rest-variation). It can't causally be linked to the RFE and the cause of this additional deviation can only be speculatively argued at this time. In phase I the RE was calculated in three steps: First, each participant's mean angle deviation

over all 16 measurements (i.e., RFE) of each condition was subtracted from all 16 individual measurements. Secondly, the absolute of these differences was determined. Lastly, the mean across the absolute differences was calculated. In phase II an additional step was added to the calculation of the RE. The absolute differences were calculated as before for the individual measuring points. Then the mean for each measuring point was determined (mean over 4 measurements per each of the 4 measuring points). The last step was taking the absolute of these means.

To enable comparisons RFE, RE and response times were sorted by condition (internal or external) and by phase (phase I or phase II). These results where then explored in respect to the effect of condition on the size of the variables. A significant difference between the varibales was postulated to be due to the differing internal and external conditions. To test this theory a repeated measure ANOVA statistical analysis of the effect and significance of phase and condition on RFE, RE and response time was conducted using IBM SPSS Statistics 24. The Bonferroni correction was used, and the estimation of effect size was of most interest. The results of within-subject-effect-tests were considered. The level of significance used was $p < 0.05$ and $\eta_p^2 > 0.14$ was considered as large effect ($\eta_p^2 > 0.06$ was considered a medium effect) (Cohen, 1988).

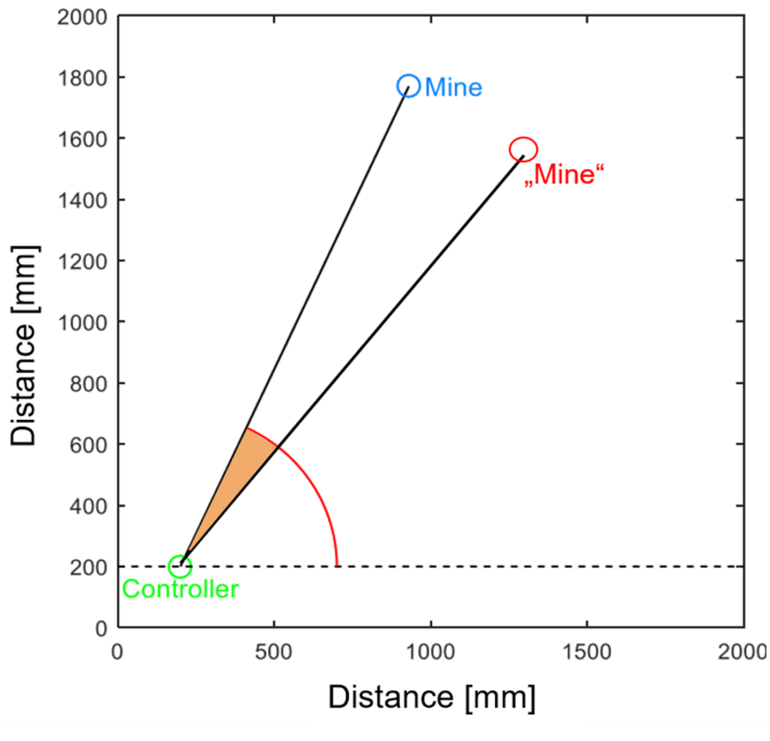

Figure 11: : Visualization of the angle deviation between actual object location (*ALA*; blue) and reported object location (*RLA*; red) in reference to VR-controller location (green). The actual angle is depicted as a red circle segment. The orange slice symbolizes the angle deviation. (Adapted from Blessing, 2016)

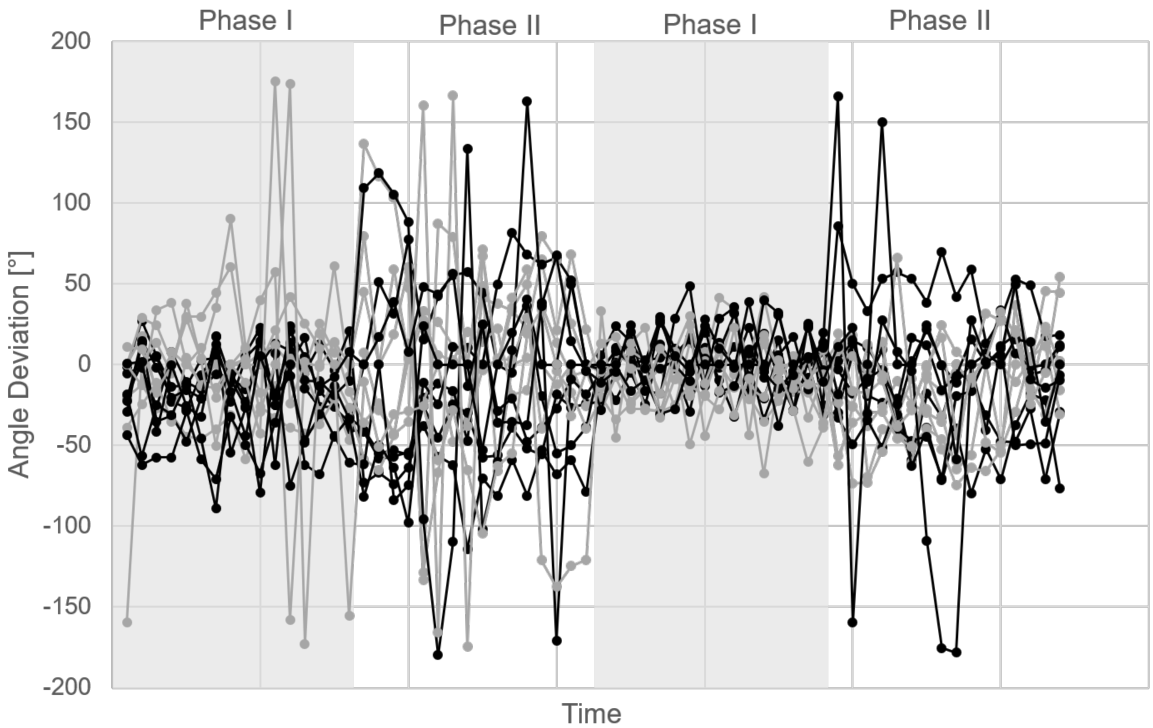

Figure 12: Angle deviation over time averaged for each participant per measurement. The angle deviation was calculated as the difference between the angles of the actual object location (0°) and the reported object location. Participants who began with the internal condition are indicated by a black line. Participants who underwent the external condition first are shown as a grey line.

4 Results

The overall data revealed a high variance in the participants individual performance. This is visible in the overall pointing angle deviation for all 15 participants and measurements over time (Figure 12).
The mean angle deviation between all participants per measurement (Attachment Figure 23) shows a similar dispersal of deviation between the two groups (internal vs. external first). The overall deviation is lower in phase I compared to phase II.
Since the angle deviation only describes a momentary shift, a closer look at the RFE is the true tell-tail of a detectable overall reference frame shift.

4.1 Global Reference Frame Shift Error (RFE)

Observation of the RFE over time (Figure 13) showed the RFE value to be higher in phase II than in phase I for most participants, regardless of condition. A comparison was conducted for the RFE between the phases I and II and between the internal and external condition (Table 1 and Figure 14, full table in Attachment Table 5).
Mean: Results (Table 1) showed that the mean RFE was higher in phase II than in phase I for both conditions. Within the phases the results for the conditions diverged. In phase I the mean RFE was higher in the internal condition, phase II on the other hand shows a higher

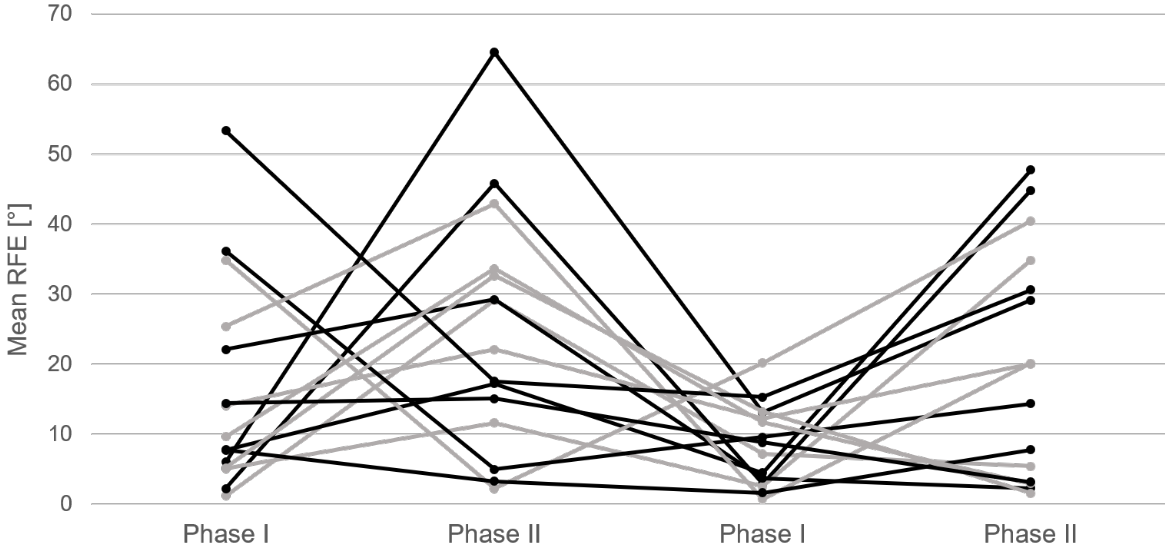

Figure 13: The mean RFE in degrees over time for each participant. Black lines indicate participants who underwent the internal condition first, grey lines represent participants who first encountered the external condition.

