Eberhard Karls Universität Tübingen
Mathematisch-Naturwissenschaftliche Fakultät

Master Thesis Cognitive Science

Modality Dependencies and Visual Updating Processes in Spatial Working Memory

Jonas Schäfer

27 March 2020

Reviewers

PD Dr. Gregor Hardieß
Cognitive Neuroscience
Biology Department
University Tübingen

Prof. Dr. Hanspeter Mallot
Cognitive Neuroscience
Biology Department
University Tübingen

Schäfer, Jonas
Belthlestr. 25, 72070 Tübingen
jonas19schaefer@gmx.net
Modality Dependencies and Visual Updating Processes in Spatial Working Memory
Thesis M. Sc. Kognitionswissenschaft
Eberhard Karls Universität Tübingen
Thesis period: 08/2019-03/2020

Erklärung

Hiermit erkläre ich, Jonas Schäfer, die Ausdrucke dieser PDF Datei in unveränderter Form dem Prüfungssekretariat des M.Sc. Kognitionswissenschaft zukommen zu lassen. Dies wird geschehen, sobald es die Maßnahmen zur Eindämmung der Verbreitung des Coronavirus SARS-CoV-2 zulassen.

Tübingen, den 27.03.2020

Selbstständigkeitserklärung

Hiermit erkläre ich, Jonas Schäfer,

- dass ich diese Arbeit selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe

- dass alle wörtlich oder sinngemäß aus anderen Werken übernommenen Aussagen als solche gekennzeichnet sind

- dass die eingereichte Arbeit weder vollständig noch in wesentlichen Teilen Gegenstand eines anderen Prüfungsverfahrens gewesen ist oder bereits veröffentlicht wurde.

Tübingen, den 27.03.2020

Abstract

Human working memory is considered a domain-general cognitive resource maintaining and manipulating incoming information of different modalities processually and goal-directed for a short time period. In the framework of the underlying thesis two behavioral experiments investigating working memory mechanisms in spatial sequence learning were executed:

The *Modality Experiment* provides evidence for a modality-segregation in processing of spatial and temporal information in working memory. Furthermore, time sensitivity of task-related learning requirements turned out to be the reason for interference of complex spatiotemporal relations (i.e. path crossings) in target patterns.

The *Updating Experiment* showed that rotatory transformation of short-term representations of spatial configuration alignments is performed more accurately when rotation of target items is initiated by ego- rather than by external motion. These findings imply that use of visual feedback in updating processes superimposes higher-cognitive mechanisms known from research on spatial updating and allocentric spatial reference frames.

Zusammenfassung

Das menschliche Arbeitsgedächtnis gilt als domänenübergreifende kognitive Ressource, die eingehende Informationen unterschiedlicher Modalitäten über einen kurzen Zeitraum prozesshaft aufrechterhält und zielgerichtet manipuliert. Im Rahmen der vorliegenden Arbeit wurden zwei verhaltenswissenschaftliche Experimente durchgeführt, welche Arbeitsgedächtnismechanismen im räumlichen Sequenzlernen untersuchten:

Das *Modality Experiment* liefert Evidenz für eine Modalitätstrennung in der Verarbeitung von räumlichen und zeitlichen Informationen im Arbeitsgedächtnis. Weiterhin zeigte sich, dass Zeitsensitivität der aufgabenbedingten Lernerfordernisse die Ursache für die Interferenz komplexer zeitlich-räumlicher Relationen (d.h. Pfadkreuzungen) in Zielmustern darstellt.

Das *Updating Experiment* zeigte, dass die rotatorische Transformation von Kurzzeitrepräsentationen räumlicher Konfigurationsorientierungen mithilfe visuellen Feedbacks akkurater bewältigt wird, wenn die Rotation der Zielobjekte durch eigene, als wenn sie durch externe Bewegung initiiert wird. Diese Resultate implizieren, dass das Nutzen visuellen Feedbacks in Updating Prozessen höher-kognitive Mechanismen, die aus der Forschung über Spatial Updating und allozentrische räumliche Bezugssysteme bekannt sind, überlagert.

Acknowledgements

I thank Dr. Gregor Hardieß for accepting my request for the thesis, for constructive exchanges on development and implementation of empiric hypotheses and for being an excellent supervisor throughout the proceeding of this thesis.

I want to thank Prof. Dr. Hanspeter Mallot for constantly being available as a reliable, competent and friendly contact person for each and any scientific and administrative concern.

Furthermore, I convey my thanks to all members of the group of Cognitive Neuroscience who were unexceptionally cooperative and helpful.

Finally, I wish to thank all of my family members and friends for their interest in my work, for extensive discussions and for encouragement.

Contents

List of Figures

List of Tables

List of Abbreviations

AI	Artificial Intelligence
ME	Modality Experiment
MOT	Multiple Object Tracking
PC	Percentage Correct
RC	Rotation Condition
RF	Reference Frame
RPL	Responded Path Length
RT	Reaction Time
SEM	Standard Error of Mean
SL	Sequence Length (in equations and tables)
SOM	Serial Order Memory
SQL	Sequence Length (as factor)
ST	Spatial Condition
STC	Spatiotemporal Condition
StatC	Static Condition
TC	Temporal Condition
TPL	Total Path Length
UE	Updating Experiment
WC	Walking Condition
WM	Working Memory

Chapter 1

Introduction

Memory enables humans to bring perceived entities, scenes and feelings into a consciously permanent state, even when their physical or situational existence is fading. As such, it lays the ground for almost any kind of conscious human behaviour. Plato describes memory (*mnêmê*) as the retention of sensations affecting body and soul unitedly (Eigler, 1990; 327[1]). Carrying on, Husserl states each vivid remembrance to have a relative and incomplete „weightiness" for a human individual (Ströker, 2009; 326). John Locke regards memory as an indispensable constituent of the self, implying the consciousness of being the person you are (Piccirillo, 2010). No less than this, human action fundamentally depends on prior experiences of the certain individual. Routinely and habitual actions are products of memorized à priori knowledge.

From the very start up to the present day, memory is one of the central topics of interest in cognitive and neuropsychological sciences. The most influential technical memory model in neuropsychology of the 20th century is the *Atkinson Shiffrin model*, also called *modal model*, by Atkinson & Shiffrin (1968). It divides memory into sensory buffer, short-term store and long-term store, according to persistence and manner of information storage.

1.1 Working Memory

Human memory as a pure storage resource raises one essential question - How can we be able to apply unfamiliar perceived information goal-directed to situational requirements within seconds? Answering an unexpected question or following instructions of a navigation device belong to a numberless amount of common such necessities. The instance enabling us to overcome these challenges is the *Working Memory*.

[1] 34 a in Stephanus-Pagination

1.1.1 Theory

Baddeley & Hitch (1974) elaborated the modal model by introducing the concept of a Working Memory (WM) which subdivides into three components: a *Visuospatial Sketchpad* storing perceived visual features and objects and recurrently representing spatial circumstances; a *Phonological Loop* including a phonological store and a rehearsal buffer; and a functionally superordinated *Central Executive* responsible for coordination and resource allocation to subsystems. While a central executive function of the WM is confirmed in contemporary findings (Hills, Todd & Goldstone, 2010), the strict separation of modalities, the assumed fixed storage capacity and lacking consideration of temporal structuralizing capabilities of spatial information became the subjects to criticism (Ward, 2001). Baddeley (2000) adapted the model by adding the *Episodic Buffer* as a fourth component that allows multimodal storage of temporally clustered information. However, the relation between central executive and the three subsystems is not unidirectional but includes bottom-up mechanisms (see Figure 1.1).

The idea of a WM attracted interest and was advanced in several directions of neuropsychological sciences. Different theories and trends have been competing for a finer-grained understanding of WM in recent decades (Baddeley, 2012; Baddeley, Hitch & Allen, 2019). Nowadays, the majority of scientific evidence agrees that understanding of WM needs to be predicated on its active processes, rather than on quantified storage capabilities or a strict structural modularity (Barrouillet & Camos, 2010). In the following sections various theories will be presented that either shaped the scientific development of WM or contributed to a coherent framework of WM. Likewise, processes and mechanisms will be outlined, which are essential to the WM. According to the purposes of this work, visual and spatial facets will be emphasized.

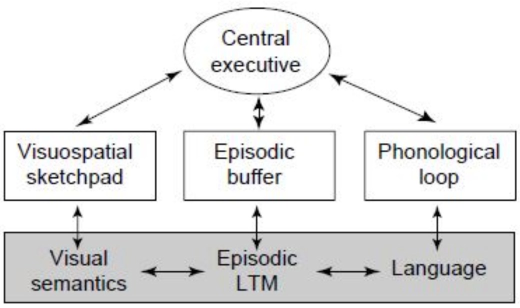


Figure 1.1: The Multicomponent Model of Working Memory; from Baddeley (2000; 421)

1.1.2 Processes and Tasks

Maintenance The majority of accounts agrees on a capacitive storage limitation as a central characteristic of the WM. Findings suggest WM capacity to correlate with fluid intelligence (Fukuda, Vogel, Mayr & Awh, 2010) and predict empathy traits (Gao, Ye, Shen & Perry, 2016). Various scientists attempted to define a discrete maximum number of information units that could be maintained simultaneously. Miller (1956), one of the first scientists to theoretically address a quantification of maintenance limitation, estimated the number of simultaneously storable information units at seven and termed this the *magic number*. Depending on inter-individual genetic differences and the information modality, he assumed a deviation latency of two units (Miller, 1956). Even though *Miller's Magic Number* remained an established figure in psychology, his accessible approach has two major pitfalls that were questioned in recent decades: the assumption of untrainability and the pure focus on quantitative definedness but not on time as a non-linear diffusion parameter in memory traces (Baddeley & Hitch, 1974). Cowan (2001) assumed four units with a potential enhancement due to efficient information organization. However, more recent accounts dissent approaches that estimate WM capacity in terms of a discrete quantification (i.e. *slot models*). Maintenance is rather regarded to be attention-based, where attention allocation shares resources with all the other WM processes - a lack of attention leads to continuous memory diffusion dependent on time passed since encoding (Barrouillet & Camos, 2007).

Grouping In order to increase the total load of maintainable information several items are perceptually connected (i.e. *grouped*) according to common properties. Although the range of connecting properties is heterogenous across the senses (temporal aspects: co-occurence, narrow temporal appearance, velocity; auditory aspects: pitch, harmony, prominence, volume), visual aspects (color, shape, contrast, resolution, salient features) appear to be most suitable for grouping strategies (Morey, 2019).
One of the main scopes of grouping is dynamic cognition, specificially *Multiple Object Tracking* (*MOT*) (Pylyshyn & Storm, 1988). Besides representing a popular psychological investigation paradigm, MOT is an inevitable cognitive skill in various everyday situations, such as participating in road traffic, doing team sports and watching a movie (Qiu et *al.*, 2018). A number of streams compete for defining the way humans visually track multiple objects simultaneously (Meyerhoff, Papenmeier & Huff, 2017 for overview). One of the most acknowledged theories of grouping mechanisms in dynamic cognition is *Target Grouping*, stating that humans consolidate a number of moving targets to an object of higher order, of which the current middlepoint (i.e. *Centroid*) is tracked (Yantis, 1992). In an eye-tracking experiment Huff, Pa-

penmeier, Jahn & Hesse (2010) demonstrated the use of target grouping to increase with increasing motion velocity of targets. Single targets are, thereby, only briefly saccadically accessed when dissociating too far from the centroid (Huff et *al.*, 2010). The idea of *Multifocal Attention* on the other hand assumes each target to be attended individually, while distractors are perceptually filtered (Cavanagh & Alvarez, 2005). Multifocal attention is thus in line with a straight-forward slot-based resource WM model. Recognition of targets is assumed to be supported by feature information or cues going beyond motional aspects (Awh & Pashler, 2000).
A more immanent form of grouping is *Binding* which describes the perceptual state of several items or features being bound together to one object of a higher order (Baddeley, Allen & Hitch, 2011). Binding mechanisms can be initiated involuntarily, e.g. by spatial proximity (Gao et *al.*, 2017).

Manipulation The term manipulation is broadly defined and subsumes a range of different processes depending on requirements. As will be discussed with respect to the *Modality Experiment* in this thesis, a differentiation according to input modality is inevitable. However, manipulation describes a mechanism by which a short-term representation is transformed in a goal-directed manner (Crone, Wendelken, Donohue, van Leijenhorst & Bunge, 2006). In the region of spatial cognition, manipulation mechanisms involve mental rotation, spatial updating and others (discussed in 1.2).

Within the framework of capacity optimization, an advantageous manipulation is *Filtering* which describes the attentional dissociation of relevant from irrelevant perceptually available information. Filtering efficiency has been shown to be highly predictive of visual WM capacity (Plebanek & Sloutsky, 2019). In modelling terms, this implies that filtering the irrelevant part of the perceptual load requires cognitive effort of a constant amount (F) while the number of targets (n) is neglectable (f_1). The effort of processing the entire perceptual load by attending targets without filtering is determined by the number of targets (f_2). Interferences and number of distractors would - according to this model - bias both strategies equally - e.g. automatized and involuntary visual attention effects (Nakashima & Kumada, 2017) are to be expected in a similar intensity. An increasing number of distractors would increase interference, although not necessarily in a linear relation. Therefore, the additional effort arising from distractors is a function of their quantity (*f(d)*). Further to this, a baseline cost is constantly present. It is symbolically added to the equations as a strategy-independent constant C.

$$f_1(n) = F + W + f(d) + C$$
$$f_2(n) = n * W + f(d) + C$$

In mathematical terms it consequently holds that, for increasing n, f_1 has an upper bound while values of f_2 increase proportionally and limitless. This model predicts the curves of both strategies to intersect at a certain point on the axis of target number (x-axis in Figure 1.2) and thus strategy one to turn into the more beneficial one. The point of intersection depends on parameter setting of filtering cost (F) and target number (n). The fact that filtering is a cognitive skill strongly varying between individuals, as shown in the meta analysis of Luria et *al.* (2016), is represented by F. This implies that a strategy trade-off is dissimilarly beneficial between subjects at a particular target number.

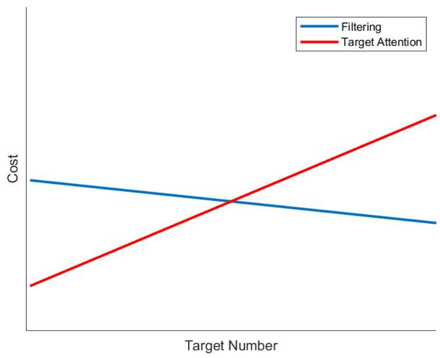


Figure 1.2: Filtering Costs

1.1.3 Neural Substrates

Different measurements of brain activity have been successful in characterizing and evidencing WM processes. Central executive processes were shown to be mainly initiated by activity in the dorsolateral prefrontal cortex (D'Esposito et *al.*, 1995). The contralateral delay activity has reliably correlates with both number of simultaneously maintained items (Störmer, Li, Heekeren & Lindenberger, 2013) and intersubjective filter efficiency (Luria, Balaban, Awh & Vogel, 2016) in visual WM. For visual input, neural correlation in the posterior cortex underlines the functional dissociation of spatial (dorsal) and non-spatial (ventral) WM (Wager & Smith, 2003).

1.1.4 Modalities

The different human senses continuously provide input of different structures to the cognitive system. In order to appropriately process incoming unfamiliar information, adequate WM capacities and processes need to be allocated and initiated. Human proficiency in handling multimodal requirements can be observed in various everyday situations, such as walking and having a phone call at the same time.
Despite assuming a superordinate central execution, the original multicomponent model distinguished between input from different senses (Baddeley & Hitch, 1974). Multimodal models, on the other hand, assume input to be processed essentially by the same mechanisms (Katus, Grubert & Eimerl, 2017). Importantly, evidence for multimodal (i.e. modality independent) theories suggest, further to a resource shared among modalities, joint processes (Knight & Tlauka, 2018). A number of studies found flexible resource trade-off between modalities, e.g. in dual-tasks (Nieborowska et *al.*, 2019), reward (Morey, Cowan, Morey & Rouder, 2011) and cross-modal interference paradigms (Spilcke-Liss, Zhu, Gluth, Spezio & Gläscher, 2019). Cross-modal binding has also been observed (Gao et *al.*, 2017). The counteridea of a modality independent WM is that there is a split between some independently operating subsystems, each responsible for processing information of a particular modality. In general, there is a broad consensus about a modality independent executive processing. The existence of capacity limitations is undoubted, while it is in discussion whether a bottleneck occurs due to demands of a specific modality or on a more general level. It was provided evidence that even after maximum capacity of visual WM is reached auditive information can be stored (Arrighi, Lunardi & Burr, 2011), which indicates that at least some processes are outsourced to domain-specific subsystems. Consequential to a cooperation of domain-general and domain-specific WM mechanisms, processing bottlenecks are possible in the context of both the respective domain subsystem and the central system.

It is important to note that sensation is not the only principle of WM categorization. The three most prominent entities which are not sense-constrained but discriminative in WM are time, space and language. Exemplifying, temporal efforts challenge WM theories in the respect of whether they concern sensory defined subsytems individually, concurrently or they are subject to the central executive. Some experimental WM tasks entail temporal requirements, such as maintenance, delay processing and timing (Hongsup, Qijia & Wei, 2017). Therefore, in this work, WM subsystems are referred to either based on the sensory or the 'task-related' modality[2].

[2] The expression *task-related modality* is chosen because information of more abstract entities (i.e. space, time and language) is to be processed depending on situational require-

The most common term combining sensory and abstract modalities in WM is *visuospatial working memory* (Van der Stigchel & Hollingworth, 2018). However, the consequent suggestion of a subsystem principally processing visual and spatial information integratively is not sustainable (Baddeley, 2000), because visual and spatial WM parts have been shown to be widely independent in terms of capacity and manipulation (Sanada, Ikeda & Hasegawa, 2015). Thus, it is more reasonable to assume both parts individually, a visual and a spatial WM.

1.1.5 Serial Order Memory

Serial Order Memory (*SOM*) subsumes cognitive processes and mechanisms enabling an agent to store a number of items according to their succession (Hurlstone, Hitch & Baddeley, 2014). This succession can be determined temporally or structurally (e.g. spatially, hierarchically). SOM is to be observed as a primarily WM-related part of memory, although considering the ability of memorizing phone numbers for years without using them proves that this attribution is not exclusive. The majority of SOM research investigates the verbal and visual modality - i.e. temporally organized sequences of either verbal units or locations and features of objects are to be learned and memorized for a time interval of seconds to a few minutes (Hurlstone & Hitch., 2015). SOM is defined according to characteristics in behavioral scientific data, that are common across modalities, rather than by neural correlates. Such characteristics are sequence length effects (longer sequences are harder to memorize), item similarity effects (similar features between items lead to transposition errors), temporal grouping effects (items with neighboring temporal occurrence are stored associatively), a primacy gradient (accuracy decreases in the course of the sequence) and others (Hurlstone et *al.*, 2014).

