The role of cognitive load in navigational walking, planning and recall

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Zusammenfassung

Gehen ist eine wichtige und häufige Verhaltensweise bei Menschen und spielt im Alltag eine große Rolle. Dennoch wurde bisher recht selten untersucht, welchen Einfluss kognitive Anforderungen auf unterschiedliche Aufgaben mit verschiedenen Schwierigkeitsgraden auf das Gehen bzw. auf die Laufgeschwindigkeit haben. Dies sollte im ersten Teil dieser Doktorarbeit untersucht werden (Experiment 1 und Experiment 2). Neben der Abnahme der Laufgeschwindigkeit mit zunehmenden kognitiven Anforderungen wurde auch vermutet, dass das Gehen einer bekannten Strecke weniger Ressourcen des Arbeitsgedächtnisses benötigen wird, als das Planen einer Route während des Gehens. Zu diesem Zweck wurde eine Laufversion des Traveling Salesman Tasks (planen während des Laufens), sowie eine Laufversion des Corsi Tasks (gehen einer bekannten Route) entwickelt. In beiden Experimenten wurden die kognitiven Anforderungen verändert, indem die Anzahl der Orte innerhalb der Route bzw. die Länge der gezeigten Sequenzen erhöht wurden.
Die Ergebnisse zeigten, dass die Versuchspersonen sehr gut im Lösen des Traveling Salesman Tasks waren und nur minimal von der kürzesten Route abwichen. Mit zunehmender Länge der Routen verschlechterte sich aber die Leistung. Auch beim Corsi Task verschlechterte sich die Leistung der Versuchspersonen mit zunehmender Länge der gezeigten Sequenzen. Entgegen der Hypothese ergab sich beim Vergleich der beiden Experimente, dass die Versuchspersonen im Traveling Salesman Task besser waren als im Corsi Task. Die Laufgeschwindigkeit nahm in beiden Experimenten mit zunehmender Routen- bzw. Streckenlänge ab. Es gab keinen Unterschied in der Laufgeschwindigkeit in beiden Experimenten, aber die Versuchspersonen standen im Corsi Task länger auf den einzelnen Quadraten als im Traveling Salesman Task. Deshalb ist davon auszugehen, dass verschiedene Ressourcen des Arbeitsgedächtnisses für das Ausführen der beiden Aufgaben benötigt werden.

Im zweiten Teil der Doktorarbeit wurde untersucht, ob die Leistung der Versuchspersonen in einem Corsi Task von der Präsentations- und Abrufweise der Corsi-Sequenzen abhängt (Experimente 2 bis 5). Dazu wurde neben der Laufversion des Corsi Tasks auch eine Computerversion entwickelt. Im vierten Experiment wurden die Corsi-Sequenzen nicht als Abfolge von einzelnen Quadraten gezeigt, sondern alle Quadrate der Sequenz wurden gleichzeitig angezeigt. Zusätzlich zu der Lauf- und der Computerversion gab es im letzten Experiment noch zwei weitere Präsentations- und Abrufweisen. Somit wurde in diesem Experiment die Leistung in vier verschiedenen Modalitätsbedingungen gemessen (d.h., Screen-Screen, Floor-Screen, Floor-Floor und Screen-Floor).
In allen vier Experimenten verschlechterte sich die Leistung der Versuchspersonen mit zunehmender Sequenzlänge; dies resultiert vermutlich aus der begrenzten Kapazität des Arbeitsgedächtnisses. Beim Vergleich der vier verschiedenen Modalitätsbedingungen ergab sich das beste Ergebnis, wenn die Versuchspersonen die Sequenz auf einem Bildschirm sahen und jene auch an diesem mit einer Maus nachklicken konnten, gefolgt von den Leistungen, wenn die Sequenz am Boden gezeigt und am Bildschirm nachgeklickt wurde, sowie am Boden gezeigt und auch am Boden nachgelaufen wurde. Das schlechteste Ergebnis kam zustande, wenn die Sequenz am Bildschirm gezeigt wurde und die Versuchspersonen sie nachlaufen mussten. Diese

Ergebnisse deuten darauf hin, dass unterschiedliche Prozesse des räumlichen Arbeitsgedächtnisses in den verschiedenen Modalitätsbedingungen beteiligt sind. Bei Screen-Screen werden lediglich für das Abrufen der gezeigten Sequenz Ressourcen des Arbeitsgedächtnisses benötigt. Bei Floor-Screen und Floor-Floor werden zusätzliche Anforderungen an das Arbeitsgedächtnis für "reference frame transformations" bzw. "spatial updating" gestellt. Bei Screen-Floor werden wiederum alle der oben genannten Anforderungen an das Arbeitsgedächtnis gestellt; dies führte zum schlechtesten Ergebnis.

Aufgrund der Ergebnisse in den vier Experimenten wird angenommen, dass die Leistung in einem Corsi Task nicht nur von der Fähigkeit eine gezeigte Sequenz zu reproduzieren abhängt, sondern auch von den zusätzlichen Anforderungen, die von den verschiedenen Präsentations- und Abrufweisen verursacht werden.

Summary

Walking is an important and common behavior in humans and is needed frequently in everyday life. Yet, not so much work has been done to investigate the influence of cognitive demands in different task difficulties on walking, more specifically on walking speed. The investigation of these parameters was the aim of the first part of this thesis (Experiment 1 and Experiment 2). Besides a decrease of walking speed with increasing cognitive demands it was also hypothesized that walking a known route will require less working memory resources than planning a route while walking. Therefore, a walking version of a Traveling Salesman task (planning while walking), as well as a walking version of a Corsi task (walking a known route) were designed. In both experiments the different cognitive demands on working memory have been varied by adding more locations to the routes and showing longer sequences, respectively.

Results indicated that participants were quite good in solving the walking version of the Traveling Salesman task and showed only a minimal deviation of the shortest route. However, a decrease of performance was found with increasing route length. For the Walking Corsi task a decrease of performance with increasing sequence length was found, too. Contrary to the hypothesis, comparing the results of the two experiments revealed that participants' performance was better in the Traveling Salesman task than in the Corsi task. In both experiments the walking speed decreased with increasing route and sequence length, respectively. There was no difference between the walking speeds in the two experiments, though, participants stood longer on the single square tiles in the Corsi task than in the Traveling Salesman task. Therefore, it is supposed that different working memory resources are required for solving the two tasks.

In the second part of this thesis it was investigated whether participants' performance in a Corsi task depends on the presentation and recalling type of the Corsi sequences (experiments 2 to 5). Besides the walking version of the Corsi task also a computerized version was designed. In Experiment 4 the Corsi sequences were not presented square by square, but all squares included in the sequences were presented simultaneously. Besides the walking and the computerized version, two additional presentation and recall combinations of the Corsi task were evaluated in the last experiment. Consequently, performance in four modality conditions was measured (i.e., Screen-Screen, Floor-Screen, Floor-Floor and Screen-Floor).

Results of the four different experiments revealed that in all experiments participants' performance decreased with increasing sequence length: This should be caused by the limited capacity of the working memory. Comparing the four modality conditions, performance was best when participants watched and reproduced the sequence on a screen, followed by watching the sequence on the floor and reproducing it on the screen as well as watching the sequence on the floor and reproducing it on the floor. The lowest performance was reached when participants watched the sequence on the screen and had to reproduce it on the floor. These findings indicate that different processes of spatial working memory are involved in the different modality conditions. For Screen-Screen only recalling the length of the sequence required working memory resources. For Floor-Screen and Floor-Floor additional demands on working memory were caused by reference frame transformation from floor to screen and spatial

updating, respectively. In Screen-Floor all of these additional demands were required and therefore performance was poorest.
Due to the results of the four experiments, it is suggested that performance in the Corsi task not only depends on the ability to recall the sequence but also on the additionally demands caused by the presentation and recall type.

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1. Introduction[1]

The aim of this thesis was the investigation of the influence of cognitive demands in different task difficulties on walking as well as the investigation of the influence of different presentation and recall types on performance. Therefore, five experiments have been designed. In the first two experiments the cognitive demands on walking while planning a route (Experiment 1) and walking a known route (Experiment 2) were investigated. In the experiments 2 to 5 different presentation and recall types of a Corsi task and their influence on participants' performance were investigated.

Locomotion

Locomotion describes the ability to move from one place to another and plays an important role in everyday life. It has long be seen to be an automatic process (Norman & Shallice 1986, Brown & Marsden 1991). A crucial role in locomotion plays the spinal cord. It contains, like the central nervous system, neuronal circuits which serve as central pattern generators which are able to produce motor behaviors. Additional afferent information of visual, vestibular and proprioceptive systems give feedback and locomotion can be adapted to external requirements e.g. by changing walking speed (Grillner 1985, Dietz 2002). The central pattern generators as well as the afferent input to the spinal cord are controlled by the brainstem (Dietz 2003).

However, it could be shown that walking is also an attention-demanding task (Lajoie et al. 1993 and 1999, Beauchet et al. 2005 a, Srygley et al. 2009), which requires more attention in older than in young adults (Woollacott & Shumway-Cook 2002, Lövdén et al. 2008) and concurrent cognitive tasks affect gait in old adults more than in young adults (Al-Yahya et al. 2011). Yogev et al. (2005) found that the walking speed decreased in patients with Parkinson's disease as well as in healthy old adults when they solved different dual tasks. Also several other studies have investigated the influence of dual task performance on walking in elderly (e.g. Camicioli et al. 1997), patients with Parkinson's disease (e.g. Bond & Morris 2000), patients with Alzheimer's disease (e.g. Camicioli et al. 1997) or stroke patients (e.g. Haggard et al. 2000). All of them reported a decrease of walking speed during solving a dual task.