mean in the external condition. It is notable, that the mean increased almost twice as much from phase I to phase II in the external condition compared to the internal condition.
Median: The same trend is visible for the median, which is also higher in phase II for both conditions. Analogue to the mean, in phase I the median is higher in the internal condition, whereas it is higher in the external condition in phase II. The increase of median from phase I to phase II in the external condition is almost four times as large as in the internal condition.
Standard deviation: The standard deviation was higher in phase II than in phase I in both conditions. Within the phases the internal condition had a higher standard deviation in both cases, due to higher statistical outliers. Statistical outliers where defined as data points either > *3*interquartile range (IQR)* above the third quartile or < *3*IQR* below the first quartile (Figure 14).
The two main possible influencing factors on the RFE are phase and condition, therefore a statistical analysis via repeated measure ANOVA was conducted. It showed that the RFE was significantly affected by the phase (phase I or II): $F(1,14) = 5.743$; $p < 0.05$; $\eta_p^2 = 0.291$. The effect of the condition (internal or external) on the other hand, was not significant: $F(1,14) = 0.096$; $p = 0.761$; $\eta_p^2 = 0.007$.

Table 1: RFE comparison of mean, median and standard deviation sorted by phase and condition (in degrees).

	Phase I		Phase II	
	Internal	External	Internal	External
Mean	14.521	10.343	21.550	23.622
Median	11.729	8.852	17.571	29.123
Standard Deviation	13.609	9.030	17.742	15.292

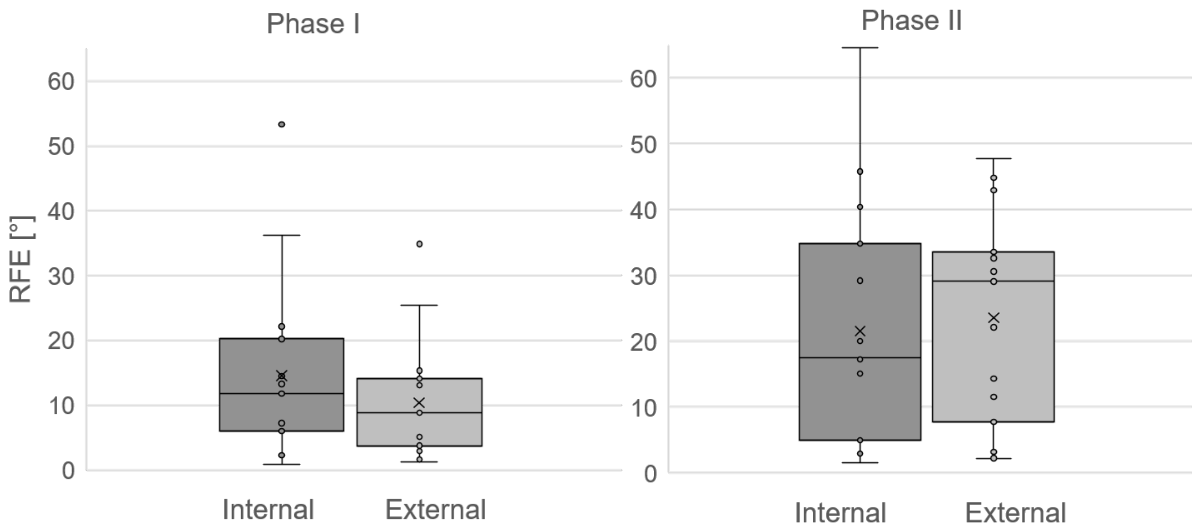

Figure 14: Boxplot of the RFE in phases I and II, sorted by condition. The Y-Axis represents the RFE in degrees. The individual measurements are presented as small dots. The boxplot includes the RFE mean as an X and the median as a horizontal line. The "whiskers" above and below the box show the minimum and maximum of the data points. Data points outside the whiskers are outliers.

4.2 Residual Error (RE)

Looking at the residual error (RE) over time (Figure 15), the most notable observation in most participants is a much higher RE in the first phase II compared to the second phase II or any of the phases I. There was no obvious difference between the conditions. A comparison of the RE values for each person was done and sorted by phase and condition (Table 2, Figure 16, full table in Attachment Table 6).

Mean: As presented in Table 2, the mean RE is always higher in phase II than in phase I for both conditions. The external condition has a higher value in both phases, whereby the difference between internal and external condition in phase II is only very small.

Median: While the RE median is also larger in phase II for both conditions it opposes the trend within the phases, where the values are higher in the internal condition.

Standard deviation: Analogue to the RFE, the RE standard deviation is always larger in phase II for both conditions. A striking observation is the large difference of RE between phase I and II for the internal condition, where phase II is over four times larger than phase I. This might be due to the small standard deviation in phase I in the internal condition, indicating a low rate of random variation in pointing angle among the participants. The external condition also shows an increase of standard deviation from phase I to II, however, the increase is comparatively small.

A repeated measure ANOVA was done to statistically quantify the effect of condition and phase on the RE. Similar to the RFE analysis, the effect of the phase was significant: F(1,14) = 7.643; $p < 0.05$; $\eta_p^2 = 0.353$. The effect of the condition on the other hand did not prove to be significant: F(1,14) = 0.167; p = 0.689; $\eta_p^2 = 0.012$.

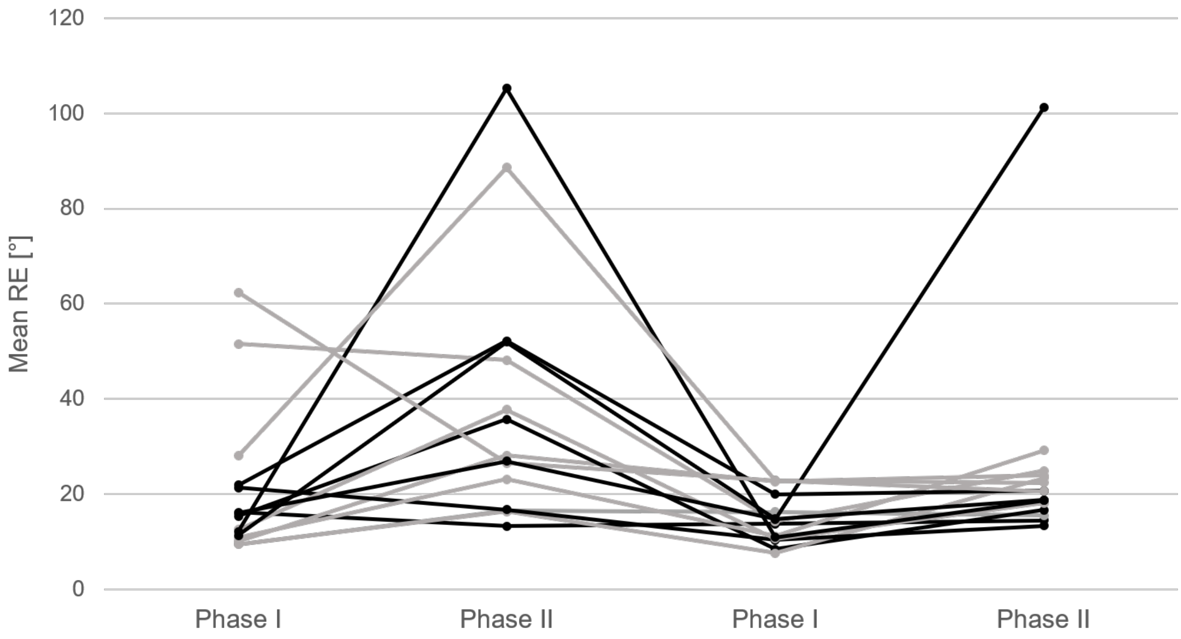

Figure 15: The mean RE in degrees over time for each participant. Black lines indicate participants who underwent the internal condition first, grey lines represent participants who first encountered the external condition.