Corsi Task

One of the most popular experimental paradigms investigating SOM and spatial WM is the *Corsi Task*, also called *Corsi's Block-Tapping Task, Corsis' Task* or *Corsi Test* (Corsi, 1972). The original task introduced by Corsi (1972) is made up of a configuration of around ten to 15 wooden blocks (i.e. *items*) which are randomly located within a restricted rectangular area (Figure 1.1.5). An experimenter taps a sample of the blocks sequentially in a steady velocity of about one tap per one to two seconds. The subject's task is to recall this sequence in the correct order. A *retention interval* is placed between presentation and recall to raise working memory demands. The duration of a retention

ments, while sensory information comes in unconsciously. The constituent *task* does not refer exclusively to an experimental task but also to challenges the WM is required to solve in several kinds of natural situations.

interval depends on experimental purposes (Bankó & Vidnyánszky, 2010). The number of items to be remembered (i.e. *Sequence Length*) commonly increases in the course of the experiment. Individual performance is determined by the number of targets recalled at the correct position of the sequence, commonly quantified by Spatial Spans (see 2.4.1). According to cognitive demands, the Corsi Task thus subdivides into three phases. During presentation the subject is asked to encode the sequence. During the temporally flexible retention interval he or she has to maintain the spatial and temporal information. In the recall phase he or she needs to reproduce the sequence.
Due to the technical progress of recent years, the Corsi Task is nowadays usually executed digitalized on a computer. This means that a number of randomly located items (typically squares) is presented on the screen (see Figure 1.4). The participants' view thus corresponds to the top-down view onto a wooden block configuration. An experimenter becomes obsolete because relevant items (i.e. *targets*) are highlighted sequentially by the executing software. Recall is performed by reclicking the targets with the mouse cursor or by finger-tapping. Appropriate computerized programs improve timing accuracy in presentation and retention interval, the opportunity of measuring reaction times automatically and provide a larger reliability and persistence of collected data. Further advantages of the computerized over the analog version are, according to Berch, Krikorian & Huha (1998), a better handling in clinical contexts and more flexibility regarding square number and duration of retention interval.
To build a graphical representation of a spatiotemporal sequence requires all pairs of subsequent targets to be interconnected by an edge (yellow lines in Figure 1.4). The distance thereby covered is referred to as *Total Path Length* (*TPL*). A *Crossing* is present whenever an edge crosses one or more other edge(s) (blue circle). Crossings and increasing TPL have both consistently been shown to decrease performance (Parmentier & Andres, 2006; Orsini, Simonetta & Marmorato, 2004).
The designs of the two experiments conducted within the framework of this thesis are variations of the computerized Corsi Task. Further explications are given in the methods sections of the experiments.

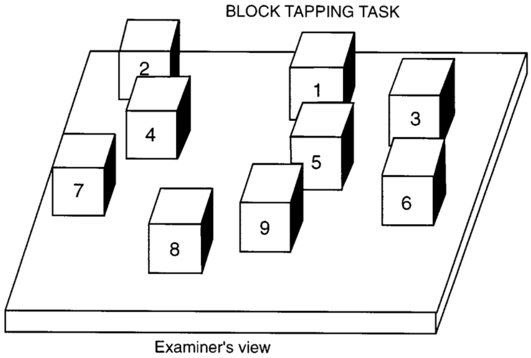


Figure 1.3: Schematic setup of an analogue Corsi block-tapping task; from Milner (1971; 275)

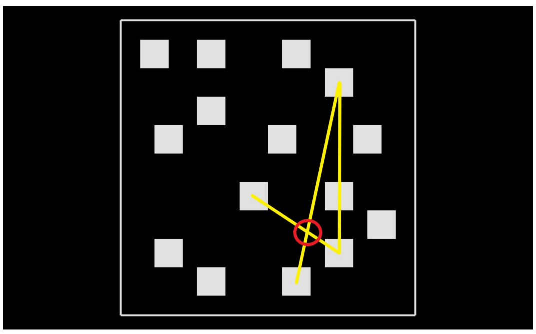


Figure 1.4: Sequence with a path crossing in a digital Corsi Task

1.2 Spatial Cognition

A number of sciences have been concerned with the question of how humans perceive their spatial surroundings. On the side of the humanities, researchers from philosophy over linguistics through to arts address questions of spatial concepts in literature, artworks and language (Earman, 1971; Levinson, 2003). On the side of the natural sciences from cognitive science over AI research through to neurobiology and psychology, interest is directed towards how human space perception and spatial behavior can be observed, modeled and transferred (Welwood, 1977; Katsumata, Taniguchi, Hagiwara & Taniguchi, 2019).

1.2.1 Reference Frames

From the cognitive perspective, a popular account of explaining humans' organization of spatial information is the concept of *Reference Frames* (*RFs*) (Meilinger, Frankenstein, Watanabe, Bülthoff & Hölscher, 2015). Thereby, a spatial reference serves as the origin of a three-dimensional coordinate system, according to which space is cognitively organized. The basic distinction is to be made between egocentric RFs that organize spatial surrounding with respect to the agents body, face or eyes and allocentric RFs that organize spatial environment relative to other objects, scenes or other visible external cues (Klatzky, 1998). Accordingly, the concept of allocentric RFs encompasses a large number of different conversions and is, equally to an egocentric RF, applicable in almost any natural situation.

1.2.2 Spatial Updating

Spatial Updating, as one of the central mechanisms in spatial cognition, describes the capability of anticipating the current spatial circumstances of oneself after ego-motion (Wiener & Mallot, 2006). Spatial circumstances primarily include the direction and distance of one's body (or eyes) from objects and scenes in the surrounding. Sensory enforcement of spatial updating is diverse (Pasqualotto & Esenkaya, 2016) but consensually vestibular and proprioceptive feedback plays an important role (Frissen, Campos, Souman & Ernst, 2011). Extending the updating of single objects, Buelthoff & Christou (2000) have shown that object locations within an configuration are remembered more precisely after one's own motion compared with configuration motion.

1.2.3 Mental Rotation

Shepard & Metzler (1971) investigated how humans recognize three-dimensional polygonal objects when they are presented in a view rotated for a certain angle. Accuracy was on a high performance level across angles (>90%) but reaction times showed a nearly linear positive correlation with angle size (Figure 1.5). This leaded to the proposition that „the average rate at which these particular objects can be thus rotated is roughly 60° per second.“ (Shepard & Metzler, 1971; 703)
Mental rotation is, however, not restricted to orientation of single objects but extends to scene recognition (Buelthoff & Christou, 2000). Mental rotation can be classified in the phases of „(1) search, (2) transformation and comparison, and (3) confirmation of a match or a mismatch” (Xue et al., 2017; 2). Whether comparison is primarily based on a canonical target representation or on visual feature cues, is subject of an ongoing debate (Kaltner & Jansen, 2016).

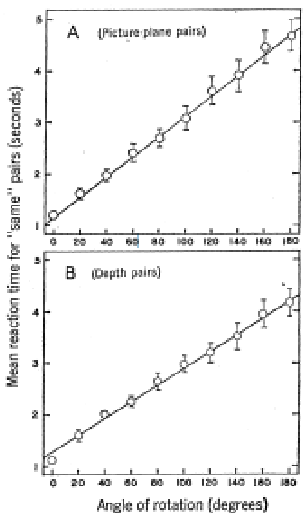


Figure 1.5: Reaction times plotted against mental rotation angle from Shepard & Metzler (1971; 702)

Chapter 2

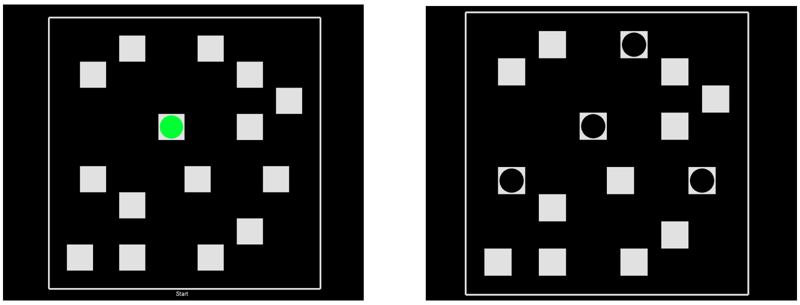
Modality Experiment

2.1 Goals

In the introductory chapter modality-dependency was discussed as a fundamental aspect of WM functionality (see 1.1.4). Against this backdrop, the first experiment aimed to compare the impact of temporal and spatial memorization requirements on WM processing. More precisely, the objective was to observe spatial and temporal task requirements of spatial sequence short-term learning, isolated from each other. Therefore, the impact of the memorized modality on accuracy and reaction time was analyzed. Collected behavioral data was further analyzed regarding qualitative response characteristics to explore whether modality-specific behavioral strategies were used. Such strategies in association with quantitative statistics should provide evidence pro or contra modality-specific WM processing mechanisms in spatiotemporal short-term learning. A further central objective was to explore whether temporal and spatial WM processes are independent of one another or whether there are shared resources, mechanisms or synergic effects. Therefore, the first experiment will be referred to as *Modality Experiment*.

2.2 Conditions

As mentioned in 1.1.5, the Modality Experiment is based on the Corsi Task paradigm. The reference condition of the Modality Experiment reflects a classical computerized Corsi Task while two of three conditions - i.e. the experimental conditions - were fundamentally modified. Information presentation (i.e. sequence displaying) proceeded identically across conditions. Operationalization of the temporal and spatial modality distinction was achieved by variation of task requirements. Consequently, three conditions differing in terms of recall requirements and maintenance circumstances were investigated.



(a) **(b)**

Figure 2.1: Presentation (a) and recall (b) display in the TC

In the *Spatiotemporal Condition* (*STC*), subjects were asked to perform a classical computerized Corsi Task (see 1.1.5). In this way, the entire displayed sequence was to be reproduced in the order of presentation after a retention interval of six seconds.

In the *Temporal Condition* (*TC*), all items contained in the sequence (i.e. *targets*) were overtly marked from the beginning of the retention interval. This means that, after presentation, black circular spots highlighted all previously presented targets simultaneously while irrelevant squares (i.e. *distractors*) remained white (see Figure 2.1 (b)). These markers were constant throughout the entire retention and recall phase. The subject's task was to click the marked targets in the order of their presentation. Thus, spatial information was cued and task requirements focused on temporal sequence components only. Despite the fact that, due to discoloration, distractors were clearly identifiable, clicking one of them was regularly registered as part of the response. Consequentially, it did not provoke an error signal. This design aspect was chosen to prevent disturbances of encoding processes due to attentional shifts (Fang, Becker & Liu, 2019).

In the *Spatial Condition* (SC) subjects were asked to click all targets in any desired order. The order of target presentation did not play any role in the task requirements. Naturally regarding experimental objectives, each target was to be clicked only once. Clicking an item a second time was registered as an error.

While the SC is designed to primarily require spatial WM demands, the TC necessitates temporal sequence learning. The STC serves as a control condition integrating spatial and temporal demands.

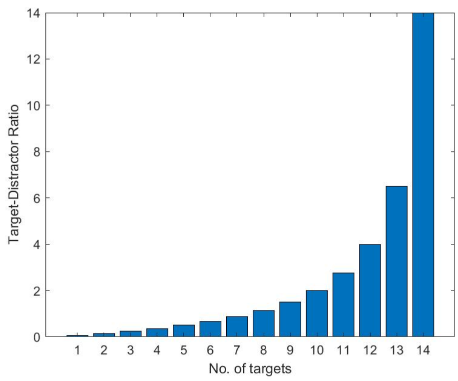


Figure 2.2: Target-distractor ratio for different sequence lengths

2.3 Methods

2.3.1 Stimuli

Basic Patterns

The basic pattern visible throughout presentation, retention and recall phase consisted of a quadratic area of 934 x 934 pixels framed by bars of six pixels width and filled with 15 squares of 90 pixels page length (see Figure 2.1 (a)). This comparably large number of squares (Hurlstone & Hitch, 2015) was appropriate for keeping the relation of targets and distractors in balance. In large sequence lengths, a lower total number of squares would have disbalanced the target-distractor ratio R considerably, which has been shown to influence performance (Geldmacher, 1996).

$$R = i/(n - i)$$

That circumstance would have provided the opportunity to attend only to distractors and maintain a 'negative copy' representation. Subsequently, the remembered squares would be mentally blocked and the remaining ones would constitute the response array. This strategy could have been beneficial especially in the TC because an accurate performance does not necessitate storage of dynamic and time sensitive aspects. Even though it is speculative whether usage of this strategy would have applied in this experimental context, the chosen set-up ensured that it was not beneficial.

Positions of the square items were randomized with the restriction of a minimum distance of 20 pixels between their outer borders in each direction. There were four basic patterns alternating between trials. Thus, they replicated for each sequence length. This provided the advantage of keeping conditions comparable by repeating sequences on mirrored patterns.

Sequences

Sequences were produced pseudorandomized such that no subsequence of three or more consecutive targets occured in multiple sequences. For each sequence length and subtrial, a distinct sequence was applied. Total Path Length (TPL; for meaning see 1.1.5) was checked for in the sense that sequences of n targets were restricted to have a smaller TPL than each sequence of n-1 and a larger TPL than each sequence of n+1 targets. Notably, an item occured not more than once within a certain sequence.

2.3.2 Participants, Apparatus and Instruction

Twelve subjects, aged between 19 and 26 years (M = 22.83, SD = 2.17; six of which were female), participated in the experiment. All were students of the University of Tübingen, Germany. They were reimbursed by course credit according to their time effort.
The experiment was conducted on a 23-inch monitor with a width of 50 cm, a height of 30.5 cm and a resolution of 1680 x 1024 pixels. Subjects sat with their eyes approximately at the height of the screen center and 70 cm frontally distant to it. Experimental implementation, visualization and data storage was programmed in and ran by Matlab (MATLAB R2018b, The MathWorks, Inc., Natick, Massachusetts, United States) with Psychtoolbox-3 extension (Brainard, 1997; Kleiner, Brainard & Pelli, 2007).
Instructions were given verbally and in written form on a sheet handed out prior to experimentation. First, subjects were introduced to the general procedure of a computerized Corsi Task. Subsequently, recall requirements of both the experimental conditions were explained extensively. Subjects were instructed to perform the task as accurately and as fast as possible. On the instructional sheet, the proceeding was additionally illustrated graphically by screenshots of the succession of a trial for each condition. Subjects were insured that participation is voluntary and can be aborted at any time without negative consequences. Before starting the experiment, subjects were offered to pose remaining comprehension questions. Subjects were naïve to scientific intentions of the experiment and to the variation of number of crossings (see 2.3.4).

2.3.3 Procedure

Each participant was assigned a condition order. Across participants, the orders were counterbalanced according to latin-square (Williams, 1949). The assigned condition order applied for each sequence length within-subject. Subjects performed twelve subtrials per sequence length, four of which in each condition. After twelve trials of a particular length, sequence length increased by one. From sequence length six onwards, procedure was adaptive. This means that a participant had to be successful in at least one of four subtrials in order to be presented with the following series in the respective condition. However, if a subject failed in all four subtrials of a series in one condition, he or she could still proceed in the remaining condition(s), as long as he or she was successful. Maximum sequence length was set to ten, so that a condition either ended with failing in all four subtrials of a particular sequence length or after finishing the final subtrial of sequence length ten.

Trial Proceeding

Initially, a between-trial display with information on condition, sequence length and trial number was shown. After three seconds, the participant could start the trial by clicking the space key. In immediate consequence, the presentation display switched to a quadratically white framed 934 x 934 pixel-sized basic pattern with 15 white squares (Color Code[1] [225 225 225]) on a black background. After 500 ms the first target of the sequence was highlighted in a light green ([0 153 0]) for 1000 ms (see Figure 2.1 (a)). Subsequently, the second target was highlighted for the same duration with a delay of 500 ms in between and so forth[2].
After the final square of the sequence was marked, the retention interval started. This means in the subsequent six seconds, subjects were required to maintain the presented sequence in memory while the basic pattern remained on screen, although items changed their color from white to gray ([122 139 139])[3]. Condition-specific adaptations of the retention interval in the TC are explained in 2.2 'Conditions'.
In the recall phase the initial cursor position was at the screen center. A clicked item was highlighted for 400 ms. Recall was locked within this time period which was indicated by an invisible mouse cursor. However, moving the cursor was technically still possible. Each item had an external range capturing all clicks of maximum five pixels absolute distance to each outermost point of the item. In other words, the capturing range of an item was a square with a page length five pixels larger than page length of the item square. In case a click did not hit any capturing range, all items were highlighted in red ([225 0 0])

[1] according to RGB Color Codes Chart

[2] The brief delay between target-highlightings was applied to prevent illusory motion perception (Davidenko, Heller, Cheong & Smith, 2017)

[3] The screen did not turn black during retention interval to offer the opportunity to use rehearsal strategies (Tremblay, Saint-Aubin, & Jalbert, 2006). Additionally, the presence of spatial cues presented during retention interval in the TC would have led to a disparity between conditions.

for 400 ms. Clicking a single item several times did neither lead to exclusion of the respective click from data collection nor to an error signal. In other words, consequences were the same as those of any other incorrect click. After clicking n times the between-trial display of the consequent trial was shown. Condition-specific recall requirements are depicted in 2.2.

2.3.4 Independent Variables

Recall Condition

The independent variable of central interest was recall requirement. There was a threefold distinction of recall requirement operationalized by three conditions (see 2.2).

Number of Crossings

In addition to differences between temporal and spatial processing in the Corsi Task, the Modality Experiment focussed on potential effects of crossings (Figure 1.4) occuring within the trajectory of a sequence on task performance.

Crossings in sequences of length three are geometrically impossible. In sequences of lengths four, five and six, the amount of crossings varied between *high* and *low* frequency. Independent of sequence length, low crossing frequency indicated that no crossings occurred in the respective trial. High crossing frequency referred to one crossing in trials with a sequence length of four and to two crossings in trials with a sequence length of five and six.

Sequence Length	High-Crossing Number	Low-Crossing Number
four	1	0
five	2	0
six	2	0

In sequences of lengths seven and above a no crossing restriction would make the trajectory hardly preventable to transform into a circular structure. On the other hand, integrating a number of crossings that is only slightly below number of edges would lead to counterintuitive formations. Therefore, a medium number of crossings was applied to all trials with a sequence length of seven and above.

Notably, whenever an edge crossed more than one of the already existing edges, one crossing was counted. Hence, each step could maximally cause one crossing.

Sequence Length

Sequence length refers to the number of targets constituting the sequence presented in a trial. It is the most elementary determinator of complexity in the Corsi Task. This is underlined by the fact that classical spatial spans (2.4.1) determine spatial WM capacity based on the sequence length a subject is able to succesfully perform (Weicker, Hudl & Thöne-Otto, 2017).

2.4 Statistical Analysis

2.4.1 Dependent Variables

Dependent variables are accuracy and reaction times. Accuracy is quantified by three measures. First, by means of the *Spatial Span* (see 1.1.5). Second, the *Weighted Span*, a modified spatial span, is computed and statistically taken into account. Third, *Percentage Correct* (*PC*) is considered as a more fine-grained measure.

Accuracy

All accuracy measures are computed for both correct trials and correct clicks. A trial is considered correct when the entire amount of targets is responded correct according to recall requirements. In the STC and TC a click is considered correct when an item is clicked at the identical place of the response sequence as it has been in the presentation sequence. In the SC a click is considered correct when an item is clicked which occured in the presentation sequence and has not been clicked in the response sequence before. Each accuracy score is computed for both the trial and click level. Accuracy measures are used for a general chart and as a basis for Analyses of Variance (ANOVA) and further quantitative statistical analyses. The most remarkable difference between PC and spans is that analyses on spans neglect the sequence length factor[4]. However, their advantage over PC is that they model performance in an appropriate descriptive manner. Computation of the three measures is explained in the following.

Spatial Span On trial level, the spatial span is descriptively calculated in the way that each correct trial is weighted one and each incorrect trial zero. Numbers of correct trials across sequence lengths are added up. Finally, the intermediate score is divided by the number of trials per sequence length. This procedure is conducted for each condition separately. Consequently, in the Modality Experiment 16 to 32 trials are taken into account per condition.