Beauchet et al. (2005 b) chose two different dual tasks, an arithmetic task and a verbal fluency task to investigate changes in gait patterns. For both dual tasks they found a decrease of walking speed and an increase of steps. Further, they reported an interference of the arithmetic task with lateral gait stability, whereas the verbal fluency task did not interfere with lateral gait stability. Thus, dual tasks should be chosen carefully, especially for older adults.

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[1] Some parts of this chapter have been used and were published in the paper Röser et al. (2016) and were adopted here almost one to one. The final publication is available at link.springer.com/article/10.1007%2Fs00221-016-4582-z.

The mentioned studies all investigated the dual task interference on gait stability or walking speed in older adults or patients. But also for young adults interference of a dual task on posture and gait velocity has been shown. Kerr et al. (1985) reported that a difficult balance task decreased performance in a concurrent spatial task, but not in a concurrent non-spatial task compared to performance of both tasks while seated. They concluded that posture and cognitive spatial processing require the same neural mechanisms.
In another study by Beauchet et al. (2005 a) young adults had to count backwards while walking. They reported that participants' gait velocity decreased while performing the dual task, therefore Beauchet et al. (2005 a) concluded that "walking is an attention-demanding task in young adults". Further, they could show that not only walking speed but also backward counting was decreased during walking compared to backward counting alone. Similar results were reported by Srygley et al. (2009). They also found a decrease of walking speed while participants counted backwards both for young and old adults, and the number of mistakes during counting increased during walking, especially in dual-tasks with higher difficulty.

Dual task

All of the mentioned studies above used dual task paradigms. In a dual task paradigm participants have to solve two different tasks simultaneously. This can lead to a performance decrease in one or both of the tasks compared to the performance when the tasks are conducted separately. A performance decrease can be found when the two tasks require the same resources of the capacity-limited working memory (Pashler 1994, Woollacott & Shumway-Cook 2002) and attention has to be divided between the two tasks (Beauchet et al. 2005 b, Yogev-Seligmann et al. 2008).
Thus, dual task paradigms are a method to investigate executive processes of the working memory (Della Sala et al. 1995).

Working memory

The concept of working memory and its modular and functional description was introduced by Baddeley & Hitch in 1974. It is a theoretical model in which information can be stored and manipulated simultaneously (Baddeley 1996, McAfoose & Baune 2009). In the initial version, this working memory model contained the "central executive" controlling two memory subsystems, i.e., the "phonological loop" and the "visuo-spatial sketchpad" (see Fig. 1.1). The two subsystems were functionally characterized by storage, maintenance and manipulation processes (Klauer & Zhao 2004, Repovš & Baddeley 2006). Later, Baddeley (2000) added the "episodic buffer" as third subsystem which is also under control of the central executive (see Fig. 1.1).
The phonological loop was the first described component of the model and it processes articulatory information. It is divided into a passive phonological store, which holds the verbal information for about 2 seconds until it decays (Barrouillet & Camos 2007), and an active articulatory control process, which upholds the information in the phonological store through rehearsal (Repovš & Baddeley 2006). Speech can enter the phonological store automatically, but input of different modalities first has to be recoded into phonological form by articulatory rehearsal (Repovš & Baddeley 2006). In contrast, visual and spatial information is processed in the visual-spatial sketchpad which is divided into a visual, e.g. color and pattern (Baddeley

1993), and a spatial subcomponent. Both have independent storage, maintenance and manipulation processes, the latter one depends on executive processes, whereas maintenance is thought to be independent (Repovš & Baddeley 2006). The visual subcomponent is related to perception and visual imagery, while the spatial component is more related to attention and action (Repovš & Baddeley 2006). The capacity of the visual-spatial sketchpad is limited to about four items (Pashler 1988) or features of a dimension (e.g. color or orientation), though further features of other dimensions (e.g. orientation, size or color) can be combined and therefore up to 16 features can be remembered when distributed across four objects in integrated objects (Luck & Vogel 1997). The episodic buffer was added later as third subsystem (Baddeley 2000). Its role is the connection to the long-term memory and it also relates the phonological loop and the visual-spatial sketchpad. Thus, information from different sources (i.e., long-term memory and the two other subsystems) can temporarily be stored and integrated (Repovš & Baddeley 2006). Similar to the other two subsystems it is limited in capacity. All of the three subsystems are under control of the central executive, which is one of the most important component of the working memory. It can control attention, divide it between the subsystems and switch it between different tasks. Further, the central executive has been seen to be responsible for the exchange between the subsystems of the working memory and the long-term memory (Baddeley 1996), though this function was transferred to the episodic buffer later. Nevertheless, the central executive seems to be involved in complex cognitive tasks, especially when information in the stores needs to be manipulated (Repovš & Baddeley 2006).

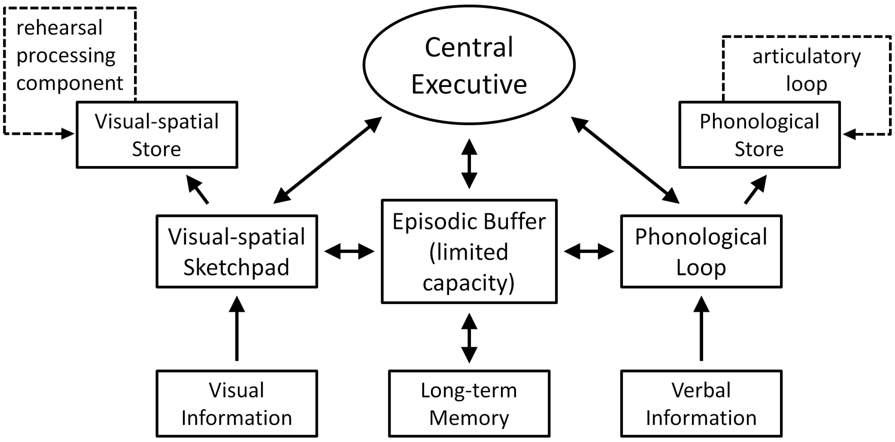

Figure 1.1.: Baddeley & Hitch' s multi-component working memory model. Baddeley and Hitch (1974) developed a working memory model which comprises different components. The central executive controls attention and divides it to the three subsystems. The phonological loop maintains and stores verbal information, whereas visual and spatial information is processed and stored by the visual-spatial sketchpad. The episodic buffer was not part of the original model, but added later. It connects the working memory to the long-term memory and interacts with the two other subsystems. Similar to the other subsystems it is under control of the central executive. The figure was adapted from McAfoose & Baune (2009) who extended and revised it from Baddeley (2000).

Chunks

As already mentioned, working memory is limited in capacity (Cowan 2000, Miller 1956) and duration (Ploner et al. 1998, Barrouillet & Camos 2007), with a working memory span between two and five (Baddeley 1996) and requires active rehearsal processes. For solving several tasks simultaneously attention needs to be split between the required subsystems of the working memory and switched between them (Barrouillet & Camos 2007). Such divided attention can result in a performance decrease in dual-task designs as described above.

Despite the limited capacity of the working memory, Luck & Vogel (1997) could show that participants were able to memorize more than four items by combining or “chunking” several features on one item. Such chunking of features and building of chunks were also described by Miller (1956). A chunk is defined as a collection of elements which have strong associations among each other but only weak associations to elements within other chunks (Gobet et al. 2001). So, by combining different features or objects it is possible to remember e.g. longer numbers or sentences easily, in contrast to remember the single digits or words which would quickly reach the capacity limit of the working memory.

Thus, the working memory has a limited memory capacity of items or chunks which can be remembered, but these items or chunks can contain a different amount of information. The fixation of such a chunk in long-term memory requires about 5 to 10 s (Simon 1974).

Spatial behavior

In spatial behavior, especially if bodily movements are involved, a number of working memory dependent processes have been identified. Such processes include path integration, imagery, spatial planning, perspective taking and reference frame transformations and spatial updating; for review see Byrne et al. (2007) and Loomis et al. (2013).

During path integration, information of bodily translation and rotation is tracked and integrated over time enabling the agent to calculate a vector pointing to the start location (Loomis et al. 1993, Wolbers et al. 2007). In imagery, spatial knowledge is recalled from long-term memory and transferred to working memory in a way depending on the current real or imagined viewpoint (Bisiach & Luzzatti 1978, Basten et al. 2012, Röhrich et al. 2014). Imagery is also involved in spatial planning, where multiple locations or decision points (e.g. places) get connected to generate a route to the goal (Wiener & Mallot 2003, Hardiess et al. 2011).

Perspective taking describes the ability to recognize the location and orientation of a specific spatial layout (arrangements of objects) from another viewpoint (Wang & Simons 1999, Amorim 2003, Meilinger et al. 2011). Reference frame transformations are involved if a spatial setup or layout of objects presented in one reference frame is to be transferred to another frame, e.g. in ultrasound-aided surgery where the surgeons guide their hand movements with the ultrasound-scanner image on a screen (Klatzky & Wu 2008). Dehaene et al. (2006) suggest that the ability for map-to-ground transformations is part of a culturally universal core knowledge of geometry. Reference frame transformations also appear in the Money Road-Map Test where participants should make decisions about turnings on a map simply by imaging and without turning the paper (Vingerhoets et al. 1996).

Montello (1993) reported that scale has an important influence on the treatment of spatial information, therefore he developed “four major classes of psychological spaces”. The first is the “figural space” which is defined to be smaller than the body and can be reached without appreciable locomotion, e.g. a picture, map or small object. The second is the “vista space” which is as large or larger than the body, such as rooms or a town square. Third is the “environmental space” which surrounds the body and is larger than it, thus locomotion is needed for apprehension. Examples for environmental spaces are e.g. buildings or cities. As fourth class the “geographical space” was introduced. It is much larger than the body and describes e.g. states or countries. For apprehension locomotion is insufficient and therefore maps are required (Montello 1993).