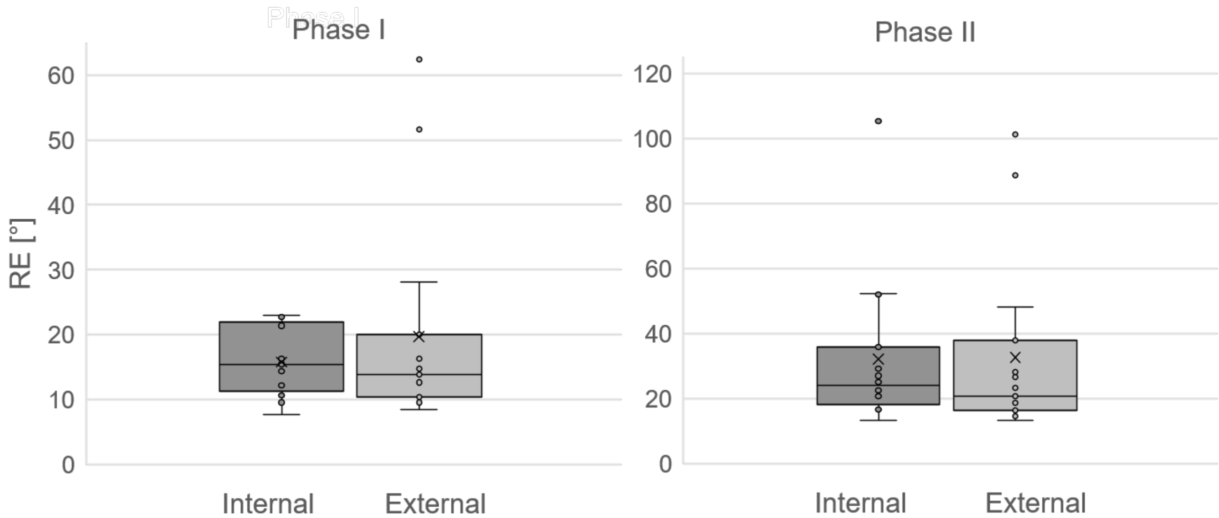

Figure 16: Boxplot of the RE in phases I and II, sorted by condition. The Y-Axis represents the RE in degrees. The individual measurements are presented as small dots. The boxplot includes the RE mean as an X and the median as a horizontal line. The "whiskers" above and below the box show the minimum and maximum of the data points. Data points outside the whiskers are outliers.

Table 2: Comparison of the RE mean, median and standard deviation, sorted by phase and condition (in degrees).

	Phase I		Phase II	
	Internal	External	Internal	External
Mean	15.756	19.649	32.096	32.550
Median	15.421	13.820	23.917	20.694
Standard Deviation	5.204	15.525	22.565	26.186

4.3 Additional Analyses

It was previously postulated that the RFE and RE are not correlated. To determine the validity of this theory the correlation was tested (Attachment Figure 24 and Figure 25). As assumed, there appears to be no correlation between RFE and RE within the phases (R^2 = 0.0204 in phase I and R^2 = 0.0075 in phase II) or within the conditions (R^2 = 0.0438 internal and R^2 = 0.067 external).

Considering that there was a high variance in angle deviation throughout participants (Figure 12 and Attachment Figure 23) additional analyses were conducted, to ensure that an effect of condition or phase wasn't being concealed or skewed.

4.3.1 Median Split

The first additional analysis applied to the data was a median split of the mean angle deviation for each participant (Figure 17). This was done to eliminate participants with an overall high angle deviation, which could be considered individuals with an overall high spatial confusion rate. Such an overall high "confusion" makes finding a baseline difficult and could influence the search for a specific effect difference between the two conditions.
The data for seven participants with a mean angle deviation above the median (29.25°) was excluded and a new comparison of the RFE and RE conducted (Figure 18, Attachment Table 7 and Attachment Table 8). Due to the median split, the trends in the RFE mean, median and standard deviation were inconsistent in regard to which condition had the higher values in which phase. For example, in phase II the internal condition was higher in mean and in median than the external condition. The overarching trend that remained the same despite the split was that the mean, median and standard deviation were higher in phase II than in phase I for both conditions.
The repeated measure ANOVA results showed there to just barely be a significant effect of phase on RFE (F(1,7) = 5.562; p = 0.05; η_p^2 = 0.443). In contrast, the effect of the condition on RFE was not significant (F(1,7) = 0.115; p = 0.744; η_p^2 = 0.016). Similarly, the RE was significantly affected by the phase (F(1,7) = 7.570; $p < 0.05$; η_p^2 = 0.520) but not by the condition (F(1,7) = 0.813; p = 0.397; η_p^2 = 0.104).

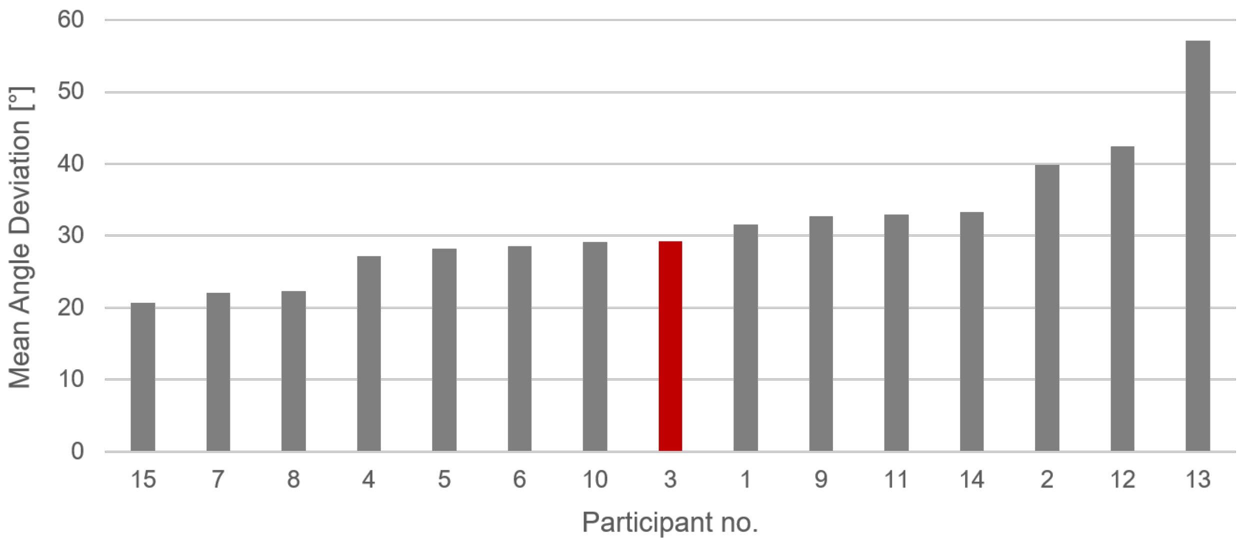

Figure 17: Mean angle deviation per participant in degrees sorted by magnitude. The red bar indicates the median of the mean angles (29.25°). Participants with a mean angle deviation $> 29.25°$ were excluded (i.e., median split).

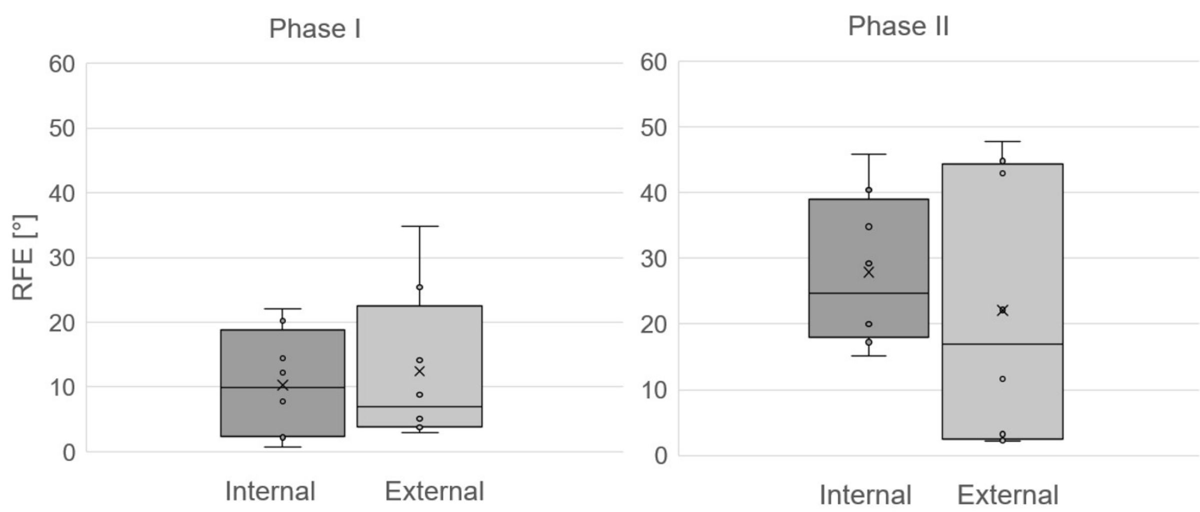

Figure 18: Boxplot of the RFE after median split, sorted by phases and conditions. The Y-Axis represents the mean RFE for each participant in degrees. The individual measurements are presented as small dots. The boxplot includes the RFE mean as an X and the median as a horizontal line. The "whiskers" above and below the box show the minimum and maximum of the data points. Data points outside the whiskers are outliers.