[4] When referring to sequence length as a statistical factor, it will be denoted as *SQL*

On click level, the spatial span is descriptively calculated in the way that each correct click is weighted one and each incorrect click zero. Numbers of correct clicks within trials of a particular sequence lengths are summed up and divided by the total number of clicks within this sequence lengths (i.e. Sequence Length * Number of Trials). Finally, intermediate scores of different sequence lengths are added up.
As sequences of short lengths (from one to two or three) are assumed to be reliably solvable, a basic constant C is added for both trial- and click-spans. This implies that the subject would have solved sequences of these lengths successfully. This assumption is reasonable in the light of scientific evidence from serial order and WM research (Hurlstone & Hitch, 2015). To ensure reliability of this assumption, data of participants failing in at least three quarters of all sequences of lowest length was excluded from all quantitative analyses. Such a performance suggests either task comprehension, motivation or cognitive abilities to be impaired during the experiment.

Trials

$$\forall\, condition \text{ one has } SpatialSpan = C + \sum_{SL=SL_{min}}^{SL_{max}} \frac{CorrectTrials_{SL}}{Trials_{SL}}$$

Clicks

$$\forall\, condition \text{ one has } SpatialSpan = C + \sum_{SL=SL_{min}}^{SL_{max}} \frac{CorrectClicks_{SL}}{Clicks_{SL}}$$

Weighted Span To enhance the role of sequence length in an aggregated individual span score, the weighted span introduces a weighting which increases linear to sequence length and thus determines the effect of a correct trial on the span score. More precisely, a correct trial is multiplied by its sequence length. The sum of the resulting products is divided by the total number of trials. The main advantage of the weighted span is that it makes span scores more discriminative. Furthermore, weighted spans are expressive because they enable compensation of errors in trials with a lower sequence length than the actual competence level. The constant score C, representing the presupposed solvable sequence lengths, would in the Modality Experiment amount to three because of the weighting factor of sequence length two.

Trials[5]

$$\forall\, condition \text{ one has } C + \sum_{SL=SL_{min}}^{SL_{max}} SL * \frac{\sum_{i=1}^{M} CorrectTrials_i}{Trials_{SL}}$$

Clicks

$$\forall\, condition \text{ one has } C + \sum_{SL=SL_{min}}^{SL_{max}} SL * \frac{\sum_{i=1}^{N} CorrectClicks_i}{Trials_{SL} * SL}$$

Percentage Correct Percentage Correct and spatial spans are equivalent in regard to variance analyses. Thus, according analyses will be reported for PC exclusively. Spatial spans will be presented for descriptive purposes.

$$PC = n_{correct}/n_{total} * 100$$

Trials

$$PC = \frac{\sum_{i=1}^{M} CorrectTrials_i}{M} * 100$$

Clicks

$$PC = \frac{\sum_{i=1}^{N} CorrectClicks_i}{N} * 100$$

Reaction Times

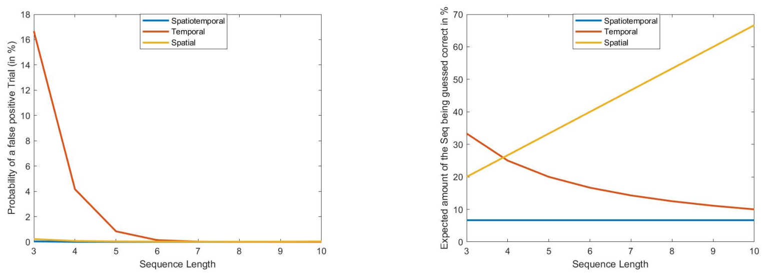
Reaction Times (RTs) were measured from the beginning of the recall phase to the click of the last item of the response sequence. As beginning of the recall phase was clearly signalized by the items turning white, this moment was more adequate to start time measurement than the first click of the response. Due to the implemented inhibition of click-sensitivity for 300 ms after each click, (n-1)*0.3 seconds were subtracted of the total RT with n referring to sequence length. Consequently, RT of each trial was divided by its sequence length to make results comparable across sequence lengths.

$$RT_{preprocessed} = \frac{RT_{total} - (SL - 1) * 0.3s}{SL}$$

[5] $N = SL * M$ and $M =$ Subtrials per length and condition

2.4.2 Guess Probabilities

To assess results adequately, consideration of probabilities of responses being correct by chance is required. In general, the classical Corsi Task paradigm stands out due to an immunity to trials being entirely correct by guessing. The two experimental conditions' (SC and TC) vulnerability, however, is higher and largely dependent on sequence length. In addition to guess probabilities on trial-level, the expected numbers of incidentally correct clicks are calculated as potential confounders for click-based analyses.
All formulas are fitted to the conditions of the Modality Experiment - differing manipulations might lead to alterations[6]. The formulas presume that no item is clicked twice within one recall period and that each click hits any item. However, the description of the STC is equivalent to the one of a classical Corsi Task. For all graphics on guess probabilities the total item number parameter (i.e. m) is, according to the Modality Experiment, set to 15. Due to significantly distinct guess probabilities between conditions in the Modality Experiment, according values are depicted in result illustrations of click data.



(a) (b)

Figure 2.3: Guess probabilities of a correct trial (a) and relative amount of correct clicks (b)

[6] Guess Probabilities of all conditions of the Updating Experiment are equal to those of the STC.

Trials

Spatiotemporal Condition

$$p_{correctTrial} = \prod_{i=0}^{n-1} \frac{1}{(m-i)}$$

Temporal Condition

$$p_{correctTrial} = \prod_{i=0}^{n-1} \frac{1}{(n-i)}$$

Spatial Condition

$$p_{correctTrial} = \prod_{i=0}^{n-1} \frac{(n-i)}{(m-i)}$$

Clicks

Spatiotemporal Condition

$$EV_{correctClicks} = \sum_{i=1}^{n} \frac{1}{m}$$

Temporal Condition

$$EV_{correctClicks} = \sum_{i=1}^{n} \frac{1}{n}$$

Spatial Condition

$$EV_{correctClicks} = \sum_{i=1}^{n} \frac{n}{m}$$

2.4.3 Data Exclusion

Datasets of subjects who correctly solved less than one third of all clicks across four-target trials were entirely excluded from analyses. Reasons for this requirement are explained in 2.4.1. Conducively to data utility, no participant met this exclusion criterion.

Most importantly, trials not being performed were treated as incorrect in aggregated analyses. A subject who disqualified for one condition (according to criteria described in 2.2) was not to be assumed solving a trial of higher sequence lengths. It is reasonable that four subtrials suffice to clarify whether a subject has the respective WM competences - especially given the fact that TPLs were homogeneous within and aligned between sequence lengths. Consequently, the described data dealing was applied.

Analyses on basis of clicks were mostly restricted to the critical sequence length range of four to six targets because of strongly disbalanced data sets from sequence length seven on. Especially, the within-subject asymmetry of reached sequence length between conditions impeded a valid analysis. A way to overcome this issue would have been to fill the empty data cells with the corresponding guess probabilities (2.4.2) which, however, would have biased the condition comparison due to large differences in higher sequence lengths (see Figure 2.3). For click-based plots, PC represents the ratio of correct and performed clicks. This means empty data cells are not considered.

Table 2.1 depicts how far participants proceeded in a particular condition.

Participant	Spatiotemp.	Temporal	Spatial
1	8	10	10
2	6	8	6
3	10	8	10
4	7	10	10
5	8	10	10
6	10	10	10
7	8	9	9
8	10	10	7
9	10	10	10
10	6	9	10
11	7	7	7
12	7	8	9
Ø	8.08	9.08	9

Table 2.1: Maximum sequence length a participant reached per condition

2.4.4 Overview

Data preprocessing, including evaluation of the accuracy and RT measures described above, was executed in Matlab (MATLAB R2019b, The MathWorks, Inc., Natick, Massachusetts, United States). Analyses of variance were conducted using SPSS Statistics software (IBM Corp. Released 2019. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY: IBM Corp.).

In each illustration of the experiment, horizontal lines inside of group bars in bar plots indicate the respective guess probability (2.4.2). Error bars in bar plots represent Standard Error of Mean (SEM; Altman & Bland, 2005). Presence of a horizontal bar above group bars represents a significant ($p < .05$) relation between both connected groups, while number of stars is assigned to the p-value of the respective relation:

*	$p < .05$
**	$p < .01$
***	$p < .001$

Constants	Independent Variables	Dependent Variables
Presentation Style	Recall Requirements	Spatial Span
Crossings from SL 7	Crossings from SL 4-6	Weighted Span
Total Path Length	Sequence Length	Percentage Correct
		Reaction Times

Table 2.2: Relevant constants and variables - Modality Experiment

Chapter 3

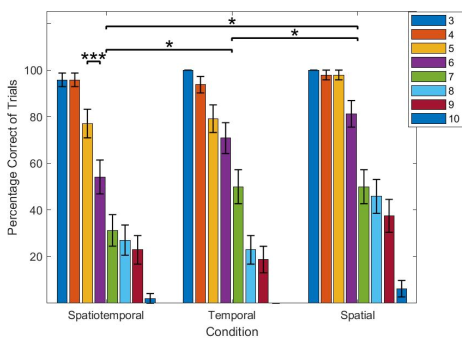
Results Modality Experiment

3.1 Accuracy

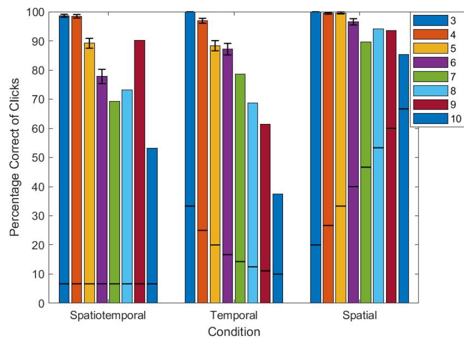
3.1.1 Global Analysis

In the first step of accuracy analysis, a global procedure was accomplished by conducting a n-way ANOVA with condition (three factor levels) and SQL (eight) as repeated measures and correct trials as input data. It showed that condition ($F(2,\ 10) = 5.41$, $p = .026$, $\eta_p^2 = .52$) and SQL ($F(7,\ 5) = 382.32$, $p < .001$, $\eta_p^2 > .99$) exhibited highly significant main effects. Significance bars in Figure 3.1 (a) symbolize the described main effects.

Based on weighted spans of all participants as input, condition main effects remained significant ($F(2,\ 10) = 4.63$, $p = .038$, $\eta_p^2 = .48$). Weighted and unweighted spans are illustrated in Figure 3.2, where color indicates participant and black dots represent the mean values. Notably, the possible range of spatial spans is two to ten and the total range of weighted spans is three to 55.

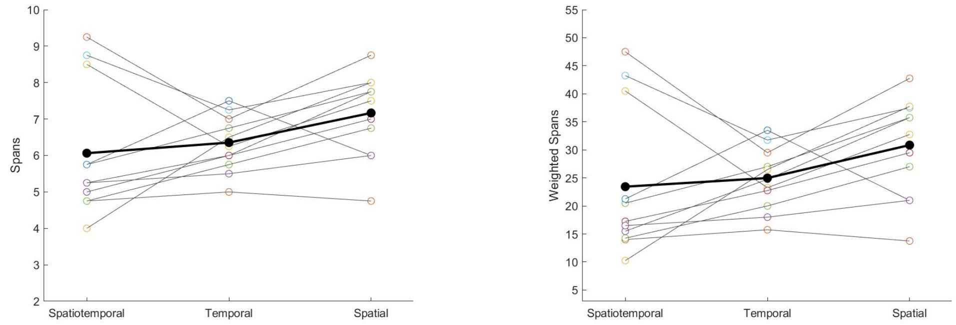


(a)



(b)

Figure 3.1: Percentage Correct of trials (a) and clicks (b)



(a) **(b)**

Figure 3.2: Trial-based spans unweighted (a) and weighted (b)

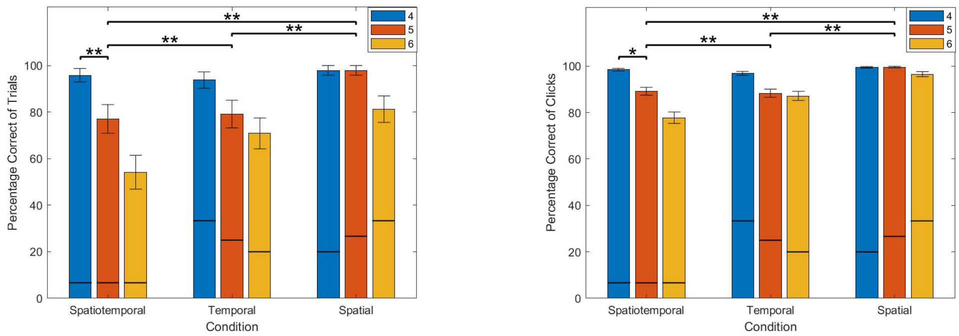
3.1.2 Crossing Range

Main analyses of the Modality Experiment focussed on data ranging from sequence length four to six. This is due to variation of crossing frequency and the fact that each participant performed all trials in the according range. Respective Percentages Correct on trial and click basis are given in Figure 3.3.

Within the according range, an ANOVA with condition (3), crossing frequency (2) and SQL (3) as repeated measures was executed. Main effects of condition ($F(2,\ 10) = 7.71$, $p = .009$, $\eta_p^2 = .61$) and SQL ($F(2,\ 10) = 8.66$, $p = .007$, $\eta_p^2 = .63$) were significant. The factor crossing did not reach significance ($F(1,\ 11) = 1.1$, $p = .317$, $\eta_p^2 = .09$). However, there were significant interaction effects of condition x crossing ($F(2,\ 10) = 6.6$, $p = .015$, $\eta_p^2 = .57$). A Tukey post-hoc test showed crossing effects to be significant in the TC only.

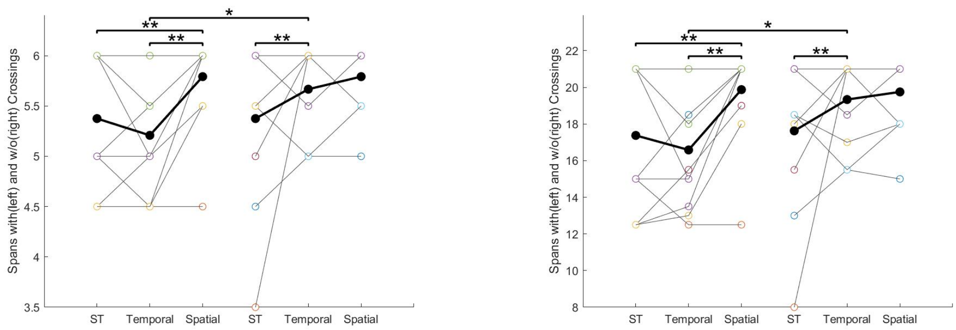
Based on click data, the identical ANOVA showed identical significant relations. Main effects of condition ($F(2,\ 10) = 9.24$, $p = .005$, $\eta_p^2 = .65$) and SQL ($F(2,\ 10) = 6.81$, $p = .014$, $\eta_p^2 = .58$), as well as interaction effects of condition x crossing ($F(2,\ 10) = 4.5$, $p = .04$, $\eta_p^2 = .47$), changed only marginally.

Spans, separated by high and low crossing frequency, are illustrated in Figure 3.8. The weighting of spans provoked different statistical outcomes compared to PC analysis. Namely, an ANOVA with trial-based weighted spans as input resulted, additionally to condition main effects ($F(2,\ 10) = 8.38$, $p = .007$, $\eta_p^2 = .63$), in a significance of the crossing factor ($F(1,11) = 6.53$, $p = .027$, $\eta_p^2 = .37$). More importantly, the condition x crossing interaction effects confirmed their significance in this measure ($F(2,10) = 6.41$, $p = .016$, $\eta_p^2 = .56$).



(a) **(b)**

Figure 3.3: Percentage Correct of trials (a) and clicks (b) within the crossing range

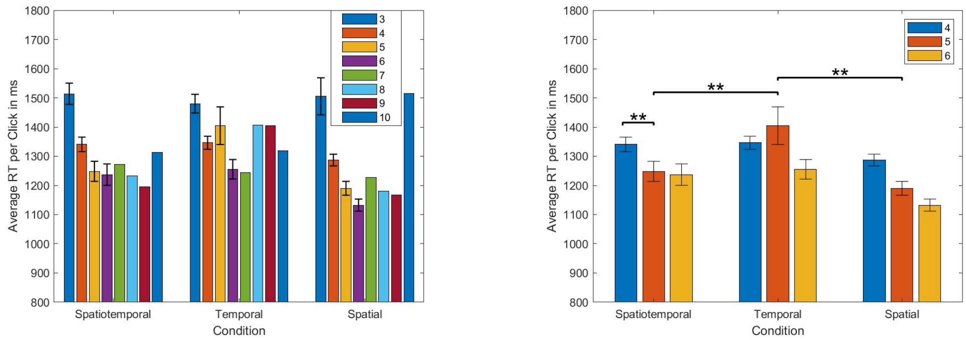


(a) **(b)**

Figure 3.4: Spatial (a) and weighted (b) spans in high (left lines) and low crossing (right lines) trials
Fat black lines indicate means.

3.2 Reaction Times

Due to a disbalanced and inhomogenous data situation in higher sequence lengths, condition and SQL effects were hardly identifiable in RT analysis. Additionally, there were obvious learning effects after sequence length three across conditions (see Figure 3.5 (a)). Therefore, the main analysis again focussed on the most relevant sequence length range from four to six (i.e. crossing range). Here, condition ($F(2{,}10) = 9.2$, $p = .005$, $\eta_p^2 = .65$) and SQL ($F(2{,}10) = 9.46$, $p = .005$, $\eta_p^2 = .65$) exhibited significant main effects, while crossing ($F(1{,}11) = 0.04$, $p = .85$, $\eta_p^2 < .01$) did not. SQL main effects are symbolized by the significance bar furthest to the left in Figure 3.5 (b). No interactions were significant.



(a) (b)

Figure 3.5: Reaction times across sequence lengths (a) and within the crossing range (b)

3.3 Comparative Analysis

In order to check the independence of spatial and temporal WM processing, data of the SC and the TC was merged (referred to as *Split Condition*) and compared to data of the STC (in this context synonymously referred to as *Integrative Condition*). This comparison was drawn according to the following formula. Closer explications on formula derivation and result interpretations are given in 3.5.2.

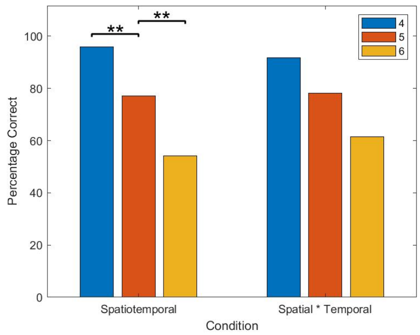
$$p(ST) = p(S) * p(T)$$

Table 3.1 shows delta values between accuracy in the STC and the conclusion of SC and TC in percent. The values are attached by the decreasing number of participants with increasing sequence length, resulting in a considerably broadening distribution.

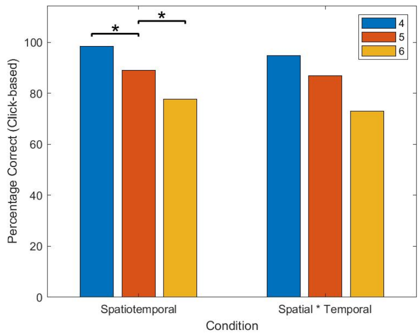
Sequence Length	3	4	5	6	7	8	9	10
Trials	4.16	-4.16	1.04	7.29	-3.12	-38.5	-62.5	-12.5
Clicks	1.39	-2.08	-1.12	6.73	3.1	-15.4	-18.98	-36.56

Table 3.1: Percentages Correct of *Integrative Condition* minus *Split Condition* for trials and clicks

A repeated measures ANOVA for the crossing range (PC in Figure 3.6) showed the comparative condition factor markedly not to be significant ($F(1{,}11) = 0.07$, $p = .8$, $\eta_p^2 < .01$).