Information about the current spatial environment is represented and updated in a so called "spatial image" (Loomis et al. 2013). The representation of scenes and object configurations in this type of working memory is viewpoint-dependent, i.e., the recognition time for a learned layout is increased if a view from a novel direction is presented (Diwadkar & McNamara 1997). Recognition is facilitated, however, if the novel views are associated with according bodily movements of the observer (Wang & Simons 1999, Burgess et al. 2004), indicating that the scene representation changes as the observer moves. This process of adjusting egocentric positions of represented objects according to the observer's ongoing movement is known as spatial updating. It occurs automatically when the observer moves and cannot be suppressed at will or replaced by mere imagination of a movement (Farrell & Robertson 1998, Klatzky et al. 1998). Spatial updating is not restricted to body turns but also occurs in translational movements (Philbeck & Loomis 1997). Thus, in walking versions of a Traveling Salesman task and a Corsi block tapping task (see below), spatial updating will occur as the participant walks about the environment and will be needed to keep track of the reproduced route or sequence.
Imaging studies of spatial working memory have been performed for a number of tasks including for example imagery of out-of-view objects (Schindler & Bartels 2013), spatial updating (Wolbers et al. 2008), viewpoint transformation (Vogeley et al. 2004, Dhindsa et al. 2014), etc.; for review see Vann et al. (2009). These findings support the view of spatial working memory as a multi-component system with variable involvement in various behavioral tasks.

The relation of the three (or four; see Baddeley 2000) working memory components of the Baddeley & Hitch model of the spatial memory processes discussed above is partially unclear. Visual imagery and viewpoint dependent processes might be considered part of the visuo-spatial sketchpad, but "allocentric" and episodic (event related) components of spatial working memory also seem to exist (see Burgess 2006 for a discussion of this issue). Therefore, it is suggested that also in the Traveling Salesman task and in the Corsi block tapping task, various subtypes or components of working memory might be involved.

Navigation

The elements mentioned before in the subchapter "Spatial behavior" are necessary for successful navigation. Navigation is needed for a lot daily activities, such as moving from one room to another, driving to work or to go shopping. It is goal-directed (Montello & Sas 2006) and this goal is maintained actively in working memory (Ciaramelli 2008, Kong et al. 2017). Navigation is based on environmental representations (e.g. texture of the ground, architectural style, different colors or sizes; Montello & Sas 2006) and different sensomotoric information (e.g. visual, tactile, auditory or olfactory) which is processed and integrated (Tedesco et al. 2017), thus, complex cognitive abilities are involved in navigation.
Navigation includes two components: Locomotion describes the movement from the current location to a goal destination and is the executive part of navigation. Further, navigation contains a planning part, which is known as wayfinding (Darken & Peterson 2001, Montello & Sas 2006). Human wayfinding is based on path integration or dead reckoning and landmark-guidance. As already mentioned path integration or dead-reckoning describes the ability to update the "position in space from velocity or acceleration signals provided by proprioception" (Klatzky et al. 1998). Landmarks are salient visual features in the environment (e.g. rivers,

buildings, etc.) that are persistent over time and can be used for reorientation, though memory is required for the particular landmarks (Foo et al. 2005). Further external tools such as a compass, global positioning system or maps can be used for navigation and also route planning, which is a common but more complex wayfinding task. Planning a route can be divided into several parts. A model by Brunyé et al. (2010) starts with reviewing the spatial relationship between the current position and a goal, followed by identifying and comparing possible routes and finally choosing a feasible path. A similar model was reported by Jul & Furnas (1997). This model starts with formulating a goal, then a strategy for reaching the goal is developed and if necessary further information for execution is collected. Next, the execution of the task starts and while doing so relevant information is collected from the environment. All the time it is assessed whether the collected information leads to the goal or if some changes, such as changing direction or maybe defining a completely new goal, are necessary. This procedure is carried out until the goal is reached or the action has to be canceled.

A widely used paradigm for investigating route planning is the Traveling Salesman task.

Traveling Salesman task

The Traveling Salesman task describes the traveling of a salesman who has to visit different locations on a tour back to his starting position. Each of the locations has to be visited exactly once. For maximum efficiency of the tour the shortest way, including all locations, back to the start should be found, an example is shown in Fig. 1.2.

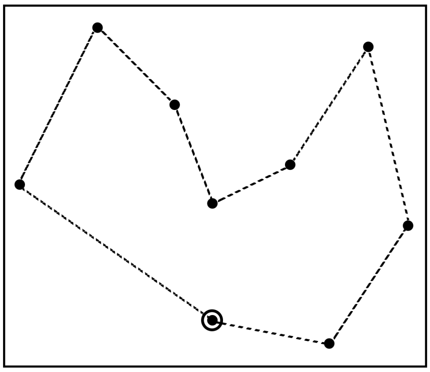

Figure 1.2.: Illustration of the Traveling Salesman task. A salesman has to travel the shortest way from the start position (circled black dot) to the eight remaining locations (black dots) and back to the beginning. The dotted lines indicate the shortest route for this example.

The Traveling Salesman problem was first known as mathematical problem. It belongs to so-called nondeterministic polynomial time complete (NP-complete) problems (e.g. MacGregor & Ormerod 1996), which means that the possible solutions increase exponentially with the number of locations and no optimal solution can be found in an appropriate time. Several algorithms and models have been developed to solve this task, e.g. the nearest neighbor model (Rosenkrantz et al. 1977), the convex hull model (MacGregor et al. 2000), the pyramidal model (Graham et al. 2000), the global-local model (Best 2005) or the African Buffalo optimization (Odili & Kahar 2016). And still, there is no algorithm to solve the Traveling Salesman problem optimally for large sizes of the Traveling Salesman task in a reasonable time. Though, it is possible to find optimal solutions for Traveling Salesman problems with small sizes. (Golden et al. 1980, Vickers et al. 2003 a).

In contrast to algorithms humans have a quite good performance in solving Traveling Salesman tasks by finding optimal or near optimal solutions and sometimes outperform the algorithms (Hill 1982, MacGregor & Ormerod 1996, Kong & Schunn 2007, Wiener et al. 2007, Blaser & Wilber 2013). So the task is not only in interest of mathematicians, but also of neuroscientist, since with the Traveling Salesman paradigm it is possible to investigate the processing and optimization of visuo-spatial information, e.g. (route) planning, spatial navigation, problem solving and decision making (Bellizzi et al. 2015, Cutini et al. 2008, MacGregor & Chu 2011).

The ability to produce good solutions on the Traveling Salesman task plays a role in everyday life. So for example for logistics companies it is important to deliver the goods on the shortest way to save time and carrying costs. But also for planning a holiday round trip with different cities or countries a short tour is beneficial. And during everyday shopping a tour through the shop is planned, too.

Different experimental setups have been developed for investigating the Traveling Salesman problem, such as paper versions (MacGregor & Ormerod 1996, MacGregor et al. 2004, De Vreese et al. 2005, Tenbrink & Wiener 2009, Blaser & Wilber 2013), computerized versions (Graham et al. 2000, Basso et al. 2001, Vickers et al. 2003 a and 2003 b, Kong & Schunn 2007, Gibson et al. 2007, Acuña & Parada 2010, MacGregor 2015) or walking versions (Wiener et al. 2007 and 2009, Blaser & Ginchansky 2012, Blaser & Wilber 2013). These examples took part under laboratory conditions, but there are also studies which examine the Traveling Salesman problem in real life, for example by investigating peoples shopping behavior (Gärling & Gärling 1988, Hui et al. 2009).

Still, it is not known which strategy humans use to solve the Traveling Salesman task and produce such good performances. There is evidence for a “global-to-local process” (Vickers et al. 2003 b) based on the convex-hull strategy (MacGregor et al. 2004). By using the convex-hull method first all locations on the boundaries are mentally linked and then the remaining inner locations are included by connecting them to the nearest outer locations, so that the route length increases only minimally. But there is also evidence for a “local-to-global process” (Vickers et al. 2003 b) based on the (hierarchical) nearest-neighbor strategy (Vickers et al 2003 a). In the nearest-neighbor method the locations which are closest next to each other are connected until all locations are chosen. Van Rooij et al. (2003) suggested that humans are aware that crossings produce not the optimal solution and therefore use an avoid-crossing strategy. In other strategies first a coarse plan is made, which is then refined to include the remaining locations, e.g. the cluster-strategy: Nearby locations are included into clusters. Clusters with the most locations are visited first (Gallistel & Cramer 1996), this allows to visit many targets together and reduces the demands on path planning. Wiener and colleagues (2009) suggested that humans combined near locations to clusters, where large clusters were visited first and the performance on Traveling Salesman problem further resulted of a combination of a cluster-strategy and a region-based strategy.

Miyata and colleagues (2014) tested the performance of children on the Traveling Salesman task. They found that children sometimes used different strategies than adults and Miyata and colleagues suggested that a reason for this could be that children were not aware of the real distances between the locations or not aware of the task at all.

Studies investigating the performance on the Traveling Salesman task were not only carried out for healthy adults, but also for patients with brain damage (Basso et al. 2001, Cutini et al. 2008, De Vresse et al. 2005). The Traveling Salesman task might also be a useful paradigm to investigate early Alzheimer disease (De Vresse et al. 2005).