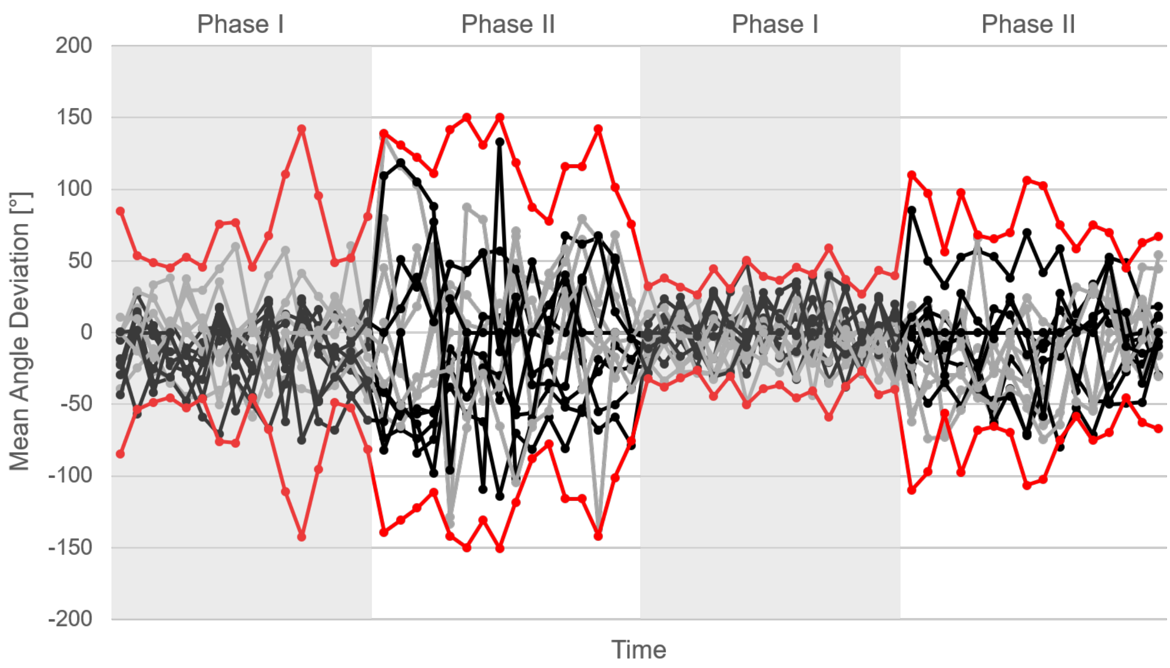

Figure 19: Angle Deviation over time averaged over participants per measurement. The red lines indicate the positive and negative double standard deviations. All individual data points above/below the double standard deviation were excluded. Black lines indicate participants who underwent the internal condition first, grey lines represent participants who first encountered the external condition.

4.3.2 Double Standard Deviation

Secondly a double standard deviation analysis was run. In this analysis all individual angle deviation measurements that exceeded the double standard deviation per measurement were excluded (Figure 19).
After the elimination of those extreme data points, as before, a comparison of RFE and RE was done (Figure 20, Attachment Table 9 and Attachment Table 10). The results showed that the RFE and RE mean were larger in the internal condition in both phases. The external condition was only higher in the RFE median in phase I. Common denominator with previous analysis was that mean, median and standard deviation were higher in phase II than in phase I for both conditions.
The repeated measure ANOVA did not uncovered a significant effect of phase ($F(1,14) = 3.732$; $p = 0.074$; $\eta_p^2 = 0.210$) on RFE, although it was a very close call. More clearly non-significant was the effect of condition ($F(1,14) = 0.187$; $p = 0.672$; $\eta_p^2 = 0.013$).
Interestingly the RE painted a slightly different picture with a clearly significant effect of the phase ($F(1,14) = 15.791$; $p < 0.05$; $\eta_p^2 = 0.530$). The condition however, once again showed no significance ($F(1,14) = 0.782$; $p = 0.392$; $\eta_p^2 = 0.053$).

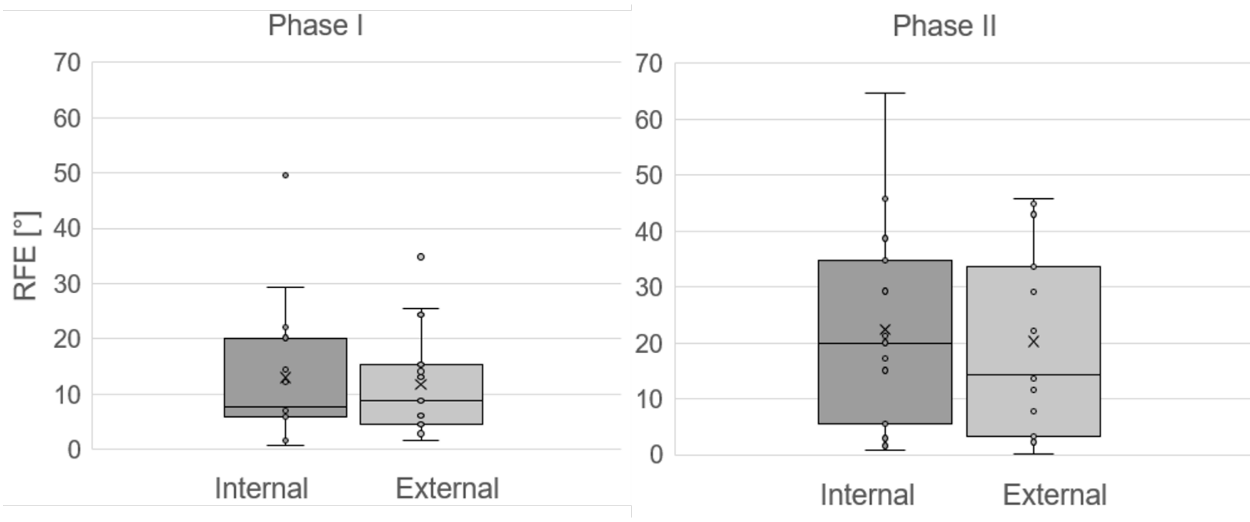

Figure 20: Boxplot of the RFE after exclusion of all data points over the double standard deviation, sorted by phases and conditions. The Y-Axis represents the Angle Deviation in degrees. The individual measurements are presented as small dots. The boxplot includes the RFE mean as an X and the median as a horizontal line. The ”whiskers” above and below the box show the minimum and maximum of the data points. Data points outside the whiskers are outliers.

4.3.3 Over 45° False Target

The circular arrangement of the images (Figure 7) showed that per set there was only one picture card placed in each quadrant of the circle. Therefore, one could assume, that the participants might sway from the original target position when blindfoldedly pointing, but would remain within the same quadrant. An angle deviation of over 45° from the actual target location implies pointing in an entirely different quadrant. This could indicate that the participant actually confused the images while blindfolded and was pointing at an entirely different image. A quantification of a reference frame shift however, is only possible under the condition, that the shift in all “correct” measurements is compared. “Correct” measurements being measurements in which the participants pointed at the intended target. This is definitely the case for a measurement with an angle deviation of 45° or lower. Therefore, the next step in the analysis was to exclude all measurements with an angle deviation of over 45°, to ensure a comparison of “correct” measurements.
A comparison of RFE and RE was done (Figure 21, Attachment Table 11 and 12). Both RFE and RE comparison offer no obvious trend in effect of condition. While the Median of the RFE is higher in the internal condition in both phases, the mean is almost identical in phase I (9.99 and 9.85) and higher in the external condition in phase II (11.35 and 12.80). Once again, mean, median and standard deviation are higher in phase II than in phase I for both conditions for RFE as well as RE. Despite this observation a repeated measure ANOVA reveals there to be no significant effect of phase on the RFE (F(1,10) = 0.406; p = 0.538; η_p^2 = 0.039) or RE (F(1,10) = 4.088; p = 0.071; η_p^2 = 0.290). The same is true for the effect of the condition on RFE (F(1,10) = 0.101; p = 0.757; η_p^2 = 0.010) and RE (F(1,10) = 0.070; p = 0.796; η_p^2 = 0.007).

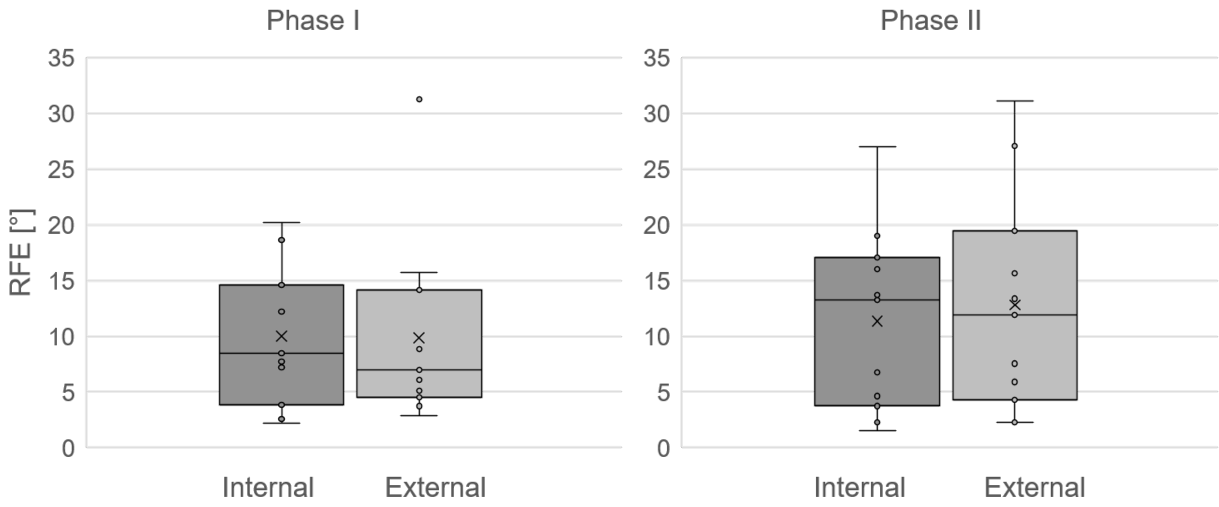

Figure 21: Boxplot of the RFE after exclusion of all measurements with an angle deviation of $> 45°$, sorted by phases and conditions. Y-Axis: Angle Deviation in degrees. The boxplot includes the RFE mean as an X and the median as a horizontal line. The "whiskers" above and below the box show the minimum and maximum of the data points.