(a)



(b)

Figure 3.6: Percentages Correct of *Integrative Condition* (left groups) and *Split Condition* (right groups) of trials (a) and clicks (b)

3.4 Qualitative Error Analysis

3.4.1 Responded Path Length

In order to examine used strategies, *Responded Path Lengths* (*RPL*) were computed in the SC. RPL refers to the total length of the trajectory interconnecting subsequent items of the response sequence. Due to the fact that succession is irrelevant in the SC, there are different options of correct response sequences. Thus, RPL of a correct response is not necessarily equivalent to the presented total path length (previously referred to as *TPL*). RPL values were normalized according to the presented TPL. This was executed for each performed trial of each participant separately. The resulting aggregated values for each sequence length are depicted in Figure 3.7. Again, it is notable that in higher sequence lengths less data is on hand which leads to a broader dispersion. Although PL effects were not significant according to total values, there is an obvious tendency of distance savings in responses. Leaving out sequence lengths three and four, in which few potential savings are provided, leads to an average RPL

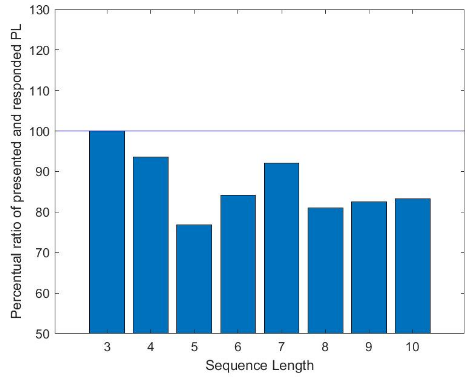


Figure 3.7: Ratio of responded and presented path lengths in %

of 83.34% relative to presentation. This is a noticeable proportion in regard to the fact that minimum RPL - i.e. the shortest possible path interconnecting all targets - amounts to 50-60% of presented TPL. Furthermore, there is not a single sequence length in which mean RPL is larger than mean presented TPL.

3.5 Discussion

The Modality Experiment aimed to characterize the WM effort, requirements of different modalities cause in spatial short-term sequence learning. Additionally, it focussed on the impact of path crossings on information encoding and maintenance of different modalities. For both accounts, the empirical results provide promising insights. Concerning modality-specific differences, it has shown that both spatial and temporal aspects noticeably contribute to the total demand of a Corsi Task. This is evident because both experimental conditions (each disregarding one modality) were performed significantly better than the STC. Furthermore, SC led to significantly better results than TC. Concerning the role of crossings, it has confirmed previous evidence stating that crossings lead to a performance decrease. Crucially, an interaction of condition and crossing showed the crossing interference to be present exclusively when task requirements involve temporal components. SQL reached a significant state across measures, conditions and participants which underlines reliability and validity of the collected data.

3.5.1 Inferences

The fact that both experimental conditions outperformed the reference condition - besides showing appropriateness of the explorative approach and implementation - clearly exhibits that the Corsi Task is a task not exclusively attaching visual WM storage capacity but additionally presenting temporal challenges. Nonetheless, the most striking finding of the Modality Experiment is that SC performance significantly surpasses TC performance, in spite of the fact that exclusively in the TC overt cues were provided. In combination with the uniqueness of presentation across conditions, this finding suggests that there are considerable differences in cognitive organization and maintenance strategies between conditions.

Grouping

A rationale for the outstanding performance in the SC is that the memorandum was organized in a more efficient way than in both other conditions. Due to consistent findings on capacity limitations in the spatial WM (Cowan, 2010), an asymmetry between conditions to this extent gives the impression of cognitive strategy use. A common way to enlarge the number of simultaneously stored information units in WM is clustering, according to spatial entities implemented by grouping (explained in 1.1.2). RPL analyses showed substantial savings in responded compared to presentated path length. Consequently, targets were frequently recalled as clusters connected due to spatial proximity. This suggests short-term representations of targets to be already clustered in the maintenance phase. Arguably, the relevant space (i.e. the basic pattern) is cognitively separated in a low number of regions for an optimized capacity economy.

Filtering

Additionally, filtering mechanisms can partially account for the significant facilities in the SC. Filtering is adequate in the SC exclusively because in both other conditions it is not to sufficient to memorize which items are targets. Regarding PC of trials, that are affected by only marginal guess probabilities, it can be observed that the decrease is comparably more abrupt in the SC. When neglecting sequence length ten in the SC, in which a floor effect (Šimkovic & Träuble, 2019) arises across conditions, decreases going beyond SEM occur exclusively from sequence length five to seven. In both the other conditions a more stepwise decrease occurs from sequence length four to seven or eight. As discussed in 1.1.2, *Manipulation*, filtering strategies can reach a beneficial state from a discrete point (i.e. sequence length) on. Thus, it is arguable that participants switched over to filtering strategies at around sequence length seven to deal with the upcoming threshold of individual target storage. However, this interpretation is to be regarded as an indication that requires additional evidence.

3.5.2 Cognitive Modality Split-up

$$p(ST) = p(S) * p(T)$$

The formula logically presumes that the probability that spatial and temporal requirements are solved within one task is equal to the conditional probability that spatial requirements are solved in a context in which temporal requirements are solved, as well. This holds for the same complexity circumstances (i.e. sequence length) between all components. If this equation proves to be - approximately - true, an independence of spatial and temporal WM processing is to be concluded. Values being larger in the integrative condition would indicate benificial synergism effects when both demands are processed simultaneously. This could arise from shared mechanisms that are cost-reducing (analogous to dual-task findings; Huestegge, Pieczykolan & Janczyk, 2018) or due to the fact that there are slight temporal demands in the SC (i.e. temporally structured encoding phase) and slight spatial demands in the TC (target locations to be remembered until retention interval). Values being larger in the split condition would indicate an advantage due to the opportunity of concentrating resources (i.e. attention and organization) on a particular modality. This could be explained due to a cognitive overload in the integrative condition that leads to a processing bottleneck which does not come about in unimodal demanding circumstances. Consequently, particular WM resources were modality-shared and would stand in competition with each other.

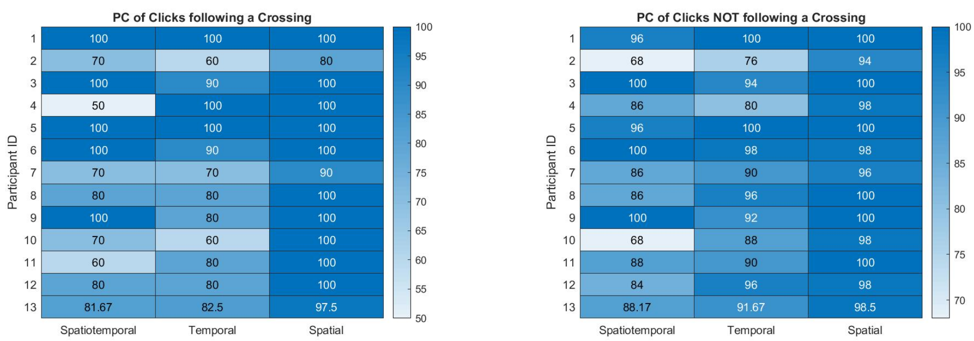
Results fit the formula remarkably well. A substantial difference between integrative and split condition could not been shown in statistical analyses. Evenmore, within the most balanced sequence length range from three to seven the highest absolute difference in correct trials between both conditions is 7.29 % (table 3.1). Adding up values within this range amounts to +5.21. Values from sequence length seven on are negative. This striking balance makes the assumption of a strict modality separation legitimate. However, it is arguable that with increasing complexity synergic effects of modality-general processing become more beneficial (indicated by diminishing values in table 3.1). Both these latter assumptions require additional evidence.

3.5.3 Crossings

Crossings have consistently been shown to worsen performance in the Corsi Task (Orsini et al., 2004). However, explanational accounts for this phenomenon are rare. The Modality Experiment gives some indication for what could cause this interference. The statistical analyses clearly revealed that impairment of crossings on performance occurs only when task requirements involve a temporal component. Although a negative correlation between crossing and PC is significant in the TC only, the error rate of clicks following a crossing is more than 50% larger relative to clicks following a regular step (see Figure 3.8). It is therefore likely that significant effects in favor of low crossing trials would have ensued with larger sequence lengths or a larger basic population.

In the SC the crossing factor was not significant and did not even exhibit a numerically obvious impact. Vandierendonck & Andres (2006) argued that crossings interfere in logical consequence of encoding rather than of rehearsal processes. The current findings contradict this assumption. In the Modality Experiment presentation proceeded identically across conditions. This does not inevitably mean that the entire encoding mechanism was identical but, as visual target marking is irretrievable, it produces a *Now-Or-Never bottleneck* (Christiansen & Chater, 2016). This means, while - or immediately after - a target is presented, at least a coarse representation needs to be generated. Thus, a first encoding step is time-critical while integration and preparation of intermediately memorized information could proceed in an internally organized manner.

Performance in the SC outperformed those in STC and SC even when crossing frequencies were balanced. Analysis of RPL showed that this effect is likely caused by grouping mechanisms. This account is compatible with the absence of crossing effects in the SC because group-based structurization according to spatial proximity does not require interconnections of targets. This does, however, not contradict the discussion on temporally structured encoding. To the contrary, taken together it leads to the closure that internal cognitive spatial structurization is hierarchically superior to external temporal structurization.



(a) (b)

Figure 3.8: Percentage Correct of clicks consequent to a crossing (a) and a regular step (b)
line 13 indicates means

3.5.4 Conclusion

The Modality Experiment explored impact and interdependencies of spatial and temporal WM demands in spatiotemporal short-term learning (i.e. Corsi Task).

The most prominent result of the Modality Experiment was that performance was considerably better when temporal recall requirements were removed. Furthermore, path crossings in sequence presentation had an influence only in time-relevant task settings. When order of target recall was arbitrary (SC), path lengths were smaller in the responded than in the presented sequence across sequence lengths.

All these three findings contribute to a coherent conclusion of spatial grouping mechanisms. Due to task requirements, these were appropriate and sufficient in the SC only. Grouping enhances spatial WM capacity which accounts for spatial spans being largest in the SC. When order of recall is arbitrary (SC), it is obvious that targets of one group are recalled back to back, which explains the savings of responded compared to presented path length. Finally, spatially organized grouping does not require temporally inducted target interconnections which inhibits vulnerability to path crossings. The latter interpretation consequently supports the assumption that crossings interfere in rehearsal rather than in encoding processes.

A statistical comparison between the baseline condition and the experimental conditions (described in 3.3) exhibited that neither beneficial nor aggravating synergic effects on performance occur, when both modalities are to be processed simultaneously, compared to when they are separated. Thus, a cognitive modality split-up of spatial and temporal processing in WM is not to be rejected.

Chapter 4

Updating Experiment

4.1 Goals and Background

In the introductory section some common mechanisms of spatial cognition were discussed. It was presented that human agents possess the ability to transform spatial information according to changes in position and orientation of him- or herself (i.e. spatial updating) and of external objects (i.e. mental rotation). Subfeeding these mechanisms, humans use spatial reference frames organizing spatial environment according to themselves (egocentric RF) and to external objects or scenes (allocentric RF). This experiment investigates whether the scope of these mechanisms comprises visual updating processes of rotatory transformation in spatial WM. The rotation is caused either by ego- or by external motion. Predictions drawn from spatial updating and allocentric RFs indicate an advantage for ego-motion over external motion. Mental rotation findings suggest a considerable impact of the amount of rotation. Therefore, this experiment will be referred to as *Updating Experiment*.

The task implementations of the Updating Experiment consisted of variations of the Corsi Task - spatial sequences were presented and after a delay reproduced by the subject (see 1.1.5). In contrast to the Modality Experiment, recall requirements included temporal and spatial aspects of the sequence across conditions. Presentation was unique in all conditions while condition-specific adaptations were implemented by distinct proceedings in the retention interval. Another substantial distinction to most Corsi Task implementations is the fact that the experiment was technically implemented and proceeded on an interactive touchscreen. Detailed information on methods, implementation and procedure is given in the upcoming subsections.

4.2 Conditions

The second experiment conducted within the framework of this thesis will be referred to as *Updating Experiment*. It aimed to figure out the impact of RFs and the principle of visual information transformation on spatiotemporal short-term learning with visual feedback. On that account, three basic conditions were investigated in a within-subject design.

The *Static Condition* (*StatC*) constitutes a classical Corsi Task.

The *Rotation Condition* (*RC*) included a rotation of the entire display content during the retention interval. Precisely after the final target was presented, all items displayed on the screen began to rotate around the screen center. The middle point of each item (x, y) was point-point-rotated around the screen center (x1, y2) by angle α, according to the respective coordination transformation formula:

$$x' = x1 + cos(\alpha) * (x - x1) - sin(\alpha) * (y - y1)$$

$$y' = y1 + sin(\alpha) * (x - x1) + cos(\alpha) * (y - y1)$$

Rotation of an item proceeded in a monotonic velocity so that its relative orientation towards the other items remained constant and the basic pattern rotated as a connected configuration. Rotation angles of 100° and 200° were investigated. The items reached their final locations exactly at the end of the six-second-lasting retention interval. Rotation velocity, thus, depended on degree value. In the consequent recall phase participants were required to press the presented items at their new locations in the correct order.

The *Walk Condition* (*WC*) required ego-motion by the participant. Participants were asked to start walking around the screen immediately after sequence presentation (closer explications of the apparatus to be walked around are depicted in 4.3.1). Angles determining the distance to be covered were again set to 100° and 200°. Irrespective of when the participant arrived at recall position, the screen interface was blocked towards presses throughout the retention interval. No participant struggled with being at the recall position in time. In recall phase the sequence was to be reproduced from a different perspective compared to the one during encoding.

For experimental procedure, RC and WC were divided in two *subconditions* each, according to transformation (i.e. rotated or to-be-walked) angle. Additionally, this fivefold condition distinction was applied for some statistical measures and illustrations.

4.3 Methods

4.3.1 Apparatus

The experimental device in the center of the experimental set-up was a touchscreen of EloTouch, accessed by a multi-touch driver[1], with a 38 cm (= 15 inch) screen diagonale (30 x 22.5 cm). It was arranged on a pedestal of 65 cm height so that the screen surface was 69 cm above the ground. A circular wood panel of seven mm width and with a horizontal external diameter of 50 cm was placed right above the touchscreen and fixed on the pedestal. A circular part was removed from the middle of the wood panel to enable insight to the screen. The panels' internal diameter amounted to 22 cm which was sufficient to keep the screen borders entirely covered. The wood panel had four wooden blocks on its downside which fixated the touchscreen. The wooden blocks themselves were attached to the top of the pedestal (Figure 4.1).

(a) (b)

Figure 4.1: Experimental setup (a) and execution (b)

[1] version 6.9.22 for Windows 10, release date 23-May-2019; © 2019 Elo Touch Solutions

4.3.2 Stimuli

Basic Patterns

The items yielding a basic pattern were circles with a diameter of 60 pixels each. A basic pattern consisted of ten items. The smaller total number of items was appropriate due to the shorter maximum sequence length (i.e. at most six targets compared to ten in the Modality Experiment). Consequently, it was impossible that the target-distractor ratio (explained in 2.3.1) exceeded 1.5. Furthermore, a total item number of ten ensured the display not to be overcrowded and, thus, made involuntary missclicks very unlikely. A pilot study verified that 60 pixel item diameters were sufficient to hit the intended item.
Basic patterns were circularly restricted themselves, in order to prevent local object-based allocentricity cues (see 1.2.1). The item locations in basic patterns were assigned pseudo-randomized with two restrictions. First, an intercircular distance of ten pixels was the obligatory minimum. Second, all x and all y coordinates needed to be distinct so that no horizontal or vertical mental orientation axis could have been built up. In sum, nine basic patterns were generated. All basic patterns used in the Updating Experiment are illustrated in the appendix.

Three of them were assigned to each sequence length. 15 trials were performed per sequence length - namely five subconditions à three subtrials. Per condition and sequence length, all three respective patterns were attached - one to each subtrial. Consequently, within one sequence length the basic patterns were repeated for each condition. To prevent learning effects by uncontrollable configuration cues, basic patterns were varied between sequence lengths.

Sequences

To make sure that a unique sequence was presented in each trial, 72 sequences were generated. To protect results against path length effects, as described in 1.1.5, an elaborate generation procedure was applied. Therefore, for each pattern, 36 random sequences were created. This was done via an algorithm written for that purpose and running on Java 8[2]. The algorithm[3] generated n random numbers within the value range of one to inclusively ten where n represents sequence length. The generated numbers refered to the circle identifier numbers of the currently underlying pattern. This implies that the algorithm avoided multiple occurences of a particular number. Consequently, the total path length (*TPL*) of the 36 randomly generated sequences was calculated on the basis of a look-up table containing absolute distances (in pixels) between

[2] Version Java SE 12, release date 19-March-2019, Update 241; © 2019 Oracle
[3] used randomization function: Math.random from java.lang.Math class

all items of the respective basic pattern. Next, the average step length of each pattern was evaluated by calculating the mean value of all entries of the look-up table. Naturally, values of the main diagonale were not taken into account for mean calculation, because self-references did not exist in the experiment. The value of average step length was multiplied by the factor n-1 resulting in the average TPL for a sequence of n targets in the respective pattern.

In the next step, the algorithm extracted the five sequences with the lowest numerical distance in TPL from the average TPL.

$$\forall \text{ seq in } G^4 \text{ find: } min\{\Delta(TPL(seq_i), TPLavg(pattern))\}$$

Finally, one further condition was to be fulfilled by each sequence. Namely, a sequence of n targets was required not to exhibit a larger TPL than a sequence of n-1 targets. In this case, the sequence was replaced by the one with the next closest distance to average TPL fulfilling the requirement.

$$\forall \text{ seq in G it holds } TPL(seq_n) > TPL(seq_{n-1})$$

Sequences used in the experiment and their corresponding TPLs can be inspected in the appendix.

4.3.3 Participants and Instruction

Seventeen subjects, aged between 20 and 28 years (M = 23.06, SD = 2.41; twelve of which were male), participated in the experiment. All of them were students of the University of Tübingen, Germany. They were reimbursted by course credit according to their time effort.
Prior to experimentation, each subject was instructed to be presented with a spatial sequence learning task on a touchscreen. An exemplary trial succession and recall requirements for each condition (see 4.2) were explained to him or her. Each participant was explicitly called on to walk counterclockwise around the pedestal in trials of the WC. Disregard of this instruction would have altered the angular degree of the visual updating to be performed and, consequently, would have biased the experimental objective. Therefore, it was controlled by the experimenter that the participant walked the right way. After the general briefing the participant was given the opportunity to request on potential ambiguities. When he or she confirmed understanding of task requirements, the participant was asked to respond as accurately and as fast as possible with correctness as first priority.