There are not only studies investigating human performance on the Traveling Salesman problem, there are also Traveling Salesman or Traveling Salesman-like studies investigating the performance of different animals, such as nonhuman primates (Menzel 1973, MacDonald & Wilkie 1990, Cramer & Gallistel 1997, Taffe & Taffe 2011, Janson 2014, Howard & Fragaszy 2014), rats (Blaser & Ginchansky 2012, Bellizzi et al. 2015) and pigeons (Gibson et al. 2007, Baron et al. 2015) on this task. Most of these animal studies showed that animals are also able to solve the Traveling Salesman problem and therefore it might be a useful paradigm to investigate spatial cognition not only in humans but also in animals (Blaser & Ginchansky 2012).

Another experimental setup to investigate spatial cognition and spatial working memory is the Corsi block tapping task.

Corsi block tapping task

Several experiments were designed to test the different components of working memory. For example Hebb (1961) used a digit span task to measure verbal memory impairment. The Corsi block tapping task is an influential and standard paradigm (also in clinical investigations) to analyze spatial working memory. Fischer (2001) reported that the Corsi block tapping task "measures a combination of sequence and location memory". The task was originally developed by Corsi (1972) and first described by Milner (1971). The Corsi block tapping task tests for the memory and reproduction of spatio-temporal sequences, a cognitive competence with great importance in route planning and navigation. It is a widely used paradigm to assess spatial working memory abilities in humans, e.g. the spatial span in adults (e.g. Smyth & Scholey 1992, Pagulayan et al. 2006, Woods et al. 2016), children (e.g. Orsini et al. 1981, Logie & Pearson 1997, Pagulayan et al. 2006, Belmonti et al. 2015) and neuropsychological patients (e.g. Vilkki & Holst 1989, Della Sala et al. 1999, Millet et al. 2009, Tedesco et al. 2017). Also, a Corsi block tapping task version to test "serial-spatial memory" in blind people was developed (Ruggiero & Iachini 2010).

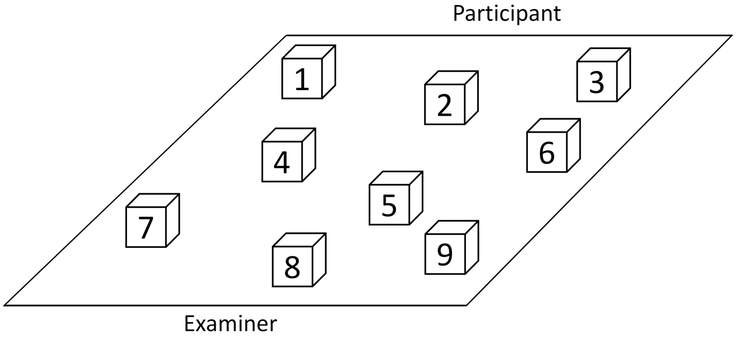

Figure 1.3.: Illustration of the Corsi block tapping task. The participant is presented with nine identical wooden blocks. Only on the examiner's side the blocks are labeled with numbers. This helps the examiner to show the correct sequence and also to check whether the participant reproduced the sequence correctly. For each given sequence length the examiner shows the sequence to remember by tapping with a stick or finger on the blocks. The experiment stops when the participant failed to recall a certain number of trials for a given sequence. The maximum number of correctly recalled blocks is the participant's Corsi span. This illustration was adapted from Corsi (1972).

In the classical version of the Corsi block tapping task, a participant is seated in front of nine identical wooden blocks arranged on a board (see Fig. 1.3) and an experimenter indicates a certain sequence by tapping on a selection of the blocks. The participant's task is to memorize (encode) the sequence and to reproduce it (recall), again, by tapping on the remembered blocks. The length of the shown sequence is increased after a certain number of trials. The maximum number of blocks correctly reproduced by the participant is defined as "spatial span" (Corsi 1972), also named "Corsi span" and quantified in healthy adults with about five (e.g. Corsi 1972, Orsini et al. 1987). Different studies reported Corsi spans between five and seven (e.g. Capitani et al. 1991, Monaco et al. 2013, Claessen et al. 2015). An overview of different Corsi spans is given by Woods et al. (2016). Though, it seems that a Corsi span of five is a reasonable mean value.

Despite its wide distribution in clinical and basic research, comparability of the Corsi block tapping task between individual studies is low. Berch et al. (1998) reviewed different studies that used the Corsi block tapping task and analyzed the methods employed in each study. They found that in none of the studies the exact distance between the blocks was mentioned, the numbers, colors and sizes of the blocks differed and the sequences are not standardized. Smirni et al. (1983) and Orsini et al. (2001) found that participants' performance in the Corsi block tapping task depends on both path length and path characteristics. Indeed, some participants failed in short sequences, but succeeded in longer ones. Thus, the difficulty of a sequence not only depends on the sequence length, but also on the number of crossings it involves. Still, sequences with the same length and the same number of crossings do not necessarily result in the same performance (Orsini et al. 2001).

Piccardi et al. (2008) designed a large-scale walking Corsi block tapping task version in order to investigate the difference in short- and long-term memory performance between a tapping and a walking condition. In the walking condition, participants had to copy sequences by walking on a carpet and stepping on the same tiles on the floor that the experimenter had stepped on earlier. Piccardi et al. (2008) found differences between the two conditions, showing that participants had higher Corsi spans in the walking version. They concluded that different working memory types are needed to solve the different Corsi block tapping task versions.

Perrochon et al. (2014) used a "magic carpet" which consisted of pressure sensitive tiles that could be highlighted. They used illumination cues to present sequences either on the floor tiles (walking version) or on the blocks of a Corsi board (electronic version). They tested the performance of healthy young and older participants and people with mild cognitive impairment and found an overall better performance in the electronic (board) version than in the walking version. Also, younger participants showed a better performance than older and mildly impaired participants. Belmonti et al. (2015) compared the performances of children, healthy and with cerebral palsy, in a classical Corsi task with the performance in a magic carpet version. The performances of both groups were lower in the magic carpet version. They also reported that children with cerebral palsy had, compared to the healthy children, a lower performance in the classical Corsi task, but there was no difference between the two groups in the magic carpet version. Therefore, they mentioned that "several strategies and brain networks can be used to solve a task like the Magic Carpet. [...] the Magic Carpet fosters a switch from ego- to allocentric spatial encoding, but it can also be solved, although less efficiently, by egocentric updating. These strategies rely on different brain networks, the former centered on hippocampal and prefrontal areas, the latter on posterior parietal and premotor cortices." (Belmonti et al. 2015).

Performances of healthy participants and participants with cerebellar lesions in a walking version of a Corsi task, in which an experimenter showed the sequence to remember, and a magic carpet version, in which the sequence was presented by highlighting the pressure sensitive tiles on the carpet, were compared by Tedesco et al. (2017). The two groups differed in the magic carpet version, but not in the walking version. They suggested that the difference in performance is caused by the different types of presentations. In the magic carpet version the sequence is presented only by highlighting single tiles one at a time, while in the walking version an experimenter showed the sequence by walking. This walking presentation could lead to trajectories which were memorized. These trajectories are easier to memorize and such trajectories require less load than single tiles that have to be recognized as sequence.

Robinson & Brewer (2016) compared the performances of a Corsi task in a classical and a tablet version and found no difference between the two versions.

Nori et al. (2015) developed a virtual version of the walking Corsi task and compared it with a real walking version. In the virtual version participants did not physically move around but had to navigate through a virtual environment while sitting on a chair. Interestingly, no difference in terms of task performance could be identified between virtual and real walking.

Vandierendonck et al. (2004) used a computerized version of the Corsi block tapping task to test the various working memory components in a series of dual-task experiments. Results indicate that loading the central executive impairs Corsi task performance while articulatory suppression showed an effect only for a reverse reproduction task.

Scientific issue

Walking is an important and frequent behavior in humans, though, not much work has been done to investigate the cognitive processes that might interact with and influence walking. Different paradigms were developed to investigate participants' performance also in walking versions of the tasks, such as walking versions of the Traveling Salesman task (Wiener et al. 2007 and 2009, Blaser & Ginchansky 2012, Blaser & Wilber 2013, etc.) or walking versions of the Corsi task (Piccardi et al. 2008, Perrochon et al. 2014, Nori et al. 2015, Tedesco et al. 2017, etc.). However, all of the mentioned studies investigated only participants' performance in the different tasks and none of them measured participants' walking speeds and compared it in different task difficulties. Perrochon et al. (2014) did analyze walking speeds but did not compare it in different task difficulties.

So the first aim of this thesis was to investigate the influence of different cognitive demands on participants' performance and walking speed. More precisely, the influence of cognitive demands on performance and walking speed which occur while (i) planning a route, as well as the influence on performance and walking speed caused by the cognitive demands which were required during (ii) walking a known route. Therefore, in the first experiment a walking version of the Traveling Salesman task (planning while walking) was designed. Participants had to find the shortest route between different numbers of locations and plan a route while walking between these locations. The results of this experiment were compared with the results of Experiment 2 in which participants were asked to solve a walking version of the Corsi task (walking a known route). In the Corsi task the sequences were presented to the participants beforehand and had to be recalled afterwards while walking. This experiment investigated the influence of cognitive demands required for walking a known route on performance and walking speed.

These two experiments should investigate the first hypothesis: Route planning while walking and walking a known route require different amounts of working memory resources and probably different working memory components. Further, it was hypothesized that walking a known route will need less working memory resources than planning a route while walking, thus, performance should be better and walking speed should be higher in the Walking Corsi task.