4.4 Response time

The length of the response time has long been believed to be additive of the stages of cognitive processing occurring at that time (eg. Sternberg, 1969). Therefore, a longer reaction time could be indicative of a higher number of cognitive processing stages. Therefore, if a longer reaction time was found in the external condition this could support the theory that the context change during the external condition caused a decline of spatial working memory.

The response time was measured as previously described and compared by phase and condition (Table 3, full table in attachment Table 13).

Comparable to the preceding study by Blessing (2016) the analysis of reaction time showed no obvious trend in regard to conditions. While the mean was larger for the internal condition in both phases, the same is only barely applicable for the median in phase I. It is interesting that the standard deviation is much higher in the internal condition in both phases. But these numbers are mainly due to participant number 7 who had the overall highest reaction time with a mean as big as 17.952 seconds in the internal phase I. Taking this participant out of the equation leaves one with standard deviations of 1.71 (phase I) and 0.82 (phase II) in the internal condition.

The observed lack of clear effect is supported by the repeated measure ANOVA revealing a non-significant effect of both phase (F(1,14) = 0.612 ; p = 0.447; η_p^2 = 0.042) and condition (F(1,14) = 1.226 ; p = 0.287; η_p^2 = 0.081) on the response time.

Table 3: Mean, Median and Standard Deviation of the response time in seconds, sorted by phase and condition. The response time was defined as the time between button and trigger pressing.

	Phase I		Phase II	
	Internal	External	Internal	External
Mean	2.680	1.997	2.972	2.341
Median	1.890	1.861	1.723	1.946
Standard Deviation	2.467	1.059	4.081	1.695

5 Discussion

The goal of the study at hand was to further investigate the influence of context change on spatial updating in a real environment. Context change was emulated by a walkway through two doorways (external condition). The contrasting non-shift condition was a walkway remaining inside the testing room (internal condition). After both conditions participants were blindfolded and asked to report the position of four previously learned card positions in two phases. Phase I did not include any rotations and therefore only required a minimal amount of spatial updating. During phase II the participants rotated around their own axis and a high amount of spatial updating was required to upkeep a correct report of the actual object locations. It was postulated that the context change would have an influence on spatial working memory, i.e., causing an increase in the two variables *response time* and *pointing angle deviation* (RFE). Against expectations no statistically significant influence of condition was found on either of the variables.

5.1 RFE and RE

An interesting first observation with possible implications for the discussion was the high variance in angle deviation found across all participants and measurements (Figure 12 and Attachment Figure 23). The mean angle deviation (Attachment Figure 23) suggests a negative bias of the angle deviations, which would mean the participants were biased towards pointing to the left of the actual object locations more than to the right. However, this bias is not evident in the overall angle deviations (Figure 12). Since the RFE and RE, the values of most interest, describe the absolutes of the angle deviations, such a bias, if present, would not influence the overall results and was thus not further investigated. Regardless of a bias, a high individual variance in angle deviation is present and means that later findings of RFE and RE might also highly differ between individuals. Caution is to be used regarding this when interpreting the weight of the variables.

The RFE investigates a participant's shift in reference frame across all measurements and is therefore the most likely to show the existence of an influence of context change. The expectation was an overall higher RFE in measurements following the external condition, since this could indicate a disruption of spatial working memory through the context change. Interestingly, the experiment's data yielded no such findings. There was a stronger increase of RFE from phase I to phase II for the external condition (Figure 14 and Table 1), but the internal condition had a higher mean, median and standard deviation in phase I. The statistical analysis of the data showed no significant influence of condition (i.e., context change) on the RFE (i.e., spatial updating) and thus contradicted the hypothesis. Interestingly, this was in line with Blessing's (2016) findings, which found no statistically significant influence of condition on RFE. He had however found a strong trend in his data, indicating that there may in fact be an effect. He argued that the lack of statistical significance was most likely due to the small number of participants. Present results gained with a higher N seem to speak against this assumption.
A similar result was observed for the RE, which describes the residual error in a participant's

angle deviations. While the causes for an RE haven't been identified it was still of interest to see whether a difference in RE between the external versus the internal condition could be found. This could be due to the disruption of working memory through context change. In the data analysis RE mean and median took turns in being higher in one condition or the other, leaving no room for a clear effect of condition (Table 2 and Figure 16). One striking observation was the large difference of the standard deviation between phase I and II for the internal condition (Table 2). This is most likely due to the generally low angle deviation in all phases I for most participants. Phase I required no rotation during the measurements and the participants were pointing at the targets from the same position they had learned them in. Therefore, much less integration of the spatial image took place, which explains why the participants would have a smaller deviation from the actual object locations in this phase. This explanation does not account for the fact that the internal condition had a much higher standard deviation in phase I than phase II in the external condition. This could be attributed to the influence of context change only present in the external condition. However, this influence was not strong enough to lead to a statistically significant effect of condition on the RE. This was again in line with Blessing's (2016) findings, which showed a lack of statistically significant influence of condition on RE.

Even additional analysis of the data by using a median split, excluding all data points above the double standard deviation and only considering measurements $< 45°$, revealed no significant influence of the condition on RFE or RE. The verdict must therefore be, that a clear verification of the claims made by Blessing (2016) are impossible, since the trend of his results was not duplicated. However, the results do mirror his results, since both experiments failed to produce unambiguous, statistically significant influences of condition. Aside from a still comparatively small number of participants these results could be accounted for by two possible overall explanations:
i) Regardless of the findings there is an influence of context change on spatial updating, which this experiment fails to unequivocally capture. Possible reasons for this assumption and ideas for potential future optimizations to the experiment are given under *5.4 Future Objective*.
ii) There de facto is no influence of context change on spatial updating and thus on spatial working memory, which explains why this experiment measured no such influence.
Possibility i) will be further explored later on. But there is also some evidence supporting explanation possibility ii). The first indication for an actual lack of influence is the fact that this experiment has been conducted twice and neither trial has delivered undisputable results, even with a higher number of participants. Blessing's (2016) findings weren't statistically conclusive and the trend he found can easily be explained by a low N and chance. Naturally, this possibility must also be validated by other studies with similar paradigms. Mou and Wang (2015) used a virtual reality paradigm for participants to learn the position of five objects. This learning was either done in a large room (no context change followed) or in a small room (with following context change). After a learning and a walking phase, participants were asked to recall the original object positions. The participants were also cued to use one of two different navigation mechanisms. Some participants were given piloting

cues (colored walls) which they could later use to recall the object position. Others were not given such cues but instead had to recall the object position on an empty floor. The first case calls for the use of the navigation mechanism called *piloting*, in which the spatial relations between visible and invisible targets are gaged. The later calls for *path integration*. This process was previously described and uses internal locomotion cues for navigation. The highly interesting result revealed that the presence of a spatial memory impairment after context change was highly dependent upon the navigation mechanism used. If the participants had been given piloting cues their performance decreased after context change. If the participants could not see the virtual testing room there was no difference in pointing accuracy between those who had walked across virtual rooms and those who had remained in the same virtual room. In other words, no cross-boundary cost was found for participants that had relied on path integration (Mou & Wang, 2015). Since this path integration paradigm resembles our spatial updating experiment this result supports the possibility of a lack of context change influence in such a paradigm. Virtual reality and real environment differ, but the study's clear position, which is in line with our findings, validates the possibility.

5.2 Phase Effect

The experiment also displayed other interesting findings worth discussing.
According to the experimental design the main two influencing factors on RFE and RE were the two variables condition and phase. As explained, condition remained statistically noninfluential. Interestingly, a significant effect of phase was found on both RFE and RE. Despite not being part of the hypothesis, this closely resembles Blessing's (2016) results. He also found a significant effect of phase on RFE and a strong trend for the RE. Both current and previous results show the RFE and RE to be higher in phase II than in phase I for most participants, regardless of condition (Figure 13 and Figure 15). This was also supported by the overall angle deviation which was repeatedly higher in phases II compared to the corresponding phases I (Figure 12). The most likely explanation for this is that the participants are rotating around their own axis in phase II but not in phase I. This means phase II is the phase in which spatial updating for the picture card location must take place across several rotations in different directions. Although this integration is done well via proprioception and vestibular system, it can be faulty at times. There is much less necessity for integration and thus less possibility of error in phase I, which explains the higher angle deviations in phase II compared to phase I. An additional factor is the issue of the time difference between the learning phase and the two phases. Timeline wise, phase II always follows phase I without an intermittent reminder of the picture card locations. This discrepancy in time could also account for a decline in working memory from phase I to phase II.

An additional interesting observation was that most participants had a much higher RE in phase II of their first run-through compared to phase II of their second run-through or any of the phases I (Figure 15). This was independent of whether the participants had undergone the internal or external condition during their first run-through. The RE measures residual angle deviations that don't follow the pattern of an overall reference frame shift, it does not necessarily make a statement about the pointing accuracy within the conditions.