4.3.4 Procedure

Experimental implementation, visualization and data storage was programmed in and ran by Matlab R2018b (MATLAB R2018b, The MathWorks, Inc., Natick, Massachusetts, United States) with Psychtoolbox-3 extension (Brainard, 1997; Kleiner et *al.*, 2007).
Before the main experiment, the participant performed a training phase of at least five trials with a sequence length of three, one in each condition. Whenever a participant solved less than three trials correctly, he or she had to repeat the incorrectly responded trials. Each participant had the opportunity to voluntarily repeat the training phase until he or she felt comfortable with task and setting. No participant performed the training phase more than three times in total. After the training phase, the participant was offered to pose comprehension questions once again. Following this, each participant was assigned a condition order. Across participants, the orders were counterbalanced according to a n=5 (subconditions) latin-square (Williams, 1949). The assigned condition order was repeated within-subject for each sequence length. The participant performed three trials per subcondition for each sequence length, starting at four. After completion of 15 trials, sequence length increased by one up to six so that 45 experimental trials were performed in total. The entire procedure lasted approximately 45 minutes.

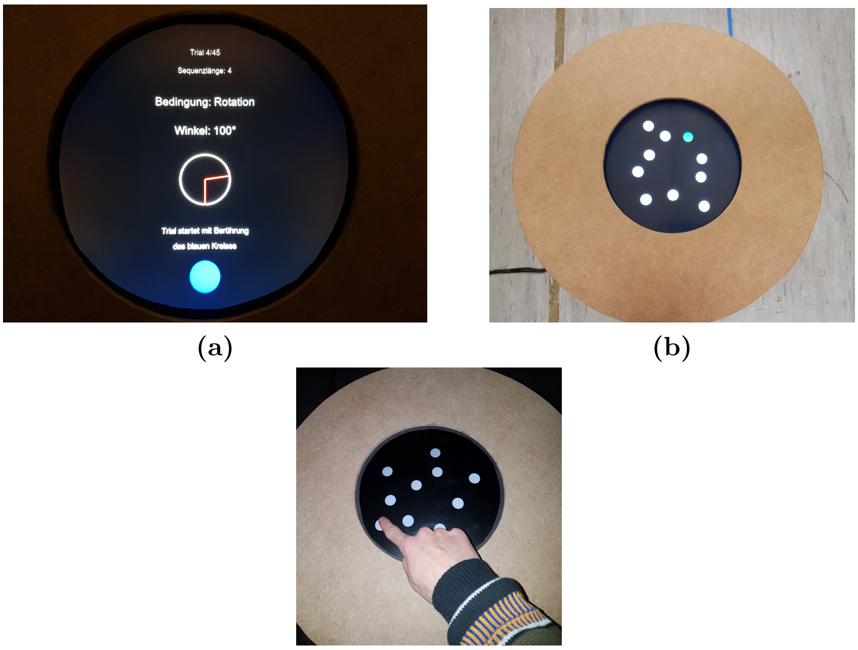
Trial Proceeding

At the beginning of each trial, the participant stood straight in front of the apparatus on a spot marked on the floor (Figure 4.1 (b)). A between-trial display with information on condition, angle, sequence length and trial number was illustrated centered on the touchscreen (Figure 4.2 (a)). After an obligatory interval lasting three seconds, the participant could start the trial by tapping a blue circle. In immediate consequence, the presentation display switched to the basic pattern of white circles (Color Code [225 225 225][5]) on black background. After 500 ms the first target of the sequence was highlighted in a light green ([0 153 0]) for 1000 ms (see Figure 4.2 (b)). Subsequently, the second target was highlighted for the same duration with a delay of 500 ms in between[6]. After the final square of the sequence had been marked, the retention interval started. This means in the subsequent six seconds items changed their color from white to gray ([122 139 139]) and recall was technically blocked[7]. Condition-specific adaptations of the retention interval are explained in 4.2.

[5] according to RGB Color Codes Chart

[6] The brief delay between target-highlightings was applied to prevent illusory motion perception (Davidenko et *al.*, 2017).

[7] The screen did not turn black during retention interval to offer the opportunity to use rehearsal strategies (Tremblay, Saint-Aubin & Jalbert, 2006).



(a) (b)

(c)

Figure 4.2: Between-trial (a), presentation (b) and recall (c) display

In recall phase (Figure 4.2 (c)) tapped items were highlighted for 300 ms each. Recall was locked within the respective time period. Each item had an external range capturing all touches of maximal five pixels absolute distance to each outermost point of the item. In other words, the capturing range of an item was a circle with a diameter five pixels larger the diameter of the item itself. In case a click did not hit any capturing range, all items were highlighted in red ([225 0 0]) for 400 ms. Tapping a single item several times did neither lead to exclusion of the respective click[8] from data collection, nor to an error signal. In other words, consequences were the same as those of any other incorrect click. After tapping n times the between-trial display of the consequent trial was shown.

4.3.5 Independent Variables

Rotation Principle

Investigation of impact of the rotation principle is the central objective of the Updating Experiment. Rotation principle determines the way rotation of the basic pattern is caused. It represents a binary optional factor: rotation due to ego- (WC) and external motion (RC).

[8] Although in this paradigm response is given by tapping rather than clicking, resulting data units are referred to as clicks for reasons of coherence between both experiments.

Rotation Angle

Rotation angle represents the degree to which the target configuration (i.e. basic pattern) changes its orientation relative to the participant's head. It represents a binary optional factor, irrespective of rotation principle: 100° and 200° rotation.

Sequence Length

As described in 4.3.5.

4.4 Statistical Analysis

Dependent variables are identical to the ones in the Modality Experiment. Guess probablilites are unique across conditions and are equivalent to the ones in the STC of the Modality Experiment. Thus, they play a minor role in the analyses.
Exclusion was scheduled for data of participants who solved less than one third of all four-target sequences. Reasons for this requirement are explained in 2.4.1. Conducively for data utility, no participant met this exclusion criterion. Respective explanations and calculations are given in 2.4.

4.4.1 Overview

Data preprocessing, including evaluation of the accuracy and RT measures described in 2.4, was executed in Matlab (MATLAB R2018b, The MathWorks, Inc., Natick, Massachusetts, United States). Analyses of variance were conducted using SPSS Statistics software (IBM Corp. Released 2019. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY: IBM Corp.).

In each illustration of the experiment, error bars in bar plots represent Standard Error of Mean (SEM; Altman & Bland, 2005) in each illustration of the experiment. Presence of a horizontal bar above group bars represents a significant ($p < .05$) relation between both connected groups, while number of stars is assigned to the p-value of the respective relation:

*	$p < .05$
**	$p < .01$
***	$p < .001$

Constants	Independent Variables	Dependent Variables
Proximal Orientation Cues	Rotation Principle	Spatial Span
Recall Requirements	Rotation Angle	Weighted Span
Total Path Length	Sequence Length	Percentage Correct
Presentation Style		Reaction Times

Table 4.1: Relevant constants and variables - Updating Experiment

Chapter 5

Results Updating Experiment

5.1 Accuracy

5.1.1 Global Analysis

In the first step of accuracy analysis a holistic analysis was conducted by a n-way ANOVA with condition (five factor levels) and SQL (three) as repeated measures and correct trials as input data. In the global analysis all five sub-conditions were treated as individual factor treatments of condition. It showed that condition ($F(4,\ 13) = 20.44$, $p < .001$, $\eta_p^2 = .86$) and SQL ($F(2,\ 15) = 57.66$, $p < .001$, $\eta_p^2 = .88$) exhibited highly significant main effects. The according interaction was not significant ($F(8, 9) = 2.35$, $p = .113$). Significance bars in Figure 5.1 (a) symbolize the described main effects.

The identical measuring procedure with correct clicks as input provided similar effects with a slightly smaller variance. Condition ($F(4, 13) = 15.24$, $p < .001$, $\eta_p^2 = .82$) and SQL ($F(2,\ 15) = 50.0$, $p < .001$, $\eta_p^2 = .87$) exhibited highly significant main effects. The according interaction was close to significance

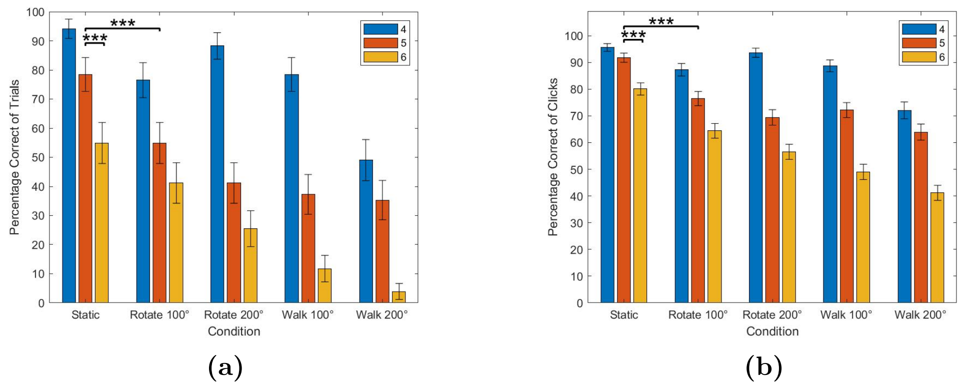
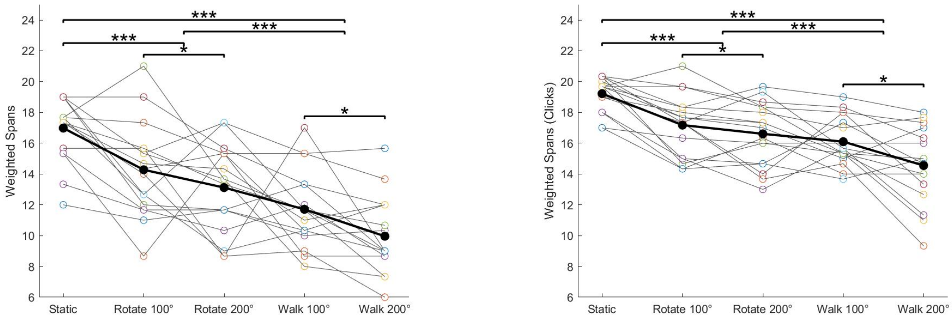


Figure 5.1: Percentage Correct of trials (a) and clicks (b)

Weighting	Basis	Static	Rotate100	Rotate200	Walk100	Walk200
No	Trial	5.27	4.46	4.3	4.04	3.67
	Click	5.67	5.28	5.2	5.1	4.77
Yes	Trial	16.98	14.27	13.12	11.71	9.96
	Click	19.22	17.18	16.61	16.1	14.55

Table 5.1: Mean spans for all weightings, conditions and inputs



(a) **(b)**

Figure 5.2: Weighted spans of trials (a) and clicks (b)
Color symbolizes participant, black fat line means

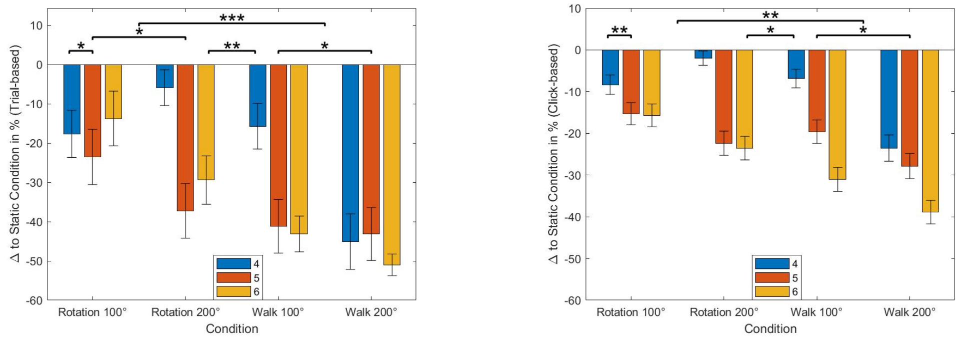
($F(8,\,9) = 2.86$, $p = .069$). Significance bars in Figure 5.1 (b) symbolize the described main effects.

Another ANOVA with weighted spans as input confirmed the main effects of condition, established in PC analysis, in terms of both trials ($F(4,\,13) = 21.14$, $p < .001$, $\eta_p^2 = .87$) and clicks ($F(4,\,13) = 16.71$, $p < .001$, $\eta_p^2 = .84$).

Both the mean values of weighted and unweighted spans across participants, show a monotonically decreasing tendency from StatC to RC to WC. Even the average span of RC 200° is larger than the one of WC 100°. As depicted in table 5.1, the average span is smaller in the 200° subcategory in both experimental conditions. This robust numeric tendency holds in the identic manner for weighted spans (illustrated in Figure 5.2). An overview of all individual spans is given in appendices.
Due to the fact that performance across conditions and sequence lengths was by far the best in the StatC, another series of analyses was executed with reduced values of the experimental conditions.

Weighting	Basis	Rotate100	Rotate200	Walk100	Walk200
No	Trial	-0.55	-0.73	-1.0	-1.39
	Click	-0.39	-0.48	-0.58	-0.9
Yes	Trial	-2.71	-3.86	-5.27	-7.02
	Click	-2.04	-2.61	-3.12	-4.67

Table 5.2: Mean spans of delta data for all weightings, inputs and conditions



(a) (b)

Figure 5.3: Delta Percentages Correct of trials (a) and clicks (b)

5.1.2 Delta

For closer statistical characterization of differences between experimental conditions and the impact of the angle factor, further analyses of *Delta Values* were executed. Delta value refers to the individual absolute difference between performance in an experimental and in the baseline (i.e. static) condition and is computed for each sequence length and participant separately. Delta values were calculated for each accuracy measure - i.e. PC (Figure 5.3), weighted and unweighted spans.

Delta values of correct trials were inputted into a repeated measures ANOVA with a 2 (main condition) x 2 (angle) x 3 (SQL) design. This resulted in significant main effects of condition ($F(1,\ 16) = 27.33$, $p < .001$, $\eta_p^2 = .63$), angle ($F(1,\ 16) = 5.02$, $p = .04$, $\eta_p^2 = .24$) and SQL ($F(2,\ 15) = 3.8$, $p = .046$, $\eta_p^2 = .34$). Further to this, the three-way interaction of all three factors became significant ($F(2,\ 15) = 6{,}61$, $p = .009$, $\eta_p^2 = .47$).

An identical ANOVA with delta values of correct clicks as input confirmed the results with the extension that significance and effect size of angle ($F(1,\ 16) = 6.43$, $p = .022$, $\eta_p^2 = .29$) and SQL ($F(2,\ 15) = 9.14$, $p = .003$, $\eta_p^2 = .55$) was more pronounced. Additionally, a significant interaction of condition x angle emerged ($F(1,\ 16) = 6.55$, $p = .021$, $\eta_p^2 = .29$).

Based on weighted delta spans, the main effects of condition ($F(1,\ 16) = 29.43$,

$p < .001$, $\eta_p^2 = .648$) and angle ($F(1,\ 16) = 5.32$, $p = .035$, $\eta_p^2 = .25$) were slightly more evident than when based on the PC ANOVA. For the click-based weighted delta span input, the ANOVA exhibited condition main effects which were slightly weaker compared to the trial-based analysis ($F(1,\ 16) = 14.62$, $p = .001$, $\eta_p^2 = .48$) while angle effects remained very similar ($F(1,\ 16) = 6.88$, $p = .018$, $\eta_p^2 = .3$).

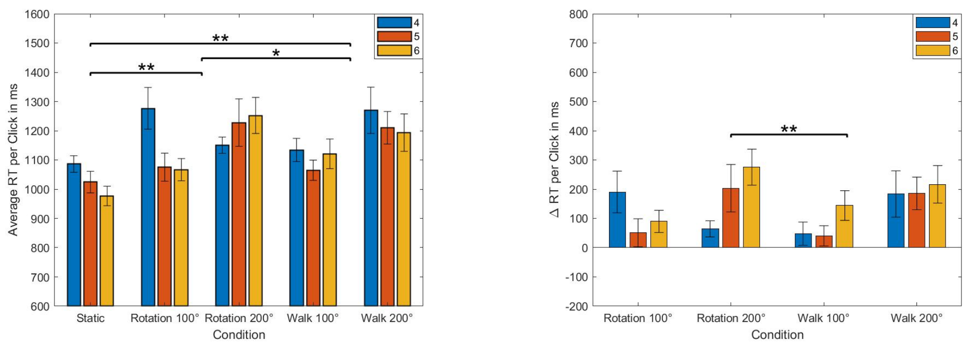
5.2 Reaction Times

5.2.1 Global Analysis

Reaction time analysis yielded the values illustrated in Figure 5.4 (a). A repeated measures ANOVA showed that the main effects of condition were significant ($F(4,\ 13) = 7.47$, $p = .02$, $\eta_p^2 = .7$). Furthermore, there was an interaction between condition and SQL ($F(8,\ 9) = 7.47$, $p = .045$, $\eta_p^2 = .75$).

5.2.2 Delta

In the analysis of delta values of the experimental conditions, none of the three factors (condition, angle, SQL) reached significant main effects. The loss of condition main effects demonstrates that exclusively RTs of the StatC overcame those in the other conditions. As can be seen in Figure 5.4 (b), delta values of each condition-sequence length combination and even the lower bounds of their SEM ranges were below respective values in the StatC. However, there was a significant three-way interaction effect of condition x angle x SQL ($F(2,\ 15) = 6.49$, $p = .009$, $\eta_p^2 = .46$). The significance bar represents the interaction effect symbolically.



(a) **(b)**

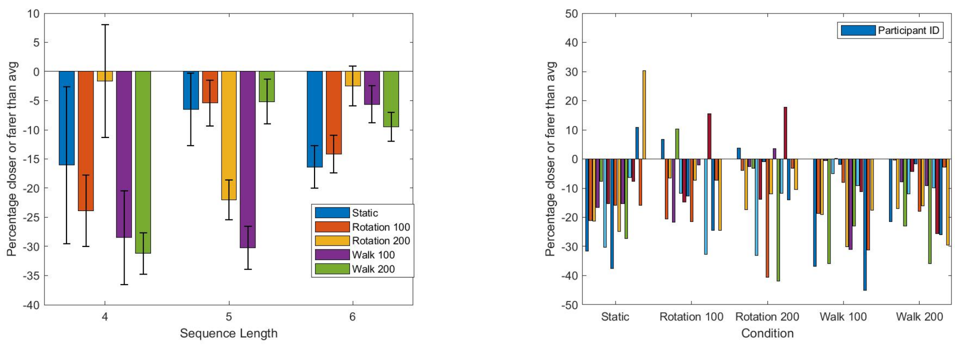
Figure 5.4: Absolute (a) and delta (b) reaction times per click in (b) 0 ms line indicates RTs in StatC

5.3 Qualitative Analysis

5.3.1 Relative Error Distance

Absolute distances between correct and given responses were measured and calculated for incorrect clicks. This means that two-dimensional euclidean distances between an incorrect click and the target item (in pixels) were separately divided by the mean distance between items within the current basic pattern. The mean distance between items within a basic pattern was calculated by summing up distances of all potential edges and dividing this by the number of edges. Thereby, self-referential edges were not taken into account. Resulting relative values were subsequently averaged over (incorrect) clicks and participants so that a mean value for each sequence length and condition was generated. According percentage values (Figure 5.5 (a)) show that in each of the 15 condition-sequence length combinations, incorrect clicks were closer to the target than would have been expected by chance. Individual participant scores averaged over sequence lengths - shown in Figure 5.5 (b) - exhibit that only eight out of 85 participant-condition combinations were further away from the target than would have been expected by chance.

Concerning RC, this qualitative error measure showed that false clicks were slightly closer to the current target than would be expected by chance. This effect was not altered by angle (-10.97% for 100° and -10.81% for 200°). Regarding WC, mean error distance was smallest across conditions with a small influence of angle (-19.08% for 100° and -15.34% for 200°).
Implications of relative error distances are discussed within the context of strategy use (5.4.2).