As mentioned above it was found by Smirni et al. (1983) and Orsini et al. (2001) that the path length and the path characteristics, such as e.g. numbers of crossings, have an influence on participants' performance in solving a Corsi task. Further, different presentation types for the sequences have been designed, such as classical, computerized, walking or virtual versions. The Corsi spans found in the different studies vary and Piccardi et al. (2008) reported that their participants visualized a pathway during sequence presentation by an experimenter which helped the participants to memorize the sequence compared to sequence presentation in a classical version of a Corsi task. Therefore, not only the characteristics of the Corsi sequences but also the type of sequence presentation could influence the performances of the participants.
This led to the second aim of the study, namely to investigate participants' performances in different presentation as well as recall types of a Corsi task. Therefore, besides the walking version of Experiment 2 a computerized version of the Corsi task was developed and tested in Experiment 3. In Experiment 4 the sequential presentation type was compared to a simultaneous presentation type. Finally, two further combinations of presentation and recall types of a Corsi task were designed and tested in Experiment 5.
Experiment 2 to 5 should investigate the second hypothesis of the thesis: Presentation type and recall type of a Corsi sequence have different demands on working memory resources and will influence participants' performance in different ways.

2. General material and methods[1]

In this chapter the general materials and methods used in all experiments are described. All experiments were purely behavioral experiments and informed consent was obtained from all individual participants included in the study prior to the experiment. The informed consent procedures adhere to the guidelines of the Declaration of Helsinki, approval by the local ethics committee was not required. Participants were able to stop the experiment at any time.

2.1. Experimental room

All experiments, except of Experiment 4: "Pattern Copying task" (p. 81 ff), were carried out in a windowless room of 6 x 8.4 m with controlled lighting (see Fig. 2.1). Controlled lighting was used to ensure the same visual conditions for all participants and prevent them from comparing the sequence shown on the computer screen with the square tiles configuration on the floor immediately after seeing it on the screen (the exact procedure of each experiment is explained in the material and methods part of the respective experiment). The same dimmed light conditions were used for all experiments which were carried out in this experimental room.

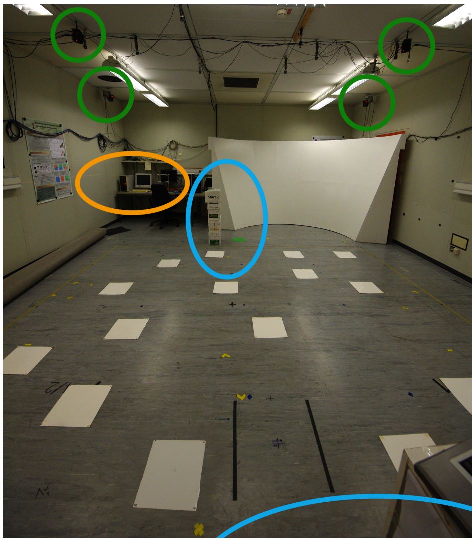

Figure 2.1.: Setup of the experimental room. In the picture the experimental room is shown. On the floor the pattern with fifteen 0.3 x 0.3 m square tiles can be seen. The pattern's frame had a size of 4 x 4 m (outlined by yellow tape). The green circles mark four of the six infrared light cameras of the motion tracking system. The orange ellipse marks the tracking-computer and the blue ellipses show the two starting positions with Start 1 in the front. Light conditions in the picture are not equal to light conditions during experiments.

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[1] Most parts of this chapter have been used and were published in the paper Röser et al. (2016) and were adopted here almost one to one. The final publication is available at link.springer.com/article/10.1007%2Fs00221-016-4582-z.

On the floor of the experimental room fifteen 0.3 x 0.3 m square tiles were laid out within a 4 x 4 m frame marked with tape. Outside of the frame, centered along the sides of the frame, two starting positions were marked with 0.25 x 0.25 m square tiles (see Fig. 2.1 and subsection 2.4 “Pattern configuration”). At the ceiling, six cameras for the tracking system (see Fig. 2.1) were installed which were controlled by the tracking-computer (see subsections 2.2 “Tracking system” and 2.3 “Computers”).

2.2. Tracking system

As already mentioned, at the ceiling of the experimental room six cameras (see Fig. 2.1 and Fig. 2.2) were installed, four in the corners of the room, two centered at the sides. They were part of the tracking system (ARTtrack/DTrack from A.R.T. GmbH, Weilheim, Deutschland) based on infrared light which captures the positions in space of special reflector spheres. Five spheres were put together as a ’target’ (see Fig. 2.3) and tracked with six degrees of freedom. The cameras had a tracking frequency of 60 Hz and enabled the exact measurement of participants’ position and walking speed during the experiments. The entire system had a real-time delay of 40 ms.

Figure 2.2.: Tracking cameras. Left: One of the four cameras in the corner is shown. Right: One of the two cameras centered along the side of the room is depicted.

During the experiments participants had to wear a helmet on which the target composed of five reflecting spheres was mounted (see Fig. 2.3). The cameras tracked the spheres’ positions in the room and the collected data was sent to the tracking-computer (see subsection 2.3 “Computers”), converted to a single position of the target in space and recorded with the software DTrack (version 1.22.2).

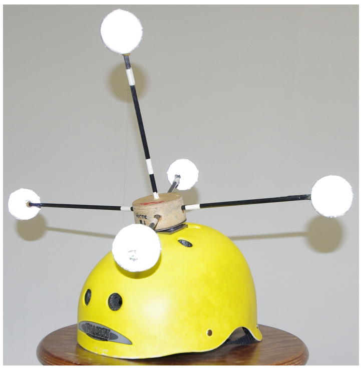

Figure 2.3.: Head tracking target. Participants were asked to wear the helmet with a tracking target, consisting of five reflecting spheres which were tracked by the infrared light cameras of the tracking system.

2.3. Computers

For the experiments three different personal computers (PC) and a laptop were used.

Tracking-computer: This computer was used to record participants' position data. It was an Intel Pentium 4 (3 GHz) PC with operating system Microsoft Windows XP Professional (version 2002, service pack 2).

Computer: This computer was used to present the stimuli and record the data when participants did not have to walk in the presentation and recall phase. It was a PC with an Intel Core i3-2100 CPU (3.1 GHz), operating system Microsoft Windows 7 (service pack 1) and MATLAB (version R2010a to R2013b; The MathWorks, Natick, Massachusetts, USA) with Psychtoolbox version 3 (psychtoolbox.org). The monitor was a Samsung SyncMaster 931BF with a size of 19" and a resolution of 1280 x 1024 pixels at 75 Hz.

Laptop: For stimuli presentation and data recording in the floor conditions, this is when participants either had to walk in the reproduction phase or the presentation took place on the floor, a laptop "Dell Precision M70" (1.73 GHz), operating system Microsoft Windows XP Professional (version 2002) and MATLAB (version R2010a, with Psychtoolbox 3) was used. The screen had a size of 15.4" and a resolution of 1680 x 1050 pixels.

Flashlight-computer: Stimulus presentation on the floor was achieved by highlighting the square tiles with flashlights mounted at the ceiling directly above each square tile (see Fig. 7.1, p. 109). These flashlights (LED, 3 watts, 170 lumen) were controlled by a MATLAB script running on an AMD Athlon 64x2 4800+ (2.50 GHz) with Microsoft Windows 7 (service pack 1) and MATLAB (version R2013b, with Psychtoolbox 3).

In the following, the computers will be called "tracking-computer", "computer", "laptop" and "flashlight-computer".

2.4. Pattern configuration

For the Traveling Salesman experiment and the presentation as well as the recall of the Corsi sequences a pattern with a configuration of fifteen square tiles was chosen (see Fig. 2.4). As routes and sequences up to ten square tiles should be tested during the experiments, the number of square tiles had to be more than ten. Fifteen square tiles seemed to be a suitable number of squares for the size of the experimental room.
In most of the experiments two different starting positions were used (see Fig. 2.4), only in Experiment 5: "Corsi task in different modality conditions" (p. 107 ff) four starting positions were required. Two starting positions were needed because participants had to solve several trials and should not learn the configuration of the square tiles immediately. The starting positions during the experiments were pseudo-randomized. In the last experiment "Corsi task in different modality conditions" two more conditions were tested and thus two more starting positions were added.

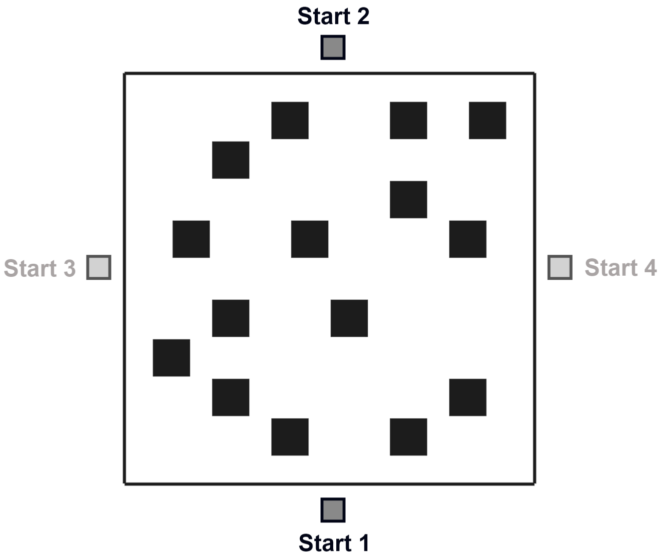

Figure 2.4.: Configuration of the square tiles. The pattern used in the different experiments is shown. Each of the fifteen square tiles had a size of 0.3 x 0.3 m in the floor conditions. On the computer screen the squares had a size of 80 x 80 pixels (visual angle about 2.5°) and on the laptop screen 100 x 100 pixels (visual angle about 2°) because of a different screen resolution. At each starting position (Start 1, Start 2, Start 3 and Start 4) a 0.25 x 0.25 m square tile was placed in the walking conditions. The starting positions were not shown on the screens but were always at the bottom and the configuration of square tiles was rotated respectively. Start 1 and Start 2 (dark-gray) were used in all experiments. Start 3 and Start 4 (light-gray) were only used in Experiment 5: "Corsi task in different modality conditions".