The findings therefore only indicate a higher level of ”undirected” angle deviations during the first run-through. It’s plausible that this is due to a learning effect causing a repetition of the task to be done with higher confidence, regardless of condition. This is fortified by the observation that many participants reported to have used strategies such as remembering the motor position of their extremities to remember the picture card locations (more on this topic to follow). But since the angles of the picture cards differed in phase II, participants may have realized their stragety to be faulty in the first run-through and thus relied more on spatial updating in the second run-through.

5.3 Response Time

The length of the response time may itself not be directly linked to spatial updating, but it’s length can be correlated to the stages of cognitive processing occurring at that time (e.g. Sternberg, 1969). Therefore, a significant difference in response time between internal and external condition could have been indicative of an influence of the context change on cognitive processing (i.e., spatial working memory). A comparison of the participant’s response times (Table 3) showed no statistical significance for either phase or condition on response time since mean, median and standard deviation were not consistent across either. This finding is in line with Blessing’s (2016) findings, although he had found a high effect size (η_p^2 = 0.340) which was not found in this experiment (η_p^2 = 0.081). There are three possible explanations for this lack of measured influence on response time, depending on which assumptions are made:
i) There is an influence of context change on both spatial updating and response time, but the experiment fails to capture this.
ii) There is an influence of context change on spatial updating, but not on response time. This could either be because the duration of the cognitive processes doesn’t increase or because this increase isn’t big enough to influence response time.
iii) There is no influence of condition on spatial updating which would explain why there is no effect on response time. No change in cognitive processing equals no change in length or number of those processes and therefore no change in response time.
Until the question about the existence of such an influence on spatial working memory has been answered it is nearly impossible to distinguish which of the presented possibilities is most likely.

5.4 Future Objective

In *5.1* two possible explanations for the lack of measured influence were given. The first of these was the possibility that there is an influence of context change on spatial updating, which this experiment fails to capture unambiguously. Arguments for this possibility are hereafter expanded upon in more detail. This is necessary because of the gravity of this position and to ensure there is no premature interpretation of the data, leading to an unwarranted dropping of the hypothesis. This study was the second time the experiment was conducted, permitting a comparison of results and offering new insight into the validity of the experiment. While the results differed in trend from previous findings, the final result remained the same. This raises the question whether the conducted experiment is a valid tool to explore the objective of the study or whether there are too many impairments. To answer this question, one must consider the multiple assumptions underlying the experiment. These assumptions can then be parallel-compared to the challenges faced in this experiment and the available literature on the applicable topics:

First assumption: The sought-after context change was sufficiently simulated by the participants leaving the testing room, walking along the hallway and reentering through a second doorway.
No influence of context change was found although many previous studies strongly suggest its existence. A possible explanation could be that the context change that was used was not strong enough. In the external condition participants actively passed through two doorways and a hallway, however the context was still spatially and contextually tightly linked to the testing room. (One participant even reported the subjective feeling of still being in the same room.)
Possible Optimization: Creating two comparable conditions (internal vs. external) is key and a larger context change makes this harder to accomplish. But it might be imperative to create a bigger context change, e.g. by expanding the walkway onto a different floor of the building or even taking the participants out of the context "university". The context change could also be reinforced non-spatially e.g. by a short intermittent concentration task outside of the testing room. Since this specific experiment is designed to take place in a real environment a virtual reality set-up is not desirable in this case.
Second assumption: Within the experiment the two run-throughs with different conditions and sets were two separate events that did not influence each other. Any within-subject differences in angle deviation could directly be attributed to the corresponding walkway.
The possibility of a *carry-over effect* is always given when conducting such a within-subject design in which the two conditions follow back-to-back. While the data gives no clear indication of a carry-over effect, both the comparison of the RFE and RE over time (Figures 13 and Figure 15) show the existence of a learning effect from the first to the second run-through. This is visible by the mean RFE and RE being lower in the second phase II compared to the first, regardless of which condition was conducted first. A carry-over effect could significantly impair or skew results.
Possible Optimization: To eliminate any learning or carry-over effect from one condition to the other, a strict between subject design might be useful. (That design would then call for the establishment of each participant's baseline ability to spatially update. This would ensure that the measured angle deviation after context change is calculated in reference to the participant's baseline angle deviation.)
Third assumption: Visual input was the only sensory modality with an influence on the participant's spatial image formation. Since this was inhibited by blindfolding in the measurement phases the spatial image was only adapted according to proprioceptive and vestibular input. Spatial updating took place and any differences in spatial updating between the two conditions must have been due to the absencee or existence of context change.
Post-experiment several participants reported using auditory information in the testing room

to re-orient themselves during the blindfolded measurement phases. Despite attempts to eliminate unnecessary sounds in the testing room complete silence was unobtainable. Examples for auditory information used by participants were the asymmetrically located room ventilation, the location of the experimenter's voice or the sound of footsteps. The idea of functional equivalence argues that spatial images can be formed from auditory perception just as well as from language or visual perception (Loomis et al., 2013). This raises the question whether the participant's spatial images were influenced (changed/adapted/updated) by means of auditory input during the experiment. Auditory information has been found to have a significant contribution to spatial updating (Genzel, Firzlaff, Wiegrebe, & MacNeilage, 2016) and to the formation of a spatial frame of reference (Goossens & van Opstal, 1999). This strongly indicates that the influence of auditory input could have disrupted or at least influenced the experiment in an unintended way. This would mean that the measured height of the variables cannot be exclusively attributed to the corresponding condition.
Possible Optimization: A countermeasure could be to have the participants wear sound cancelling wireless head phones. Instructions could exclusively be communicated via the head phones (by Bluetooth or similar wireless technology). This would eliminate unwanted auditory influences on the spatial image or updating.
Fourth assumption: The only way participants learned and remembered the actual object locations was by forming a spatial image and integration hereof. Conclusively, the reported object location is a direct reflection of the ability to update a spatial image.
Several participants reported having used memory of the physical motor positions of their limbs and/or core as a gage of object location. This may have been effective in phase I where the participants pointed at the objects from the same position as in the learning and testing phase. This method was not useful in phase II where the pointing angles differed from the learned ones. Considering this, the results might be skewed by the influence of motor position memory being used.
Possible Optimization: The participants must be aware that remembering motor positions won't aid performance during the measuring phases. This could be facilitated by a learning phase that more closely mirrors phase II instead of phase I, e.g. by including rotations and/or different angles than the measuring phases. Participants would be forced to form an adequate spatial image of the object positions instead of relying on other mechanisms such as motor position memory. Another possibility would be to completely eliminate phase I.
Fifth assumption: The timeline and time delays between the different phases in the experiment had no unintended influence on the resulting data.
Time delay has been shown to have an influence on spatial working memory. An early study on the spatial memory functions of neurons subjected primates to an oculomotor delayed-response task. The primates were trained to fixate a central spot on a screen while a peripheral cue was given and during a delay period. They then made a saccadic eye movement to the location of the previous cue. Eye movement and single neurons were recorded. Delay periods of three and six seconds were tested and correct performance of about 90% was seen for all cue locations. Despite the small difference of three seconds between the two tested delay periods a difference of performance was measured (Funahashi, Bruce, & Goldman-Rakic, 1989). A difference in accuracy of spatial working memory after a delay period of

as little as three seconds strongly indicates a certain decay of spatial working memory over time. Considering these findings it is necessary to acknowledge that the two phases in the present experiment followed each other without an intermittent reminder of the object locations. This led to a significant time difference from learning to measurement for phase I to phase II. This could be another explanation for the higher angle deviation in phase II compared to phase I in both conditions (Figure 12). This influence on the variables could interfere with the actual objective of the study.
Fifth Optimization: Eliminate phase I, since phase II is where the largest amount of spatial updating is expected to take place and thus where the influence of context change would be seen more. By eliminating phase I the time between learning phase and phase II measurement is significantly reduced, reducing the time dependant decrease of spatial working memory.

5.5 Concluding Remarks

The result of the study at hand was that no influence of context change on spatial updating in a structured real environment was found. Nonetheless, the acquired data does not unequivocally prove there to be de facto no influence. Two possible overall explanation possibilities were explored and arguments found for both: i) There is an influence of context change on spatial updating, which this experiment fails to capture; ii) There is no influence of context change on spatial updating. Both possibilities have their validity, yet the majority of sources indicate the presence of an influence of context change on spatial updating (as seen in the introduction of this paper). Furthermore, it was shown that the experiment at hand is based on multiple simplified or even flawed assumptions in the design and execution. The combination of the observations leads to the conjecture that possibility i) is more likely.
The necessary conclusion thus must be that further investigation of the matter is imperative, possibly under some of the given optimizations for the experiment. An optimization of the paradigm and further investigation are expected to lead to a settlement of the debate by finding an unambiguous influence of context change on spatial updating in a real structured environment.

6 Attachments

Table 4: Overview of the assigned conditions and picture sets for the study participants. The order was randomly assigned upon the participants arrival in the testing lab.