(a) (b)

Figure 5.5: Aggregated (a) and individual (b) distances in incorrect clicks

5.4 Discussion

The reported study, referred to as Updating Experiment, aimed to characterize visual updating processes in spatial WM of serial order by comparing reproduction of spatial sequences after ego- and external motion. Results revealed significant costs of visual updating in general - performance in baseline condition was by far best. Updating was more efficient in the condition of external motion than in the condition of ego motion. The latter finding contradicts predictions reasoned on the basis of allocentric RFs as well as spatial updating theories. Furthermore, an increasing rotation angle elicited a significant decrease in performance, across conditions, which identifies the rotatory transformation cost to be a function of complexity rather than a constant. SQL main effects that were present across conditions and accuracy measures are a clear indication that criteria set in stimuli generation (4.3.2) fulfilled their purpose and, in consequence, sequence length is a straight indicator of task complexity in the Updating Experiment. As spans represent values in immediate dependence of sequence length, the large SQL effects support objectivity of the collected data.

5.4.1 Placement

Mental Rotation

Mental Rotation refers to the ability to anticipate imperceptible alterations of the orientation of spatial objects or scenes (1.2.1). Differing from classical mental rotation paradigms, in the Updating Experiment, subjects were confronted with visual feedback illustrating the rotation. Results suggest that this visual feedback alters cognitive processes of rotating a mental image. However, in the light of segmentation theories of mental rotation (Xue et *al.*, 2017) it is plausible to view the basic pattern as a unique hierarchically organized structure because its constituents (i.e. the circular items) are feature- and orientationless and might, as such, be regarded as minimal segments. Consequently, typical observations in mental rotation were possible, despite the continuous visual rotatory input. In former studies, mental rotation costs were infered from both RTs (Bülthoff & Christou, 2000) and accuracy measures (Simons & Wang, 1998).

Accuracy analyses exhibited significant main effects of angle for PC and weighted spans, based on both trials and clicks. Exclusively in the click-based weighted spans - which arguably are the most exhausting measures - angle factor was involved in interaction effects with condition. This interaction arose from the fact that an increasing angle had a stronger diminishing impact on WC than on RC. Based on the assumption that total transformation costs of rotatory visual updating are the sum of a basic constant for transformation and a linearly increasing function of degree, cost functions were generated. The functions for both experimental conditions were calculated according to spatial spans. The resulting cost functions yield the number of targets being lost from memorization and are shown below. The corresponding graphs are illustrated in Figure 5.6.

RC

$$0.6448 + degrees * 0.001667$$

WC

$$0.8672 + degrees * 0.003703$$

Potential reasons for basic costs to be higher in the WC will be further discussed later in this chapter. However, an explanatory approach for the cost subfunction of angle size to be more than twice as high in the WC than in the RC is that walking itself requires motoric and cognitive effort. Because in the WC walking and visual updating co-occurs, the walking effort is a cost function proportional to the transformation subfunction of angle size. Thus, it also is in immediate dependence on angle size. The pure cost of mental rotation with visual feedback is assumed to amount approximately to 0.1667 targets lost from memory per 100 degrees of rotation. Confirmation of the assumption of linear walking costs and the precise cost values requires further evidence.

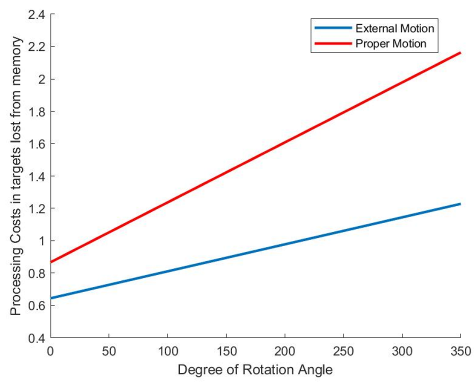


Figure 5.6: Transformation cost functions for RC (blue line) and WC (red line)

The scientific origin of mental rotation is based on the findings of Shepard & Metzler (1971) that RTs are almost linearly correlated with the angle to be rotated (see Figure 1.5). Figure 5.7 shows mean RT differences between the 100° and 200° treatment for each condition. Negative values indicate that the 100° treatment has been performed more quickly. Except for one condition-sequence length combination (*RC four*), there is a numeric tendency in favor of the smaller angle in both conditions. However, as has been discussed in 5.2 angle size did neither provoke main nor interaction effects in the RT analyses. Nevertheless, a study investigating more and closer adjacent angles to shed light on the RT curve of updating processes in serial order memory would be promising.

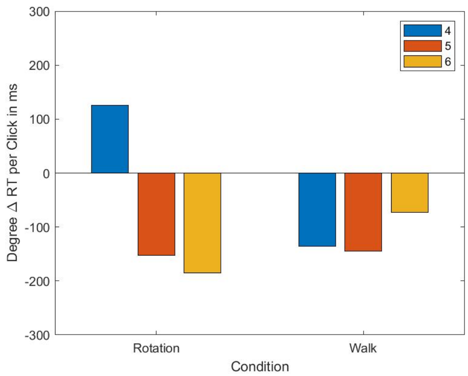


Figure 5.7: Delta RTs between angles for both experimental conditions

Reference Frames

One main objective of the Updating Experiment was to encounter the role of spatial reference frames in visual serial order memory (for assumed backgrounds on RFs see 1.2.1). The experimental apparatus was designed such that potential local reference objects and features in the immediate surrounding of the visible screen part (i.e. the item pattern) were occluded from view. Nevertheless, it is not to be excluded that remote objects or scenes in the experimental room served as allocentric references.
Cells of table 5.3 state whether, according to a particular RF domain, pattern orientation was identical or different between presentation and recall. The egocentric RF was equivalent to the retinal image while the allocentric RF was represented by the outer visuospatial circumstances in the experimental room. The line *Congruency* indicates whether pattern orientation development within a trial of a particular condition was same (*True*) or distinct (*False*) between egocentric and allocentric RFs.

The two experimental conditions differed with respect to allocentric RFs because identical spatial relations were present in the WC, but not in the RC.

RF	Static	Rotation	Walk
Egocentric	Identical	Different	Different
Allocentric	Identical	Different	Identical
Congruency	True	True	False

Table 5.3: Comparison of states of different reference frames between presentation and recall

This would predict an advantage for the WC. However, results are opposed. Neuropsychological research widely agrees on the assumptions that visual perception is non-euclidean and that spatial cognition is not entirely egocentric, but that spatial interrelations between external objects and scenes provide the basis of many processes at the perception-cognition interface (Meilinger & Vosgerau, 2013). However, this does not exclude use of egocentric RFs in general. Assuming an interplay of egocentric and allocentric RFs, in the Updating Experiment, leads to a valid explanation for the observed results. Namely, as shown in table 5.3, there is an incongruency of RF state developments in the WC. It indicates that pattern orientation is same for allocentric but different for egocentric RFs. This incongruency might interfere with transformation processes in the way that the interplay between egocentric and allocentric RFs leads to mental confusion of spatial relations.

An arguable alternative explanation is that there is little or no use made of allocentric reference cues. This would be in accordance with Avons (2007), whose results indicated very proximal allocentric RFs to be used in the Corsi Task. Overt proximal allocentric reference cues are absent in the Updating Experiment due to the apparatus setup. This explanation would imply that remote allocentric cues are not influential in spatial sequence learning and that results could not be reasoned due to spatial RFs.

Spatial Updating

Considering spatial updating theories (Liu & Xiao, 2018), the underlying findings exhibit a contradictory tendency. It is notable that spatial updating in the narrower sense excludes visual feedback during ego-motion which is one reason for the titling of the current experiment. Thus, respective findings need to be limited to the role of orientation. Spatial updating, besides proprioceptive feedback, benefits from constant external visual circumstances. Regarding the Updating Experiment, spatial updating would exclusively apply for the WC. In the light of findings from spatial updating (e.g. Bülthoff & Christou, 2000) the WC would consequently have been predicted to outperform the RC because updating appeared to be more accurate in ego-motion. The opposite is reflected in the results which may be caused by one of two reasons. Either, allocentric RFs play a minor role in the underlying paradigm of visual updating (see above). Or, continuous visuospatial input suppresses representations drawn from spatial self-perception. Both described accounts are arguably strengthened by the assumption that subjects attentionally focus on task-relevant space (i.e. the item pattern) and requirements (i.e. maintenance of spatial and temporal information).

5.4.2 Strategies

In both experimental conditions it was required to recall the sequence in another orientation compared to presentation. The entire rotation was visible, which provided subjects with the opportunity to update the pattern orientation continuously. To successfully perform this transformation, at least one of two basic strategies needed to be used:

One opportunity was to make use of *rehearsal* processes (Tremblay et *al.*, 2006). This means, according to the Corsi Task paradigm, that the presented sequence is visually repeatedly reacquired during retention and - especially in long sequences - towards the end of presentation. The way this reacquisition is executed is not trivial and is not necessarily limited to repositioning of the sequence trajectory (Godijn & Theeuwes, 2012)[1]. In the experimental conditions of the Updating Experiment a rehearsal-based updating process would need to be dynamic because each single item rotates uninterrupted. This concretely implies that each saccade would target a novel location of the following item of the remembered sequence. Therefore, an anticipation of the covered distance of the consequent item during eye movement is required. Assuming peripheral visual perception to provide sufficient spatial information on a non-fixated item, this anticipation would consist of calculating the route that the item takes during saccade duration. This route is to be added to the current location of the subsequent item. Notably, even though the angle per time ratio is unique across items, the motion velocity varies according to the distance to the screen center. Therefore, the individual item velocity needs to be estimated and integrated into the anticipation function. Assuming peripherally provided visual information is not sufficient, the anticipation would even require the route an item takes within the duration of n (i.e. sequence length) saccades and n-1 fixations. The advantage of this strategy is that WM load could be reduced by filtering distractors (see 1.1.2).

The concurrent opportunity was to keep spatial information on the pattern and spatiotemporal information on the targets upright. During rotation, the orientation of the entire pattern, rather than the locations of the single items,

[1] As eye movements have not been measured in the current experiment, this aspect should not be discussed in depth.

would thus be updated (referred to as *Holistic Rotation*). In the recall phase target information - represented either as a connecting line or as relative item locations with sequential indices - is applied to the novel oriented pattern. Given the evidence of studies on dynamic cognition, a continuous fixation of the pattern center can be assumed (Huff et *al.*, 2010). Furthermore, this theory would be in accordance with the concepts of target grouping (Yantis, 1992) and of mental rotation when regarding the basic pattern as one bound entity (Lehmann, Vidal & Bülthoff, 2008). The advantage of this strategy is that transformation is simplified when treating the pattern as an object. This means that updating is not dynamic but monoton. Disadvantages are a higher WM load because information on both the pattern and spatial and temporal aspects of the target is necessary. Consequently, with increasing sequence length, the strategy would become less beneficial.

With the aim of approaching used strategies, absolute distances between correct and given responses were measured and calculated for incorrect clicks (see Figure 5.5). At first view, results showed that not all missclicks were due to guessing or to a temporal disposition (e.g. entire sequence is shifted for- or backwards), but that at least a considerable part of these was directed intentionally to a correct screen region. Consequently, some of the missclicks could be interpreted as transposition errors. This finding is reinforced by the fact that a minimum error distance lies at around 30 - 40% of the average error.

The Holistic Rotation strategy would predict an error pattern with random error quality because the mental construct of pattern and trajectory becomes entirely inadequate when tracking is lost. Additionally, when adapting the Holistic Rotation strategy a sequence length main effect is to be expected because the strategy gets less beneficial with increasing sequence length. Results depict an inconsistent course of sequence length impact (Figure 5.4 (a)). In combination with an error distance systematically below the average, the assumption of Holistic Rotation use is to be rejected.

The rehearsal strategy is vulnerable to transposition errors to a greater extent because the dynamic updating needs to be highly precise. Even a small deviation in a parameter of the motion-calculation function can lead to transposition with a neighboring item. Use of a rehearsal strategy would thus predict a considerable amount of transposition errors. While there are two parameters for this function in the experimental conditions (target position and anticipated target motion), which are both vulnerable to imprecisions, there is only one such parameter in the StatC (target position). Therefore, transposition errors - expressed in a decreasing error distance - are to be expected in the StatC as well. Absolute delta values are depicted in Figure 5.8 showing a main effect

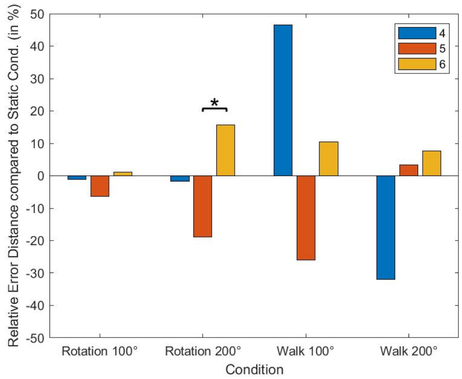


Figure 5.8: Delta values of relative error distances for both experimental conditions

of SQL ($F(2, 15) = 14.62$, $p = .034$) and a three-way interaction of condition, angle and SQL ($F(2, 15) = 10.52$, $p = .01$). Both these effects are due to an inconsistent course of SQL factor between subconditions and will, therefore, not be further considered.

An average missclick in the StatC was slightly closer (-14.92 %) than in the RC. However, in the WC, mean error distance was smallest across conditions with a moderate impact of angle (-19.08% for 100° and -15.34% for 200°). During walking, rehearsal strategies benefit from the self-determined visual rotation velocity. For interpreting the fact that error distances are closer in the WC compared to the StatC, it is to be considered that total error number is largest in the WC. Following this, the absolute number of random errors might be similar between WC and StatC because they arguably occur due to general resource limitations of the WM. However, the number of transposition errors appears to be larger in the WC because of the larger vulnerability towards imprecisions. This leads to an error ratio in favor of transposition errors in the WC and, consequently, a closer error distance on average.

However, it is notable that there were moderate intervidual variations. For each angle, average error responses of three participants were further away from the target than chance expectation (two of which were the same for both angles).

In conclusion, rehearsal strategies are assumably used in the current experimental paradigm. It might, however, not be the only strategy in use. According to this qualitative error analysis, rehearsal strategies - regarded isolatedly - are more accurate during ego- compared to external motion. However, other task requirements in the WC (e.g. sensomotoric and cognitive walking costs, fixation stability) surpass this advantage in regards to overall accuracy.

5.4.3 Derivation

Attention

According to current literature, event boundaries provoke attentional boosts and the entities constituting this event attract attention in both action (Hard, Recchia & Tversky, 2011) and perception (Swallow, Zacks & Abrams, 2009). Initiation and termination of the walking mechanism in the WC are arguably both to be seen as an event boundary. As presentation was finalized before subjects started walking in the Updating Experiment, encoding here was not being interfered with attentional losses due to an event boundary. Concerning the event boundary of walk termination, subjects were explicitly asked to stand still at the recall spot as precisely as possible. This demand could have enhanced cognitive effort and probably needed to be supported by repetitive saccades to the recall position marker on the touchscreen border during walking. As WM is considered to be a resource consistently driven by attention processes (Barrouillet & Camos, 2007), walking boundaries (i.e. initiation and termination) might interfere with maintainance of the memorandum and, consequently, lead to a performance decrease in the WC.

Worth mentioning, there are technical accounts, related to attention, that could have contributed to the high cognitive effort required in the WC. Namely, the manner to walk around the apparatus is orbital which is not the most intuitive gait in humans (Srinivasan & Ruina, 2006).

Predictive Cognition

WC provided potential advantages over RC that go beyond coherences on higher cognitive areas such as reference frames and mental transformation processes (discussed in 5.4.1). In the first place, a self-determined walking velocity is to be named. Walking velocity and rhythm determines the perceived pattern rotation in immediate consequence, which is externally specified in the RC. Visual perception is, besides attention, shaped by expectation (Summerfield & Egner, 2009). *Predictive Coding* theories claim that neural expectations (i.e. *predictions*) are adjusted with perceived visual input and are continuously updated accordingly by an iterative feedback mechanism (Stefanics, Heinzle, Horvath & Stephan, 2018). Applied to the Updating Experiment, this would imply subjects to constinuously predict the orientation of the basic pattern in a consequent time step during retention interval. The fact, that visual motion is retinal perceived substantially smoother in the RC compared to the WC, would make the results fit into a predictive coding framework.

In the WC a variable possibly confounding with continuity of visual input is the stability of eye movements. During walking the retinal image is continuously exposed to oscillations. However, compensatory mechanisms of locomotion artefacts have been shown to operate in a solid manner by gaze anticipation (Authie, Hilt, N'Guyen, Berthoz & Bennequin, 2015). Still it is arguable that such mechanisms are not entirely compensating retinal locomotion artefacts. Furthermore, compensation mechanisms are likely to raise cognitive effort which withdraws resources that attention-based maintenance processes require.

5.4.4 Conclusion

The Updating Experiment explored the processing of a visible orientation change (transformation) of a basic pattern (visual updating), according to which an encoded and briefly maintained spatiotemporal information array was to be reproduced. Spatial tranformation was initiated by either ego- or external (i.e. display content) motion.
It resulted in the finding that there are general visual updating costs which are, however, larger in association with ego- than with external motion. The latter finding is contradictory to processes evidenced in association with spatial updating and allocentric RF use, which leads to the conclusion that continuous visual feedback - as a more worthy cue - suppresses respective processes of proprioception and spatial organization. The disadvantage in ego-motion performance is reasoned according to concurrent costs of walking itself and a less stable visual focusing. The angle of rotation correlated negatively with task performance. This suggests that, in addition to constant general costs, continuous visual updating includes a variable cost factor proportional to the rotation angle. The latter conclusion is in line with mental rotation theories.

Chapter 6

General Discussion

6.1 Cross Comparison

In both experiments, executed within the framework of the underying thesis, there was a reference condition that reflected a classical Corsi Task executed on different devices (PC with mouse and touchscreen). Primary, these conditions were investigated as a statistical benchmark for the subjects' performances and secondary, in order to keep the results comparable to Corsi Task measurements of other studies.

In the Modality Experiment the STC served as a baseline, in the sense of requiring the greatest extent of cognitive effort, because in both experimental conditions, no additional task requirements were assigned but some were removed. Thus, the STC was expected to be the hardest condition. In the Updating Experiment the StatC served as a baseline condition. All experimental conditions had additional demands. Ipso facto, the results in the StatC represent optimal performance of a participant. Both these assumptions were clearly confirmed by the results showing the STC to entail poorest performance across conditions in the Modality Experiment and the StatC to outperform experimental conditions in the Updating Experiment, in almost any data cell. In other words, STC and StatC represented classical Corsi Tasks and results confirmed that they are appropriate references for the experimental conditions. To investigate whether both experiments are comparable regarding basic task complexity, noise and avoidance of confounding variables (e.g. device effects), results of both named conditions were compared. It showed that results were strikingly similar (table 6.1).

A two-sample t-test of both conditions results in a p-value of 0.994 showing that the null-hypothesis (i.e. statistical dependence) is not nearly to be rejected. A relative identity measurement (Goebl, 1998) resulted in 98.22%, 98.28% and 98.67% (increasing sequence lengths) congruency between conditions. The implementary difference of total number of items between experiments (15 in

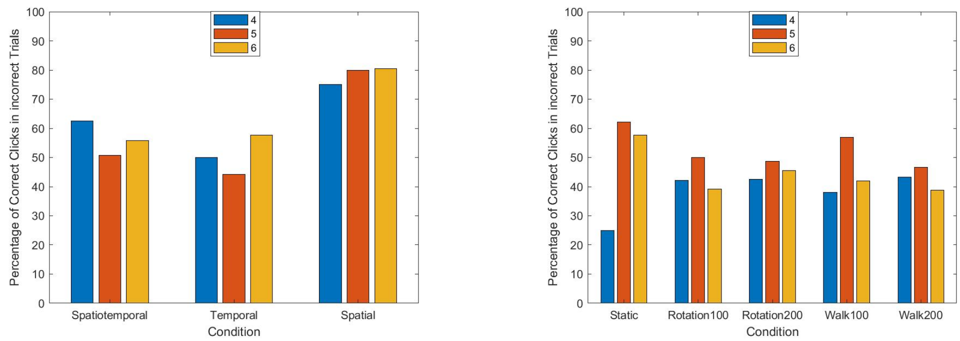
Sequence Length	Spatiotemporal	Static
four	94.12	95.83
five	78.43	77.08
six	54.9	54.17

Table 6.1: Percentage Correct of reference condition in both experiments

Modality, ten in Updating Experiment) has no obvious effect on the depicted results. It is arguable that the target-distractor ratio has an impact on performance only when it amounts to two at least (i.e. two thirds of all items are targets).