For the analyses distances with equal lengths were needed (see appendix Tab. A.1, p. 184), though there should not be an obviously symmetric pattern. Therefore a honeycomb pattern was chosen, which was underlying the configuration of the square tiles (for illustration see Fig. 2.5). With such a pattern it is easier to create configurations of square tiles and routes or sequences that feature equidistant route and sequence segments.

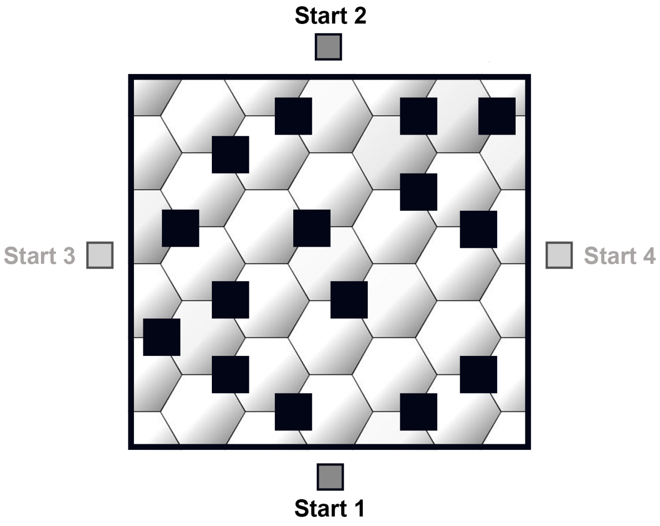

Figure 2.5.: Square tiles configuration with underlying honeycomb pattern. The position of the fifteen squares within the honeycomb pattern and also the four starting positions are depicted.

2.5. Analyses and statistics

All data were analyzed with MATLAB (version R2013a). Statistics were calculated with IBM SPSS Statistics (version 22). The main effects are addressed in the results section and post hoc analyses (always computed with Bonferroni corrections) are denoted with p-values in the text and with stars in the figures, where $p < 0.05 =$ *, $p < 0.01 =$ ** and $p < 0.001 =$ ***. Significant differences between two (or more) conditions or experiments were always denoted with stars above the means of the experiments in the figures. If most of the comparisons between conditions or experiments resulted in significant differences, for reasons of presentation only the non-significant differences are marked with “n.s.” in such figures.

Results were plotted with MATLAB (version R2013a) and the post processing of the figures (such as cropping, annotations, ...) was accomplished with Photoshop CS6 (Adobe Systems, San José (CA), USA).

3. Experiment 1: Traveling Salesman task

Traveling from one location to another requires working memory resources for planning the route between the targets. The more targets should be visited along the route the more working memory processes are involved, because besides of the working memory load for walking itself, the order of the targets has to be planned and also the already visited targets have to be kept in mind.

In the first experiment, wayfinding while planning a route and the influence on walking should be investigated further.

In a study by Basso et al. (2001) it was shown that participants plan the next step of a route during walking. Hence, for this thesis a Traveling Salesman paradigm was developed in which participants had to find the shortest routes to different target locations. The lengths of the routes have been varied and therefore the demands required for wayfinding and planning the route were altered.

It is assumed that with increasing route length the increasing demands on working memory will influence participants' performance in solving the task and also walking itself. This should result in a decrease of performance and/or a slower walking speed in longer route lengths.

3.1. Material and methods

3.1.1. Participants

Fifteen participants took part in this experiment. One had to be excluded because of measurement and recording problems. The remaining fourteen volunteers, seven males (mean age: 27.14 years, standard deviation (SD): ± 3.76) and seven females (mean age: 26.29 years, SD: ± 2.98) were all university students with normal or corrected to normal sight. Participants were paid 8 € per hour. As already mentioned the study was a purely behavioral experiment and informed consent was obtained from all individual participants included in the experiment.

3.1.2. Experimental setup and design

Participants' position data were recorded with the tracking-computer (see subsection 2.3 "Computers", p. 15). The data recording was started by the experimenter when participants were about to begin the current trial and stopped by the experimenter when participants were back at the starting position. In this experiment, the square tiles which were required to be visited in a trial were marked with a black dot with a diameter of 0.2 m (see Fig. 3.1). The selection of the square tiles was done by the experimenter before each trial and was not visible to the participants until the trial started (for selection see appendix Fig. A.1 to Fig. A.4, p. 177 ff).

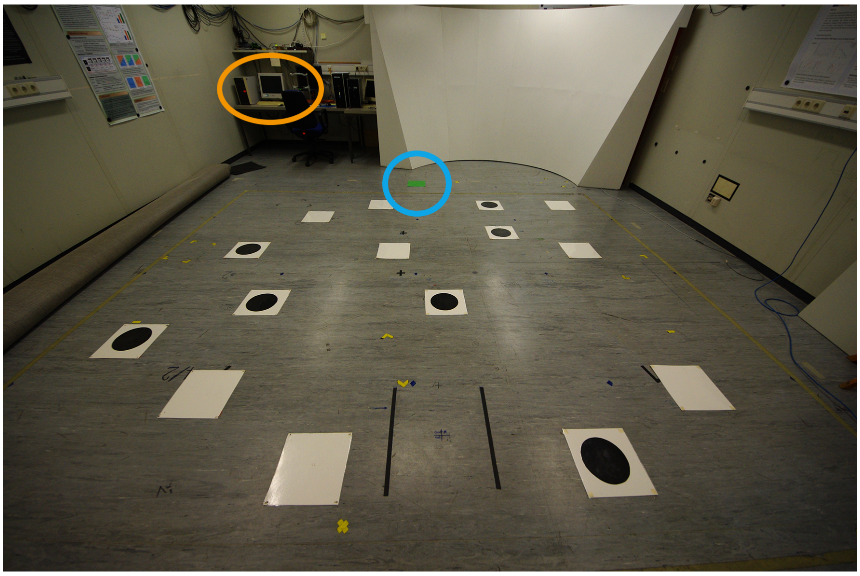

Figure 3.1.: Experimental setup. The figure shows the configuration of the fifteen square tiles within a 4 x 4 m frame (yellow tape). The black dots (with a diameter of 0.2 m) indicate the squares for which the participants should find the shortest route from starting position back to the same starting position after visiting all of the marked squares. In this example a route length of seven has to be solved. The orange circle marks the tracking-computer. With the blue circle one of the two starting positions (Start 2), indicated with a green 0.25 x 0.25 m square tile centered outside the frame, is marked. The second starting position (Start 1) is located outside the frame in the front, but not visible in the picture.

3.1.3. General procedure

This experiment as well as the experiments “Walking Corsi task” (p. 39 ff) and “Corsi task” (p. 65 ff) were passed by the same fourteen participants and therefore tested in a within-subject design. The Traveling Salesman task and the two Corsi tasks were tested in randomized order and balanced across participants on two days, if possible on two consecutive days. The two different Corsi conditions were always tested on the same day due to measurement reasons (see subsection 4.1.3 “General procedure”, p. 41).

Prior to the experiment the whole procedure and data usage was explained to the participants in oral and written form. Emerging questions were answered and participants gave informed written consent. Participants were able to stop the experiment at any time.

Participants began the experiment without practice trials. Before each trial the next starting position was told to the participants by the examiner. The starting positions were pseudo-randomly chosen, but with the same order for each participant.

First, participants were standing with their back to the pattern configuration at the starting position while the examiner placed the black dots on the square tiles. After that, the examiner started the tracking-computer and participants turned around. They were able to look at the pattern configuration, but had to start walking by no later than two seconds after turning around. Participants were instructed to step on the visited square tiles with both feet. When participants kept standing too long on a square tile, which means longer than about 2 s, they were told to move on quicker by the examiner. Participants should not stop walking between the square tiles, only on the square tiles they were able to stand. When participants were back at the starting position the data recording was stopped by the examiner, the participants moved to the next starting position (Start 1 or Start 2) and waited with their back to the

pattern configuration for the next trial to start while the examiner placed the dots for the upcoming trial.
The route length of each route increased after each fourth trial regardless of participants' performance, starting with a route length of three marked square tiles up to ten marked square tiles. Thus, participants had to solve 32 different Traveling Salesman routes (8 route lengths x 4 repetitions). The lengths of the different routes were between 10 m and 15 m with a mean distance length of 11.83 m (SD: ± 1.33). An example for a route is depicted in Fig. 3.2. In this case not only the clockwise and counter-clockwise options could be chosen, but there were also two alternative route sections with the same length (orange and blue lines in Fig. 3.2). So, for this particular trial four correct shortest routes were possible.

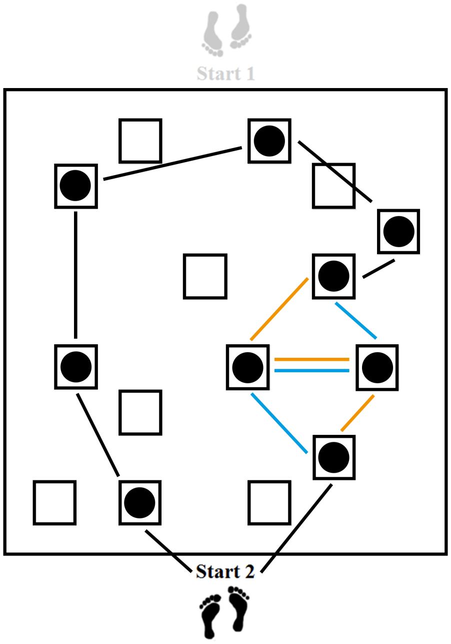

Figure 3.2.: Example for the shortest route. By way of example a route with nine squares to visit was chosen. In all trials participants could choose between two possible routes: clockwise and counter-clockwise. In this example there are two more alternatives for the shortest route, they are depicted with orange and blue lines. So in this case participants could use four different ways as the shortest route.