	Phase I		Phase II	
participant no.	Set	Condition	Set	Condition
1	A	Intern	B	Extern
2	A	Extern	B	Intern
3	B	Intern	A	Extern
4	B	Extern	A	Intern
5	A	Intern	B	Extern
6	A	Extern	B	Intern
7	B	Intern	A	Extern
8	B	Extern	A	Intern
9	A	Intern	B	Extern
10	A	Extern	B	Intern
11	B	Intern	A	Extern
12	B	Extern	A	Intern
13	A	Intern	B	Extern
14	A	Extern	B	Intern
15	B	Intern	A	Extern

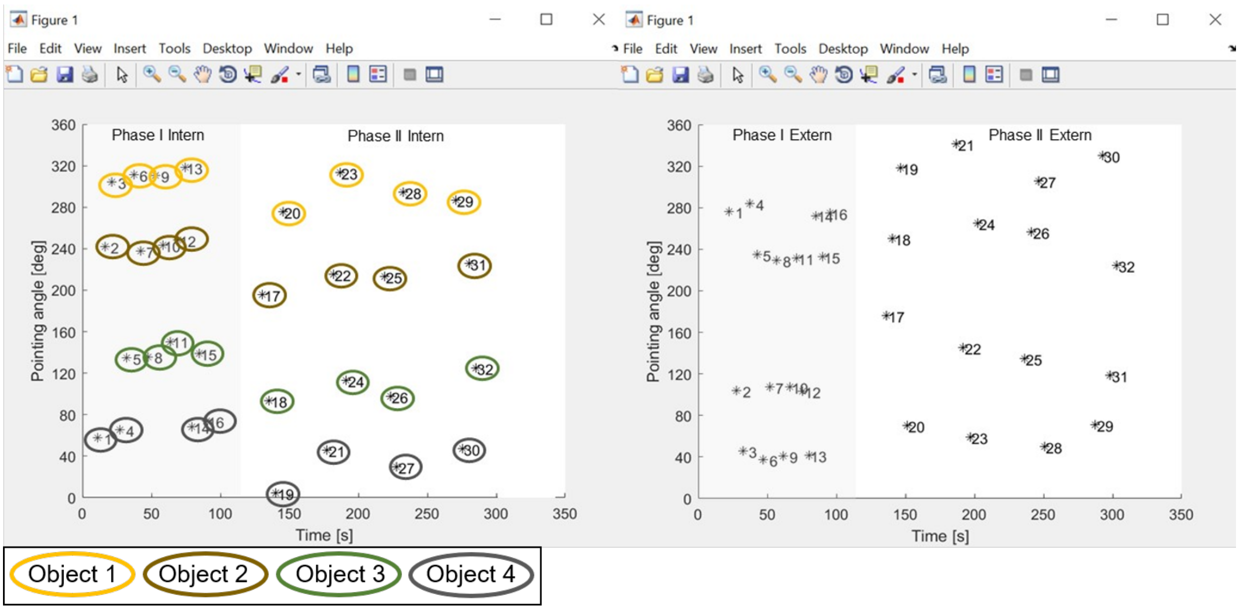

Figure 22: Example of data extracted via MatLab. This data depicts the pointing angles per Measurement over time for one participant. The colored circles were added for visualization purposes to show which measurement corresponds with which object. Ideally all the measurements for one object would be in a straight horizontal line along the object's actual angle.

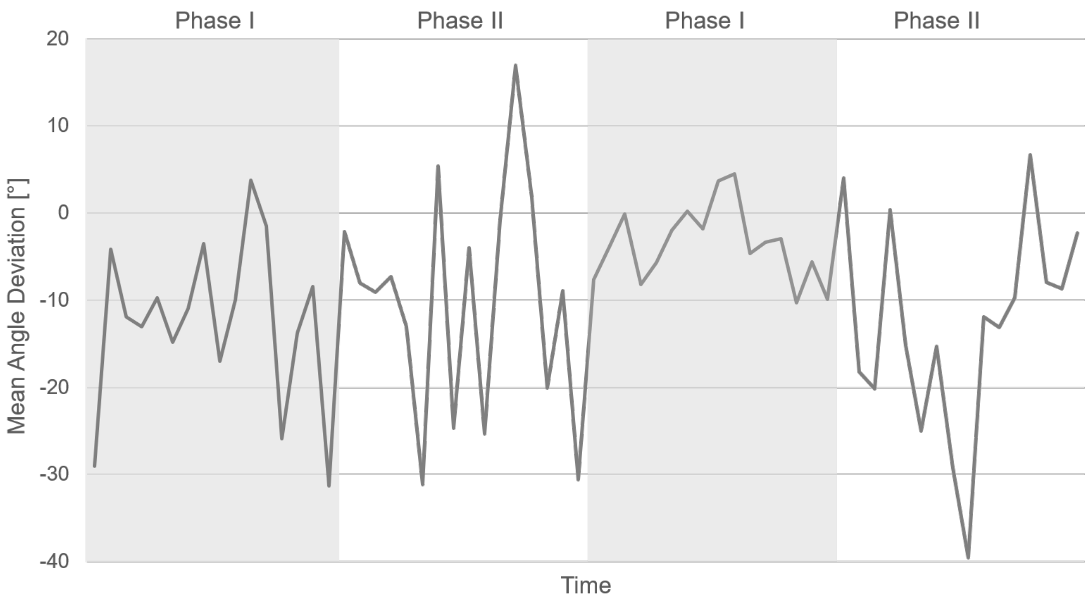

Figure 23: Mean angle deviation over time, averaged over all participants per measurement (in degrees). The angle deviation was calculated as the difference between the angles of the actual object location (0°) and the reported object location.

Table 5: Global Reference Frame Shift Error (RFE) in degrees per participant, sorted by condition and phase.

	Phase I		Phase II	
Participant no.	Internal	External	Internal	External
1	6.024	13.087	64.559	29.125
2	7.188	1.214	5.453	29.123
3	2.234	2.886	45.831	44.833
4	2.564	5.112	34.832	11.623
5	7.736	4.498	17.237	47.741
6	20.191	34.841	40.427	2.247
7	22.132	3.727	29.229	2.288
8	12.255	14.118	20.021	22.138
9	36.162	9.588	5.013	14.367
10	0.779	25.412	20.144	42.943
11	7.802	1.636	3.276	7.790
12	13.246	5.224	1.589	32.657
13	53.318	15.303	17.571	30.615
14	11.729	9.651	2.966	33.628
15	14.449	8.852	15.100	3.205
Mean	14.521	10.343	21.550	23.622
Median	11.729	8.852	17.571	29.123
Standard Deviation	13.609	9.030	17.742	15.292

Table 6: Residual Error (RE) in degrees per participant, sorted by condition and phase.

	Phase I		Phase II	
Participant no.	Internal	External	Internal	External
1	16.225	13.820	13.312	14.522
2	14.299	51.593	24.961	48.186
3	9.509	16.296	16.561	15.530
4	22.689	10.182	23.917	28.178
5	15.421	8.472	35.732	16.681
6	7.665	9.509	23.397	16.361
7	21.352	10.399	16.757	13.378
8	11.231	10.931	29.187	23.174
9	21.931	19.997	52.209	20.694
10	10.599	12.596	18.133	37.770
11	12.141	10.952	105.222	18.671
12	22.914	28.048	22.434	88.606
13	11.390	14.720	51.994	101.177
14	22.913	62.397	20.681	26.524
15	16.055	14.826	26.949	18.804
Mean	15.756	19.649	32.096	32.550
Median	15.421	13.820	23.917	20.694
Standard Deviation	5.204	15.525	22.565	26.186

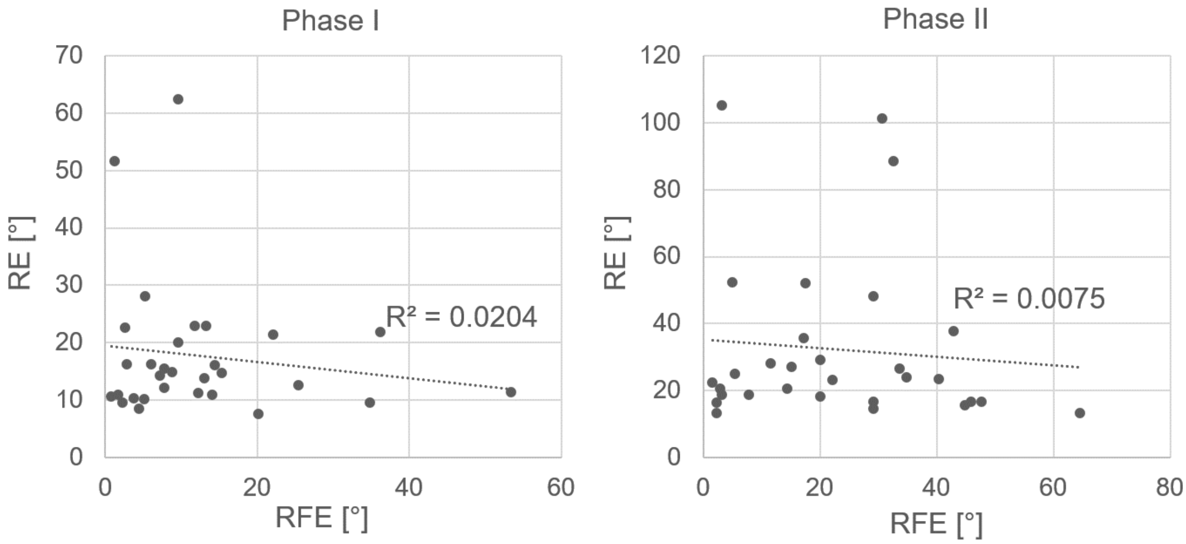

Figure 24: Correlation of RE and RFE (both in degrees)within each of the phases I and II.