The similarity between the STC and the StatC tends to be extendable to the amount of correct clicks in incorrect trials, except for sequence length four (Figure 6.1). Notably, the SC is positively biased by guess probabilities (see 2.4.2). According to this measure, there is no indication of learning effects in the course of either experiment.

Conclusively, this minor control analysis gives strong support for the reliability of the collected data. Furthermore, it supports the reliability of touchscreen use for spatial sequence learning tasks.



(a) (b)

Figure 6.1: Amount of correct clicks in incorrect trials - Modality Experiment (a) and Updating Experiment (b)

6.2 Outstanding Research Questions

As informative as the findings of the two reported experiments are, as much they arise consequent research questions. The hints of modality segregation between spatial and temporal WM processing, observed in the Modality Experiment, require verification by follow-up studies using other experimental paradigms. Thereby, it is essential to retain integration of both modalities into a cohesive task. Dual-Tasks or cross-modal interference were thus not appropriate. Particularly informative would be an analogue investigation on verbal sequence learning.

Additionally, a consequential research step was to conduct the Updating Experiment without visual feedback. Experimental conditions would, in such a paradigm, directly adress mental rotation (RC) and spatial updating (WC) in SOM. In case the advantage of the RC, observed in the Updating Experiment, would remain, the lack of spatial updating benefits could be attributed to serial order demands. Furthermore, a comparison with the currently reported results would define the role of visual feedback in spatial transformation processing more precisely. Accuracy in the Updating Experiment indicated cognitive costs to increase with angle size for both ego- and external motion. A further promising following step was to challenge the linearity of this correlation by assigning a close-meshed series of angles. This would exhibit a potential horizontal axis effect at 180°, as has been shown by Shepard & Metzler (1971) for mental rotation. Absence of this effect would indicate that mirrored stimuli are not flipped (Kung & Hamm, 2010) when rotation is visible. This would further suggest that visual feedback overrides prototypical representations of encoded spatial arrangements.

6.3 Conclusion

This thesis addressed aspects in human WM that were mostly disregarded in previous research. The empirical part was implemented by two experiments designed by variations of the Corsi Task, known as the gold standard for measuring spatial WM capacity (Baddeley, 2003).

The Modality Experiment investigated differences, similarities and interdependencies in WM processing of the abstractly conceptualized information modalities space and time. The results arising thereby validate to draw three conclusions.

First, the Corsi Task challenges both spatial and temporal WM scopes. The fact, that performance was markedly best when temporal task requirements were excluded, compromises the Corsi Task as a straight measure of spatial WM capacity. This should be considered in future research and diagnostics when interpreting spatial spans.

Second, there is no indication of a cognitive modality integration of time and space in the Corsi Task paradigm. Results suggest that information of these modalities is organized and maintained largely independent.

Third, complex spatiotemporal target patterns (i.e. containing path crossings) aggravate encoding processes when task requirements include temporal aspects. When only spatial information is task-relevant, efficient grouping strategies are applied to overcome the aggravation during encoding already.

The Updating Experiment investigated visual updating of spatial rotation occuring due to either subject or target motion. The results lead to the following conclusions.

Transformations of spatiotemporal representations, maintained in the WM, generate cognitive costs which are composed of a constant cost for transformation and a flexible cost depending on the extent of transformation. This can be inferred from the findings that performance was most accurate when no transformation was required (i.e. in the StatC) and that angle size of the spatial modification (i.e. rotation) decreased accuracy.

Transformation processes in WM favor to exploit visual information on the spatial modification over proprioceptive and vestibular feedback. This means that external is preferred over internal information, at least when it is highly informative for task requirements. This was evidenced by the finding that no benefit could be derived from ego-motion (i.e. walking), as it would have been predicted by spatial updating studies. Moreover, ego-motion impaired performance due to cognitive and sensomotoric walking costs (i.e. initiation, physical activity, termination at a given spot).

The underlying findings contribute to a better understanding of task allocation and problem solving in the WM. The WM is a functionally highly complex system with a wide-spread neuronal connectivity. Nevertheless, some relevant subystems operate widely independent of each other. This study has shown once more, how flexible the WM adapts to unfamiliar situations and how intelligent and strategical it solves complex requirements. In this way, it capacitates humans to handle diverse challenges and elementary actions in everyday life. From the perspective of science, working memory remains a fascinating cognitive resource.

Chapter 7

References

Altman, D. G., & Bland, J. M. (2005). Standard deviations and standard errors. *BMJ (Clinical research ed.), 331*(7521), 903. doi.org/10.1136/bmj.331.7521.903

Arrighi, R., Lunardi, R., & Burr, D. (2011). Vision and Audition Do Not Share Attentional Resources in Sustained Tasks. *Frontiers in Psychology, 2*(56). doi:10.3389/fpsyg.2011.00056

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In Spence, K. W., Spence, J. T. (eds.). *The psychology of learning and motivation, 2,* 89-195.

Authie, C. N., Hilt, P. M., N'Guyen, S., Berthoz, A., & Bennequin, D. (2015). Differences in gaze anticipation for locomotion with and without vision. *Front Hum Neurosci, 9*, 312. doi:10.3389/fnhum.2015.00312

Awh, E., & Pashler, H. (2000). Evidence for split attentional foci. *Journal of Experimental Psychology: Human Perception and Performance, 26*(2), 834–846. doi.org/10.1037/0096-1523.26.2.834

Baddeley, A. D. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences, 4*(11), 417-423. doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*, 829 – 839.

Baddeley, A. (2012). Working Memory: Theories, Models, and Controversies. *Annual Review of Psychology, 63*(1), 1-29. doi:10.1146/annurev-psych-120710-100422

Baddeley, A., Allen, R. J., & Hitch, G. J. (2011). Binding in visual working memory: The role of the episodic buffer. *Neuropsychologia, 49*(6), 1393–1400. doi:10.1016/j.neuropsychologia.2010.12.042

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. Bower (ed.), *Recent Advances in Learning and Motivation* (Vol. 8, pp. 647–667). New York: Academic Press.

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2019). From short-term store to multicomponent working memory: The role of the modal model. *Mem Cognit, 47*(4), 575-588.

Bankó, E. M., & Vidnyánszky, Z. (2010). Retention interval affects visual short-term memory encoding. *J Neurophysiol, 103*(3), 1425-1430.

Barrouillet, P., & Camos, V. (2007). The time-based resource-sharing model of working memory. In The Cognitive Neuroscience of Working Memory (pp. 59-80).

Barrouillet, P., & Camos, V. (2010). Working Memory and Executive Control: A time-based Resource-sharing Account. *Psychologica Belgica, 50*(3&4), 353-382.

Berch, D. B., Krikorian, R., & Huha, E. M. (1998). The Corsi block-tapping task: methodological and theoretical considerations. *Brain Cogn, 38*(3), 317-338.

Brainard, D. H. (1997). The Psychophysics Toolbox, *Spatial Vision 10*, 433-436.

Buelthoff, H. H., & Christou, C. G. (2000). The Perception of Spatial Layout in a Virtual World. *Lee SW., Buelthoff H.H., Poggio T. (eds) Biologically Motivated Computer Vision. BMCV 2000. Lecture Notes in Computer Science, 1811*, 10-19.

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends Cogn Sci, 9*(7), 349-354. doi:10.1016/j.tics.2005.05.009

Christiansen, M., & Chater, N. (2016). The Now-or-Never bottleneck: A fundamental constraint on language. *Behavioral and Brain Sciences, 39*, E62. doi:10.1017/S0140525X1500031

Corsi, P. M. (1971). Human memory and the medial temporal region of the brain. (PhD of philosophy). McGill University, Montreal. (exclusively published at the university)

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *Behav Brain Sci, 24*(1), 87-114; discussion 114-185. doi:10.1017/s0140525x01003922

Cowan, N. (2010). The Magical Mystery Four: How is Working Memory Capacity Limited, and Why? *Curr Dir Psychol Sci, 19*(1), 51-57. doi:10.1177/0963721409359277

Crone, E. A., Wendelken, C., Donohue, S., van Leijenhorst, L., & Bunge, S. A. (2006). Neurocognitive development of the ability to manipulate information in working memory. *Proceedings of the National Academy of Sciences, 103*(24), 9315-9320. doi:10.1073/pnas.0510088103

Davidenko, N., Heller, N. H., Cheong, Y., & Smith, J. (2017). Persistent illusory apparent motion in sequences of uncorrelated random dots. *J Vis, 17*(3), 19. doi:10.1167/17.3.19

Diamantopoulou, S., Poom, L., Klaver, P., & Talsma, D. (2011). Visual working memory capacity and stimulus categories: a behavioral and electrophysiological investigation. *Exp Brain Res, 209*(4), 501-513.

D'Esposito, M., Detre, J., Alsop, D., Shin, R. K., Atlast, S., & Grossman, M. (1995). The neural basis of the central executive system of working memory. *Nature 378*, 279–281. doi.org/10.1038/378279a0

Earman, J. (1971). An Introduction to the Philosophy of Time and Space. *The Philosophical Review, 80*, (4), 516-522

Eigler, G. (ed.). (1990), 2: Platon Werke Griechisch-Deutsch in 8 Bänden. Darmstadt: Wiss Buchges. ISBN 3-534-11280-6

Fang, M. W. H., Becker, M. W., & Liu, T. (2019). Attention to colors induces surround suppression at category boundaries. *Sci Rep, 9*(1), 1443. doi:10.1038/s41598-018-37610-7

Frissen, I., Campos, J. L., Souman, J. L. & Ernst, M. O. (2011). Integration of vestibular and proprioceptive signals for spatial updating. *Exp Brain Res 212*, 163–176. https://doi.org/10.1007/s00221-011-2717-9

Fukuda, K., Vogel, E., Mayr, U., & Awh, E. (2010). Quantity, not quality: the relationship between fluid intelligence and working memory capacity. *Psychonomic bulletin & review, 17*(5), 673–679. doi.org/10.3758/17.5.673

Gao, Z., Wu, F., Qiu, F., He, K., Yang, Y., & Shen, M. (2017). Bindings in working memory: The role of object-based attention. *Atten Percept Psychophys, 79*(2), 533-552. doi:10.3758/s13414-016-1227-z

Gao, Z., Ye, T., Shen, M., & Perry, A. (2016). Working memory capacity of biological movements predicts empathy traits. *Psychon Bull Rev 23*, 468–475. doi.org/10.3758/s13423-015-0896-2

Geldmacher, D. (1996). Effects of Stimulus Number and Target-to-Distractor Ratio on the Performance of Random Array Letter Cancellation Tasks. *Brain and Cognition, 32*(3), 405-415.

Godijn, R., & Theeuwes, J. (2012). Overt is no better than covert when rehearsing visuo-spatial information in working memory. *Mem Cognit, 40*(1), 52-61. doi:10.3758/s13421-011-0132-x

Goebl, H. (1998). Dialektometrische Beschreibung der Romania. In: Lexikon der Romanistischen Linguistik (LRL), Holtus, Günter / Metzeltin, Michael / Schmitt, Christian (ed.), Volume VII, Tübingen: Niemeyer, 977-1003.

Hard, B. M., Recchia, G., & Tversky, B. (2011). The shape of action. *Journal of Experimental Psychology: General, 140*(4), 586–604. doi.org/10.1037/a0024310

Hills, T. T., Todd, P. M., & Goldstone, R. L. (2010). The central executive as a search process: priming exploration and exploitation across domains. *Journal of experimental psychology. General, 139*(4), 590–609.

Hongsup, S., Qijia, Z., & Wei, J. M. (2017). The effects of delay duration on visual working memory for orientation. *Journal of Vision, 17*(14):10. doi.org/10.1167/17.14.10.

Huestegge, L., Pieczykolan, A., & Janczyk, M. (2018). Backward crosstalk and the role of dimensional overlap within and between tasks. *Acta Psychol (Amst), 188*, 139-147. doi:10.1016/j.actpsy.2018.06.004

Huff, M., Papenmeier, F., Jahn, G., & Hesse, F. W. (2010). Eye movements across viewpoint changes in multiple object tracking. *Visual Cognition, 18*(9), 1368-1391. doi:10.1080/13506285.2010.495878

Hurlstone, M. J., & Hitch, G. J. (2015). How is the serial order of a spatial sequence represented? Insights from transposition latencies. *J Exp Psychol Learn Mem Cogn, 41*(2), 295-324. doi:10.1037/a0038223

Hurlstone, M. J., Hitch, G. J., & Baddeley, A. D. (2014). Memory for serial order across domains: An overview of the literature and directions for future research. *Psychol Bull, 140*(2), 339-373. doi:10.1037/a0034221

Kaltner, S., & Jansen, P. (2016). Developmental Changes in Mental Rotation: A Dissociation Between Object-Based and Egocentric Transformations. *Advances in* *cognitive psychology, 12*(2), 67–78. doi.org/10.5709/acp-0187-y

Katsumata, Y., Taniguchi, A., Hagiwara, Y., & Taniguchi, T. (2019). Semantic Mapping Based on Spatial Concepts for Grounding Words Related to Places in Daily Environments. *Frontiers in Robotics and AI, 6*(31). doi:10.3389/frobt.2019.00031

Katus, T., Grubert, A., & Eimerl, M. (2017). Intermodal Attention Shifts in Multimodal Working Memory. *Journal of Cognitive Neuroscience, 29*(4), 628-636.

Klatzky, R. L. (1998). Allocentric and Egocentric Spatial Representations: Definitions, Distinctions, and Interconnections. Spatial Cognition. Lecture Notes in Computer Science. 1404. pp. 1–17. $doi : 10.1007/3-540-69342-4_1$. ISBN 978-3-540-64603-7.

Kleiner, M., Brainard, D., & Pelli, D. (2007). "What's new in Psychtoolbox-3?" Perception 36 ECVP Abstract Supplement.

Knight, M. J., & Tlauka, M. (2018). Map learning and working memory: Multimodal learning strategies. *Quarterly Journal of Experimental Psychology, 71*(6), 1405–1418. doi.org/10.1080/17470218.2017.1326954

Kung, E., & Hamm, J.P. (2010). A model of rotated mirror/normal letter discriminations. *Memory & Cognition 38*, 206–220. doi.org/10.3758/MC.38.2.206

Lehmann, A., Vidal, M., & Bülthoff, H. H. (2008). A High-End Virtual Reality Setup for the Study of Mental Rotations. *Presence: Teleoperators and Virtual Environments, 17*(4), 365-375. doi:10.1162/pres.17.4.365

Levinson, Stephen. (2003). Space in Language and Cognition: Explorations in Cognitive Diversity. Vol. 5. 10.1017/CBO9780511613609.

Liu, C., & Xiao, C. (2018). Dual Systems for Spatial Updating in Immediate and Retrieved Environments: Evidence from Bias Analysis. *Front Psychol, 9, 85.* doi:10.3389/fpsyg.2018.00085

Luria, R., Balaban, H., Awh, E., & Vogel, E. K. (2016). The contralateral delay activity as a neural measure of visual working memory. *Neurosci Biobehav Rev* 62, 100-108.

Meilinger, T., Frankenstein, J., Watanabe, K., Bülthoff, H. H. & Hölscher, C. (2015). Reference frames in learning from maps and navigation. *Psychological Research 79*, 1000–1008. doi.org/10.1007/s00426-014-0629-6

Meilinger, T., & Vosgerau, G. (2013). Putting Egocentric and Allocentric into

Perspective. *Spatial Cognition VII: International Conference Spatial Cognition 2010*, 207-221.

Meyerhoff, H. S., Papenmeier, F., & Huff, M. (2017). Studying visual attention using the multiple object tracking paradigm: A tutorial review. *Atten Percept Psychophys, 79*(5), 1255-1274. doi:10.3758/s13414-017-1338-1

Miller G. A. (1956). The Magical Number Seven, Plus or Minus Two Some Limits on Our Capacity for Processing Information. *Psychological Review, 101*, 343-352.

Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27*, 272-277.

Morey, C. C., Cowan, N., Morey, R. D., & Rouder, J. N. (2011). Flexible attention allocation to visual and auditory working memory tasks: manipulating reward induces a trade-off. *Atten Percept Psychophys 73*, 458–472. doi.org/10.3758/s13414-010-0031-4

Morey, C. C. (2019). Perceptual grouping boosts visual working memory capacity and reduces effort during retention. *Br J Psychol, 110*(2), 306-327. doi:10.1111/bjop.12355

Nakashima, R., & Kumada, T. (2017). The whereabouts of visual attention: Involuntary attentional bias toward the default gaze direction. *Atten Percept Psychophys, 79*(6), 1666-1673. doi:10.3758/s13414-017-1332-7

Nieborowska, V., Lau, S. T., Campos, J., Pichora-Fuller, M. K., Novak, A., & Li, K. Z. H. (2019). Effects of Age on Dual-Task Walking While Listening. *J Mot Behav, 51*(4), 416-427. doi:10.1080/00222895.2018.1498318

Orsini, A., Simonetta, S., & Marmorato, M. S. (2004). Corsi's block-tapping test: some characteristics of the spatial path which influence memory. *Percept Mot Skills, 98*(2), 382-388. doi:10.2466/pms.98.2.382-388

Parmentier, F. B., & Andres, P. (2006). The impact of path crossing on visuospatial serial memory: encoding or rehearsal effect? *Q J Exp Psychol (Hove), 59*(11), 1867-1874. doi:10.1080/17470210600872154

Pasqualotto, A., & Esenkaya, T. (2016). Sensory Substitution: The Spatial Updating of Auditory Scenes "Mimics" the Spatial Updating of Visual Scenes. *Frontiers in behavioral neuroscience, 10*, 79. doi.org/10.3389/fnbeh.2016.00079

Piccirillo, R. A. (2010). The Lockean Memory Theory of Personal Identity: Definition, Objection, Response. *Inquiries Journal/Student Pulse, 2*(08). Retrieved from http://www.inquiriesjournal.com/a?id=1683

Plebanek, D. J., & Sloutsky, V. M. (2019). Selective attention, filtering, and the development of working memory. *Developmental Science, 22*(1), e12727. doi:10.1111/desc.12727

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision, 3*, 179-197.

Qiu, F., Pi, Y., Liu, K., Li, X., Zhang, J., & Wu, Y. (2018). Influence of sports expertise level on attention in multiple object tracking. *PeerJ, 6*, 1-11.

Sanada, M., Ikeda, K., & Hasegawa, T. (2015). Shape and spatial working memory capacities are mostly independent. *Frontiers in psychology, 6*, 581.

Shepard, N. S., & Metzler, J. (1971). Mental Rotation of Three-Dimensional Objects. *Science, 171*, 701-703.