3.1.4. Analysis

In this experiment participants' performance in finding the shortest route was investigated. As dependent variables a) the number of correct trials, b) the deviation from the shortest route in the false trials, c) participants' walking speed and d) the standing time on the square tiles were analyzed.
For measuring the deviation from the shortest route, the accurate distance between the visited square tiles was used and not the measured data of the headtracker. The reason is that participants often moved their head while walking to the next square tile and therefore the measured headtracker distances were in some cases longer than the actual walked distances. Before evaluating participants' walking speed it was controlled if participants really were standing on a square tile or if they were only slowing down walking speed while walking from one square tile to another. Only the pure walking speed between square tiles was used to calculate participants' walking speed, that means the time participants rested on a square tile

had no influence on walking speed. For the analyses of the standing times on the different square tiles only the squares visited in the route were evaluated, the standing times on the starting and ending square tiles (Start 1 or Start 2) were ignored.
To define the shortest route of each trial the algorithm for Traveling Salesman problems by Kirk (2007) was used. This algorithm was also used by Logie et al. (2011) for solving a “Travelling salesman task”. It was also used by Hu et al. (2012), when they attempted to calculate gene order. Moyo & du Plessis (2013) used the algorithm as “method to optimize the inspection of power lines” by “Unmanned Aerial Vehicles”.

3.2. Results

In this experiment participants were required to find and walk the shortest route between marked squares. Two of these walking trajectories are shown in Fig. 3.3 as examples.

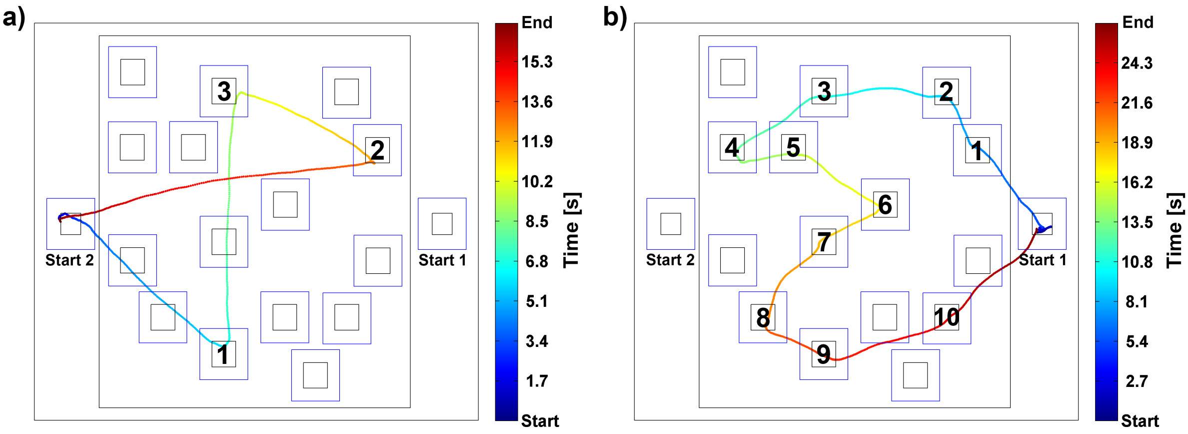

Figure 3.3.: Walking trajectories. a) A walking trajectory of a short route (3 squares) is depicted. The route began and ended at Start 2. This route was not solved correctly by the participant. b) A long route (10 squares), starting and ending at Start 1, is shown. For this route the shortest way was found by the participant. The numbers in the squares mark the square order of the shortest route. Correct routes were walked from low to high numbers or from high to low numbers. The color gradient from blue (early) to red (late) indicates time across the trial.

3.2.1. Analysis of correct trials

As first analysis of this experiment participants’ performance was evaluated. Therefore, the percentage of correct trials was analyzed. Ten of the fourteen participants reached an overall mean value between 60-70 % of correct trials (see Fig. 3.4 a)). Three of the remaining participants (number 5, 7 and 14) reached mean values between 81 % and 87 %. One participant (number 14) had a mean value of 50.00 % (SD: ±29.88).
The mean percentage of correct trials decreased over the route lengths from 96.43 % (SD: ±13.36) in route length three to 57.14 % (SD: ±24.86) in route length ten (see Fig. 3.4 b)). Though, in route length four participants reached only 75.00 % (SD: ±16.98) and in route length five again 92.86 % (SD: ±11.72). Also in route length seven a stronger decrease could be observed: Participants recalled 42.86 % (SD: ±15.28) of the trials correctly, whereas in route length eight the performance increased again to 75.00 % (SD: ±24.02). Over

all route lengths and participants a mean of 70.09 % (SD: ± 18.92) of correctly solved trials was observed.

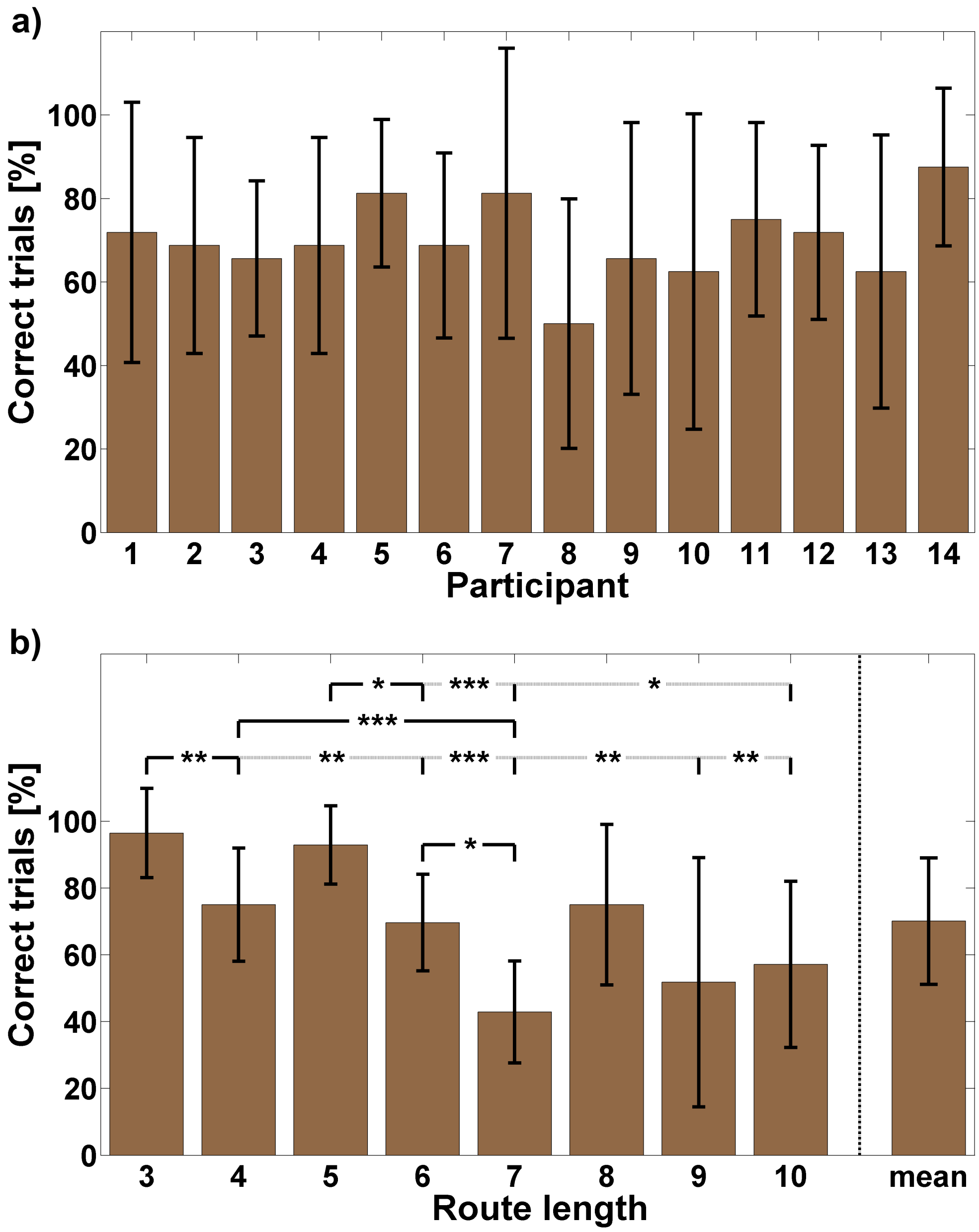

Figure 3.4.: Percentage of correct trials. a) For each participant (x-axis) the mean percentage of correct trials (y-axis) over all 32 trials is depicted. b) The mean percentage of correct trials (y-axis) over all fourteen participants per route length (x-axis) is shown. The performance decreased over the different route lengths from three to ten. The higher route lengths (seven to ten) showed no differences among each other. The right bar shows the mean performance over all route lengths, averaged over all participants. Significant differences between the route lengths are depicted with stars. Note: For reasons of presentation the depiction of significant differences between route lengths are condensed. The dotted lines indicate the extension of the solid lines, e.g. route length three differed significantly from route length four, but also from route length six, seven, nine and ten. Error bars indicate the standard deviation.

To analyze main effects, a one-way repeated measures ANOVA for the factor route length was conducted. A highly significant effect for this factor was found, showing a decrease in performance with increasing route length (F(7, 91) = 11.978, $p < 0.001$, $\eta_P^2 = 0.480$). A post hoc analysis revealed highly significant differences between the route lengths three and seven, four and seven and five and seven ($p < 0.001$), as well as significant differences between the route lengths three and four, three and six, three and nine and three and ten ($p < 0.01$). Also for the route lengths five and six, five and ten and six and seven significant differences were found ($p < 0.05$; see also depicted stars in Fig. 3.4 b)). No differences between the higher route lengths seven to ten were found.