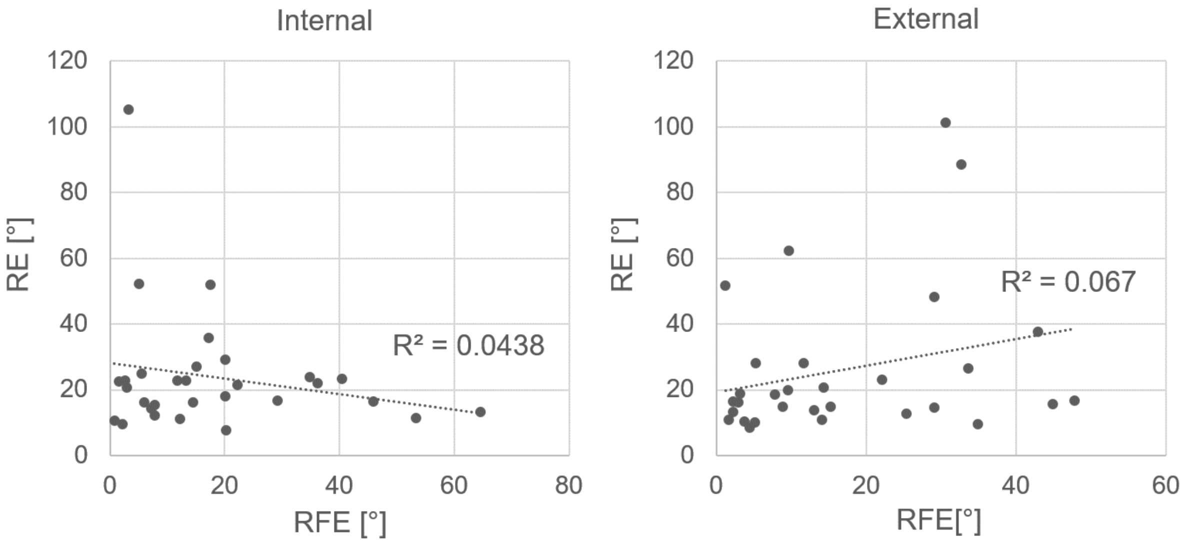

Figure 25: Correlation of RFE and RE (both in degrees) within each of the conditions (internal and external).

Table 7: Mean, Median and Stardad Deviation of (A) RFE and (B) RE after subjecting the data to a median split. The data is sorted by phase and condition (in degrees).

(A) RFE	Phase I		Phase II	
	Internal	External	Internal	External
Mean	10.293	12.431	27.853	22.127
Median	9.996	6.982	24.687	16.881
Standard Deviation	7.754	11.010	10.771	18.915

(B) RE	Phase I		Phase II	
	Internal	External	Internal	External
Mean	14.315	11.651	23.829	21.234
Median	13.326	10.665	23.657	17.742
Standard Deviation	5.179	2.537	6.281	7.666

Table 8: Mean, Median and Stardad Deviation of (A) RFE and (B) RE after exclusion of all data points over the double standard deviation. The data is sorted by phase and condition (in degrees).

(A) RFE	Phase I		Phase II	
	Internal	External	Internal	External
Mean	12.959	11.761	22.357	20.205
Median	7.736	8.852	20.021	14.367
Standard Deviation	12.527	9.344	17.266	15.837

(B) RE	Phase I		Phase II	
	Internal	External	Internal	External
Mean	18.129	16.013	29.926	25.620
Median	16.302	15.000	23.917	18.804
Standard Deviation	7.699	6.408	16.119	15.376

Table 9: Mean, Median and Stardad Deviation of (A) RFE and (B) RE after exclusion of all individual measurements with an angle deviation of $>45°$. The data is sorted by phase and condition (in degrees).

(A) RFE	Phase I		Phase II	
	Internal	External	Internal	External
Mean	9.988	9.852	11.354	12.796
Median	8.496	6.982	13.226	11.897
Standard Deviation	5.862	7.806	7.798	9.347

(B) RE	Phase I		Phase II	
	Internal	External	Internal	External
Mean	14.871	14.673	18.341	17.240
Median	14.601	14.826	17.576	16.361
Standard Deviation	4.715	5.675	6.140	8.001

Table 10: The response time in seconds for each participant, sorted by phase and condition. The response time was defined as the time between button and trigger pressing.

	Phase I		Phase II	
Participant no.	Internal	External	Internal	External
1	2.065	2.419	2.351	2.692
2	3.038	2.528	4.227	7.163
3	2.131	2.106	2.063	2.460
4	2.264	1.558	1.522	1.784
5	1.404	2.095	1.886	2.270
6	1.513	0.956	1.444	0.841
7	9.547	5.267	17.952	5.532
8	1.595	1.861	1.508	1.537
9	8.013	2.975	2.911	2.250
10	1.463	1.354	1.723	1.374
11	1.170	1.000	1.410	0.952
12	2.084	1.831	1.579	1.946
13	0.666	0.739	0.728	0.757
14	1.352	1.399	1.200	1.518
15	1.890	1.873	2.073	2.032
Mean	2.68	2	2.97	2.34
Median	1.89	1.86	1.72	1.95
Standard Deviation	2.47	1.06	4.08	1.7

7 References

Avraamides, M. N., Galati, A., & Papadopoulou, C. (2013). Egocentric updating of remote locations. *Psychological Research, 77(6)*, 716-727.

Blessing, C. (2016). Positionsfortschreibung in strukturierter Umgebung mit Kontextwechsel. *Bachelorarbeit der Mathematisch-Naturwissenschaftlichen Fakultät der Eberhard-Karls-Universität Tübingen*.

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (second ed.). New York: Lawrence Erlbaum Associates.

Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24(1)*, 227-233.

Funahashi, S., Bruce, C. J., & Goldman-Rakic, P. S. (1989). Mnemonic coding of visual space in the monkey's dorsolateral prefrontal cortex. *J Neurophysiol, 61(2)*, 331-349.

Genzel, D., Firzlaff, U., Wiegrebe, L., & MacNeilage, P. R. (2016). Dependence of auditory spatial updating on vestibular, proprioceptive, and efference copy signals. *J Neurophysiol, 116(2)*, 765-775.

Goossens, H. H., & van Opstal, A. J. (1999). Influence of head position on the spatial representation of acoustic targets. *J Neurophysiol, 81(6)*, 2720-2736.

Hardieß, G., & Blessing, C. (2017). Prinzipielle Berechnung des (R)eference (F)rame shift (E)rrors (RFE). *Lab of Cogitive Neuroscience of the Eberhard-Karls-Universität Tübingen*.

Horn, D., & Loomis, J. (2004). Spatial updating of targets in front and behind. *Paidéia (Ribeirão Preto), 14*, 75-81.

Land, Michael F. (2012). The Operation of the Visual System in Relation to Action. *Current Biology, 22(18)*, R811-R817.

Loomis, J. M., Klatzky, R. L., & Giudice, N. A. (2013). Representing 3D Space in Working Memory: Spatial Images from Vision, Hearing, Touch, and Language. In S. Lacey & R. Lawson (Eds.), *Multisensory Imagery* (pp. 131-155). New York, NY: Springer New York.

Mallot, H. A. (2012). Raumkognition. In H.-O. Karnath & P. Thier (Eds.), *Kognitive Neurowissenschaften* (pp. 217-224). Berlin, Heidelberg: Springer Berlin Heidelberg.

Mou, W., & Wang, L. (2015). Piloting and path integration within and across boundaries. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41(1)*, 220-234.

Radvansky, G. A., & Copeland, D. E. (2006). Walking through doorways causes forgetting: Situation models and experienced space. *Memory & Cognition, 34(5)*, 1150-1156.

Radvansky, G. A., Krawietz, S. A., & Tamplin, A. K. (2011). Walking through doorways causes forgetting: Further explorations. *The Quarterly Journal of Experimental Psychology, 64(8)*, 1632-1645.

Radvansky, G. A., Tamplin, A. K., & Krawietz, S. A. (2010). Walking through doorways causes forgetting: Environmental integration. *Psychonomic Bulletin & Review, 17(6)*, 900-904.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15(6)*, 1157-1165.

Speer, N. K., & Zacks, J. M. (2005). Temporal changes as event boundaries: Processing and memory consequences of narrative time shifts. *Journal of Memory and Language, 53(1)*, 125-140.

Sternberg, S. (1969). Memory-scanning: Mental processes revealed by reaction-time experiments. *American Scientist, 57(4)*, 421-457.

Swallow, K. M., Zacks, J. M., & Abrams, R. A. (2009). Event boundaries in perception affect memory encoding and updating. *Journal of Experimental Psychology: General, 138(2)*, 236-257.

Trullier, O., Wiener, S. I., Berthoz, A., & Meyer, J.-A. (1997). Biologically based artifical navigation systems: Review and prospects. *Progress in Neurobiology, 51(5)*, 483-544.

Waller, D., & Hodgson, E. (2006). Transient and enduring spatial representations under disorientation and self-rotation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32(4)*, 867-882.

Wraga, M., Creem-Regehr, S. H., & Proffitt, D. R. (2004). Spatial updating of virtual displays. *Memory & Cognition, 32(3)*, 399-415.