Šimkovic, M., & Träuble, B. (2019). Robustness of statistical methods when measure is affected by ceiling and/or floor effect. *PLoS One, 14*(8), e0220889. doi:10.1371/journal.pone.0220889

Simons, D. J., & Wang, R. F. (1998). Perceiving Real-World Viewpoint Changes. *Psychological Science, 9*(4), 315–320. doi.org/10.1111/1467-9280.00062

Spilcke-Liss, J., Zhu, J., Gluth, S., Spezio, M., & Gläscher, J. (2019). Semantic Incongruency Interferes With Endogenous Attention in Cross-Modal Integration of Semantically Congruent Objects. *Frontiers in integrative neuroscience, 13*, 53. doi:10.3389/fnint.2019.00053.

Srinivasan, M., & Ruina, A. (2006). Computer optimization of a minimal biped model discovers walking and running. *Nature, 439*(7072), 72-75.

Stefanics, G., Heinzle, J., Horvath, A. A., & Stephan, K. E. (2018). Visual Mismatch and Predictive Coding: A Computational Single-Trial ERP Study. *J Neurosci, 38*(16), 4020-4030. doi:10.1523/JNEUROSCI.3365-17.2018

Störmer, V., Li, S.-C., Heekeren, H. R., & Lindenberger, U. (2013). Normative shifts of cortical mechanisms of encoding contribute to adult age differences in visual-spatial working memory. *NeuroImage, 73*, 167-175.

Summerfield, C., & Egner, T. (2009). Expectation (and attention) in visual cognition. *Trends Cogn Sci, 13*(9), 403-409. doi:10.1016/j.tics.2009.06.003

Ströker, E. (ed.). (2009), 1: Edmund Husserl - Ideen zu einer reinen Phänomenologie und phänomenologischen Philosophie. Hamburg: Felix Meiner Verlag. ISBN 978-3-7873-1919-0

Swallow, K. M., Zacks, J. M., & Abrams, R. A. (2009). Event boundaries in perception affect memory encoding and updating. *J Exp Psychol Gen, 138*(2), 236-257. doi:10.1037/a0015631

Tremblay, S., Saint-Aubin, J., & Jalbert, A. (2006). Rehearsal in serial memory for visual-spatial information: Evidence from eye movements. *Psychonomic Bulletin & Review 13*, 452–457. doi.org/10.3758/BF03193869

Van der Stigchel, S., & Hollingworth, A. (2018). Visuospatial Working Memory as a Fundamental Component of the Eye Movement System. *Current Directions in Psychological Science, 27*(2), 136–143. https://doi.org/10.1177/0963721417741710

Wager, T. D., & Smith, E. E. (2003). Neuroimaging studies of working memory: a meta-analysis. *Cogn Affect Behav Neurosci, 3*(4), 255-274. doi:10.3758/cabn.3.4.255

Ward, G. (2001). A critique of the working memory model. In J. Andrade (ed.), *Working memory in perspective* (p. 219–239). Psychology Press.

Weicker, J., Hudl, N., & Thöne-Otto A. (2017). „Was misst eigentlich die Blockspanne?“ – Der Goldstandard im Fokus. *Zeitschrift für Neuropsychologie, 28*(1), 45-54. doi:10.1024/1016-264X/a000194

Welwood, J. (1977). On psychological space. *Journal of Transpersonal Psychology, 9*(2), 97–118.

Wiener, J. M., & Mallot, H. A. (2006). Path Complexity Does Not Impair Visual Path Integration. *Spatial Cognition & Computation, 6*(4), 333–346. doi:10.1207/$s15427633scc0604_3$

Williams, E. J. (1949): Experimental designs balanced for the estimation of residual effects of treatments. *Australian Journal of Scientific Research, A 2*, 149-168.

Xue, J., Li, C., Quan, C., Lu, Y., Yue, J., & Zhang, C. (2017). Uncovering the cognitive processes underlying mental rotation: an eye-movement study. *Sci Rep, 7*(1), 10076. doi:10.1038/s41598-017-10683-6

Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology, 24*, 295–340. doi:10.1016/0010-0285(92)90010-y

Chapter 8

Appendices

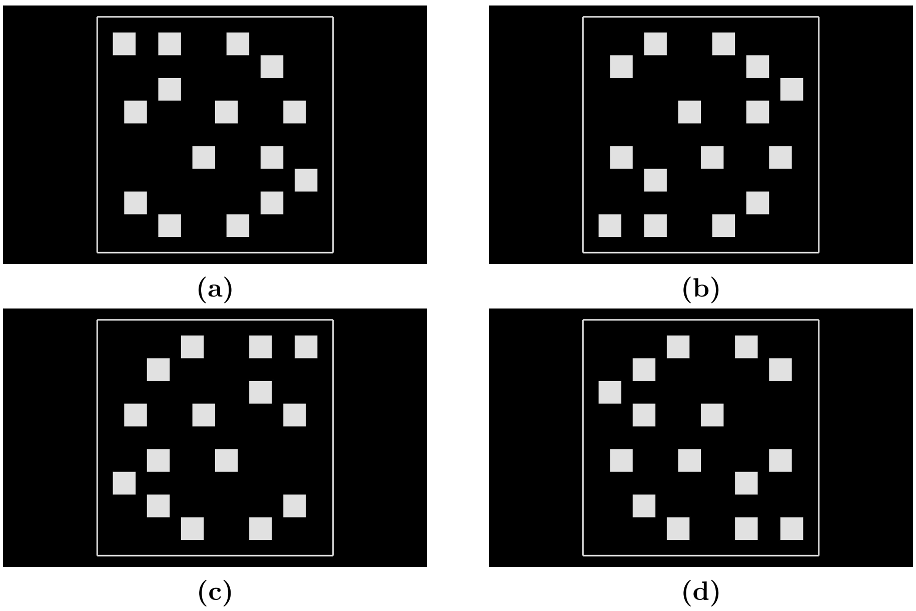


Figure 8.1:
Basic patterns of the Modality Experiment

Figure 8.2:
Spatial spans based on trials - Modality Experiment
line 13 indicates mean

Figure 8.3:
Weighted spans based on trials - Modality Experiment;
line 13 indicates mean

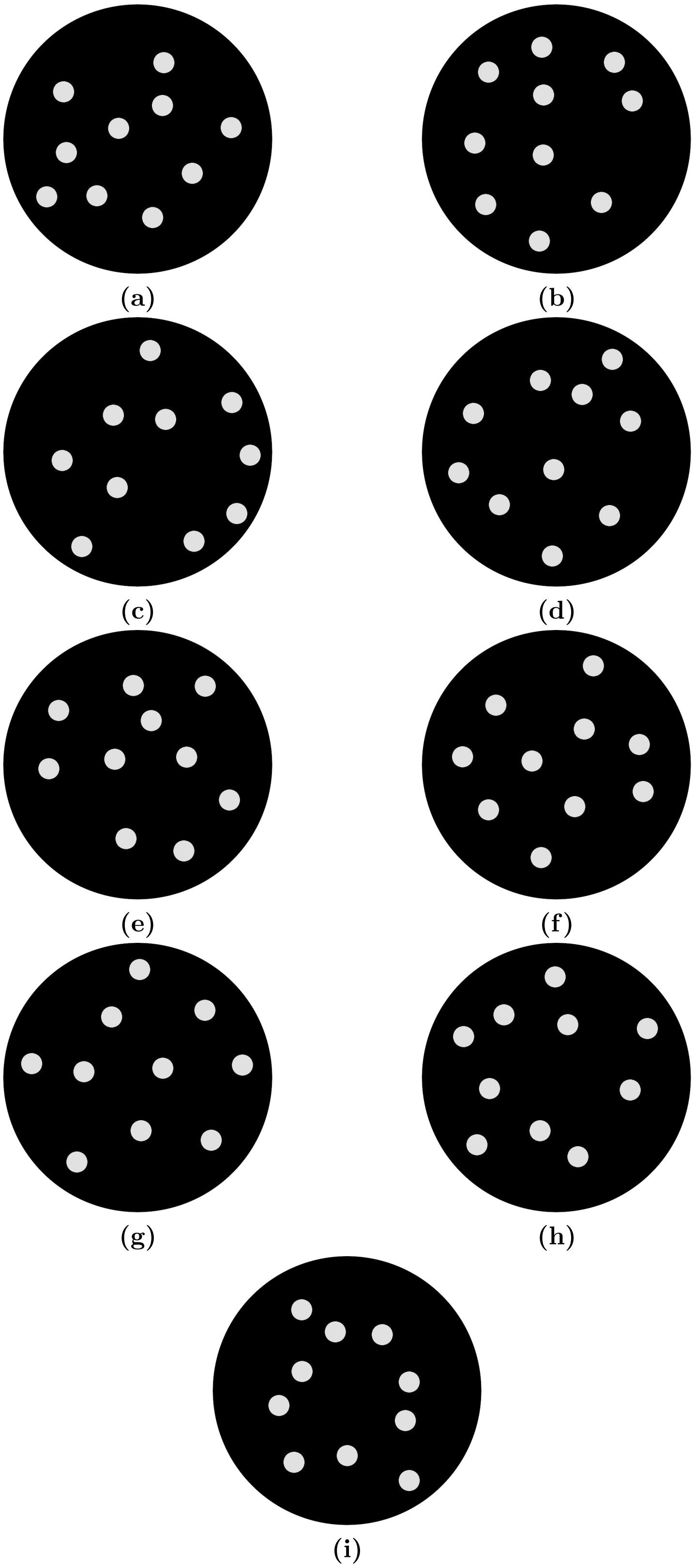


Figure 8.4:
Basic patterns of the Updating Experiment

Pattern ID	Initial Circle Positions	
	x	y
(a)	395	545
	252	548
	300	249
	582	288
	457	353
	667	481
	778	351
	586	166
	554	607
	308	422
(b)	474	429
	279	395
	318	193
	470	122
	728	275
	310	570
	463	674
	475	258
	677	165
	640	564
(c)	591	291
	442	279
	296	408
	453	485
	547	95
	352	653
	780	243
	832	393
	794	559
	672	638
(d)	663	565
	500	680
	349	534
	233	443
	466	180
	504	434
	275	274
	723	296
	585	220
	671	120

Pattern ID	Initial Circle Positions	
	x	y
(e)	446	368
	651	362
	499	158
	550	258
	704	160
	643	629
	478	594
	258	395
	286	229
	773	484
(f)	468	648
	318	512
	244	361
	339	214
	442	373
	564	503
	759	460
	748	326
	617	102
	591	282
(g)	521	535
	358	367
	209	344
	437	211
	338	624
	703	192
	810	348
	583	357
	517	76
	721	562
(h)	465	535
	321	415
	722	419
	573	609
	544	233
	362	205
	247	267
	508	97
	771	244
	285	575

Pattern ID	Initial Circle Positions	
	x	y
(i)	678	469
	383	329
	382	153
	317	426
	612	224
	512	569
	360	588
	689	359
	478	216
	689	640

Table 8.1:
Table of item coordinates - Updating Experiment

Pattern	Sequence	PL(pixels)
(a)	9 6 7 2	988.74
	9 2 4 5	974.16
	4 6 2 3	997.79
	5 3 6 7	990.48
	3 4 6 10	984.57
	7 5 8 9	1020.34
(b)	7 6 5 9	836.24
	3 4 5 2	952.55
	4 5 7 10	1040.55
	1 10 2 9	1072.24
	6 9 5 1	964.83
	2 6 5 4	999.97
(c)	8 7 5 3	849.33
	2 3 9 1	1051.41
	4 3 8 10	1055.93
	10 7 2 1	898.89
	4 3 6 8	1024.32
	7 2 1 10	845.72
(d)	6 7 1 2 5	1457.20
	7 2 8 5 10	1422.99
	6 5 1 9 7	1308.35
	5 2 8 9 3	1516.07
	9 4 3 10 8	1272.12
	2 5 6 10 1	1477.09
(e)	9 7 4 3 10	1294.15
	4 9 5 2 3	1152.48
	9 4 8 2 5	1191.34
	8 1 3 9 6	1167.17
	3 6 2 1 9	1176.67
	5 9 8 7 1	1116.90
(f)	1 5 8 9 7	1230.44
	3 8 5 2 1	1203.54
	5 6 3 8 10	1196.63
	2 5 4 7 9	1247.59
	2 6 1 8 5	1156.36
	5 4 2 8 9	1216.18

Pattern	Sequence	PL(pixels)
(g)	8 7 3 1 2 6	1814.93
	6 3 1 5 4 8	1717.34
	8 5 3 9 2 7	1862.93
	7 6 9 5 4 10	1861.07
	7 3 8 1 4 6	1765.11
	8 1 5 6 2 7	1796.78
(h)	3 9 10 6 7 8	1589.79
	7 2 1 5 4 9	1599.35
	2 7 3 9 4 8	1915.12
	3 1 2 9 10 7	1849.15
	5 8 2 9 10 4	1825.61
	6 10 7 5 3 4	1570.50
(i)	10 8 5 3 6 9	1529.89
	8 6 1 7 3 4	1651.98
	2 7 3 4 5 9	1665.71
	10 9 8 7 4 1	1755.96
	10 2 8 4 3 9	1591.10
	6 10 4 8 3 2	1619.66

Table 8.2:

Sequences and corresponding path lengths - Updating Experiment

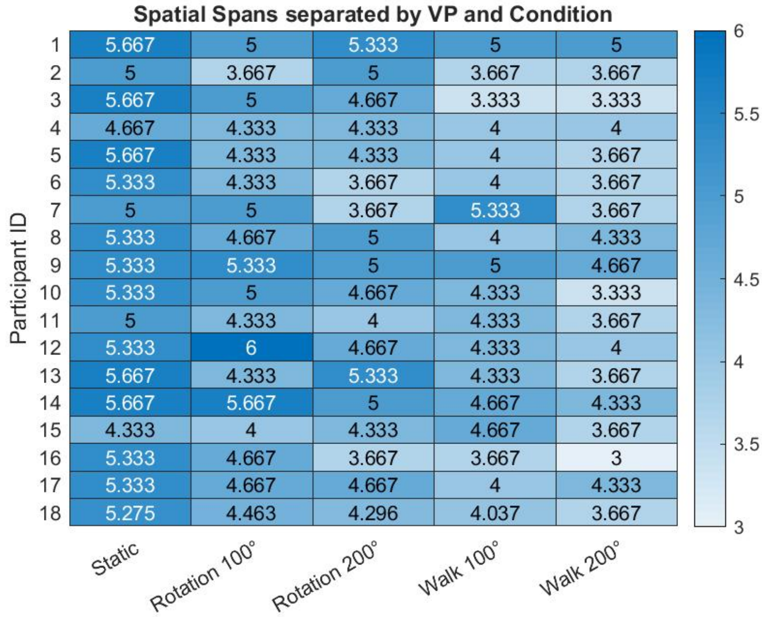


Figure 8.5:
Spatial spans based on trials - Updating Experiment
line 18 indicates mean

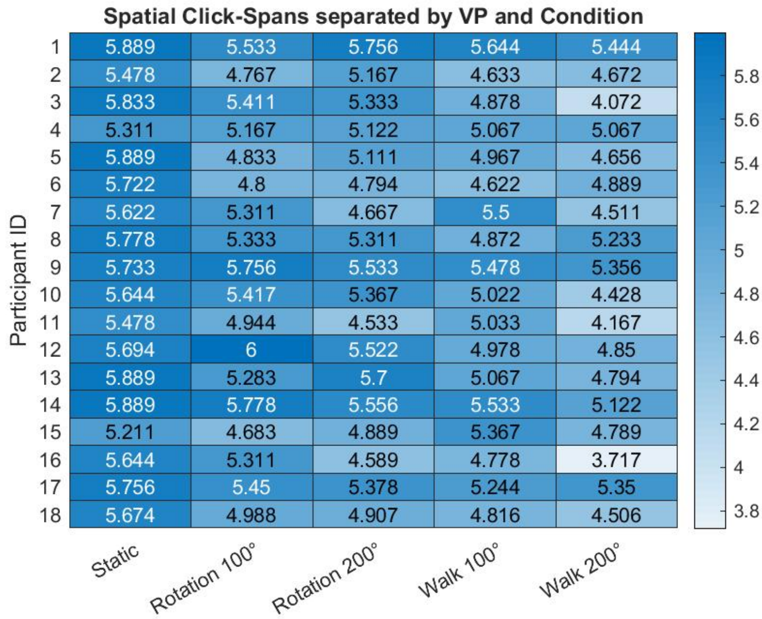


Figure 8.6:
Spatial spans based on clicks - Updating Experiment
line 18 indicates mean

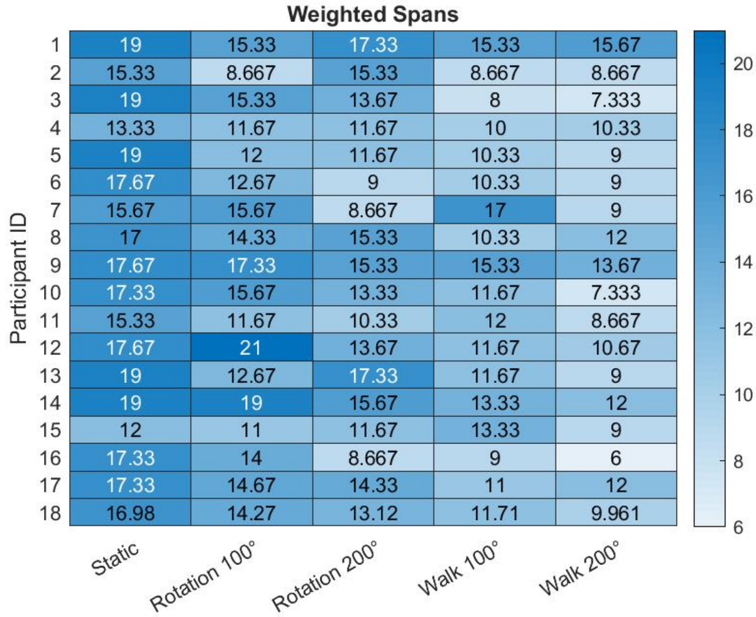


Figure 8.7:
Weighted spans based on trials - Updating Experiment
line 18 indicates mean

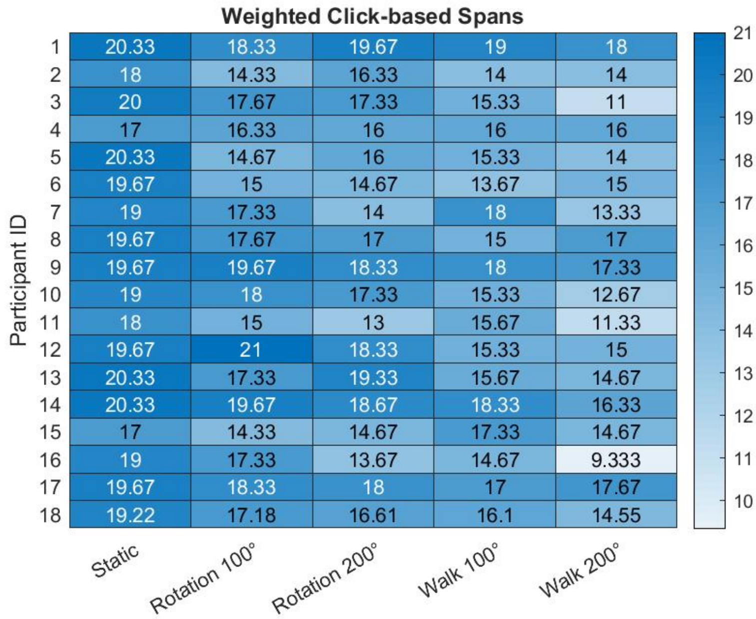


Figure 8.8:
Weighted spans based on clicks - Updating Experiment
line 18 indicates mean