3.2.2. Analysis of deviation from shortest route

Besides the percentage of correct trials also the deviation from the shortest route was evaluated. This was made for the false trials only. Participants' individual deviation in percent differed across route lengths (see Fig. 3.5 a)). In route length three only one participant showed a deviation of 13.91 % (SD: ± 0) while the other participants made no mistake at all. In route length five only four participants had a deviation from the shortest route. Participants' mean deviation for each route length is shown in Fig. 3.5 b). In route length four (2.78 %, SD: ± 3.74), six (2.17 %, SD: ± 0.79) and seven (2.57 %, SD: ± 1.53) about the same deviations from the shortest route were present. The deviation in route length five was 5.84 % (SD: ± 2.22) and the highest deviation could be found in route length ten (7.16 %, SD: ± 6.34). T-tests against zero revealed highly significant effects for the route lengths six, seven, eight, nine and ten ($p < 0.001$). The route lengths four and five also differed significantly from zero ($p < 0.05$). The overall deviation of the shortest routes of all participants in false trials was 4.00 % (SD: ± 3.83) and a t-test showed a highly significant difference from zero (t(74) = 9.061; $p < 0.001$). A one-way ANOVA revealed highly significant effects for the factor route length (F(7, 67) = 4.372, $p < 0.001$, $\eta_P^2 = 0.314$). A post hoc analysis indicated significant differences between the route lengths three and six as well as between the route lengths three and seven (both $p < 0.05$). Also between route length six and ten ($p < 0.01$) and between route length seven and ten ($p < 0.05$) significant differences were found. All significant differences between route lengths are depicted with stars in Fig. 3.5 b).

Since the relation between deviation from shortest route and route length is not clearly obvious in Fig. 3.5 b) because of varying numbers of participants who actually had deviations, another analysis with adjusted measures was conducted (see Fig. 3.6). Therefore, for each route length in which mistakes were made the sum of deviations was divided through the total number of participants.

A one-way ANOVA showed a significant increase of deviation from the shortest route with increasing route length (F(7, 67) = 3.522, $p < 0.01$, $\eta_P^2 = 0.269$). A post hoc analysis revealed significant differences between route length four and ten ($p < 0.05$) and between route length six and ten ($p < 0.01$). Also between the route lengths seven and ten as well as nine and ten significant differences were found (both $p < 0.05$; all differences are depicted with stars in Fig. 3.6).

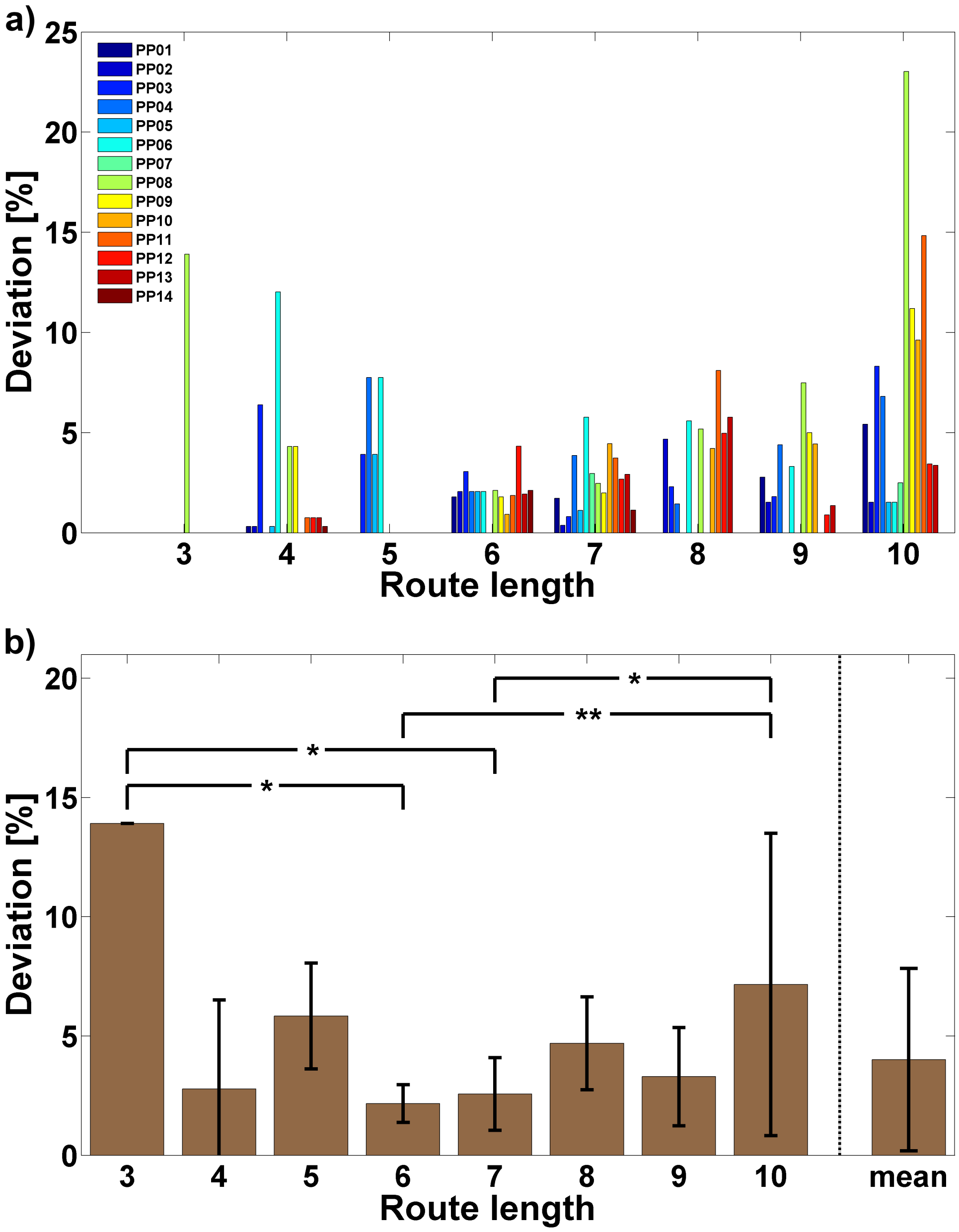

Figure 3.5.: Deviation from the shortest route in percent for each route length. a) The mean deviation from the shortest route in percent (y-axis) is depicted for each participant in each route length (x-axis). Only false trials were considered here. The different color bars indicate the fourteen participants. b) The mean deviation in percent (y-axis) from the shortest route of all participants for the false trials is shown per route length (x-axis). The right bar shows the overall mean over all these participants and all route lengths. Note: The deviation in route length three was caused by only one participant. Error bars indicate the standard deviation.

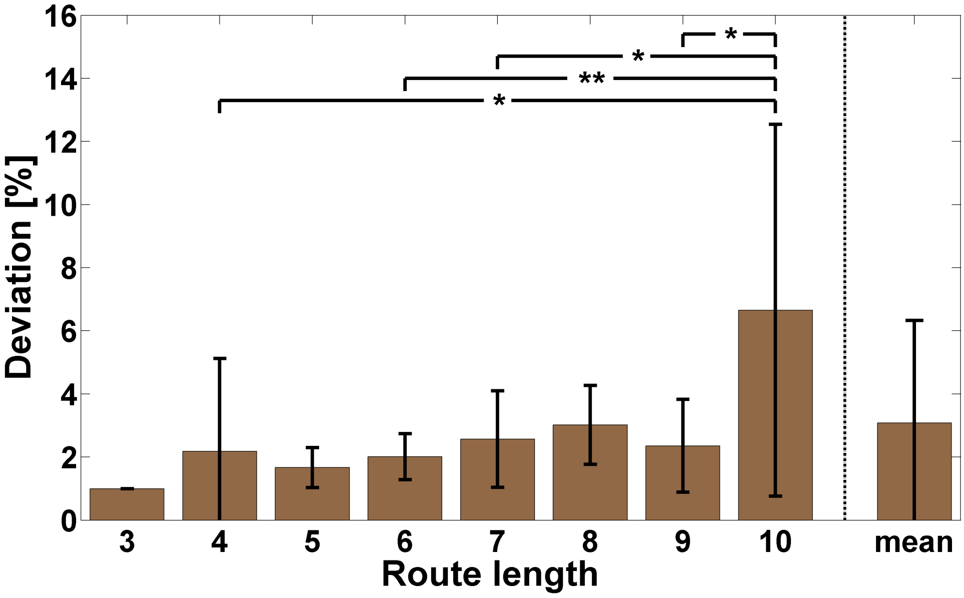

Figure 3.6.: Deviation from shortest route in percent of each route length normalized for cases with deviation and participants. The mean deviation in percent (y-axis) is depicted for each route length (x-axis). In this depiction the sum of deviations per route length was divided through the total number of participants (n = 14). Significant differences between route lengths are depicted with stars. Error bars indicate the standard deviation.

3.2.3. Analysis of walking speed

For calculating participants' walking speed only the pure walking speed between the square tiles of each route was used. Participants' walking speed decreased over the route lengths, starting with an average speed of 3.50 km/h (SD: ± 0.26) in route length three and ending with an average speed of 2.71 km/h (SD: ± 0.16) in route length ten (see Fig. 3.7). The mean walking speed over all route lengths and all participants was 3.03 km/h (SD: ± 0.25).
Because the assumption of sphericity had been violated as Mauchly's test indicated ($\chi^2(27) = 64.317$, $p < 0.001$) Greenhouse-Geisser ($\epsilon = 0.351$) corrected values were used. A conducted one-way repeated measures ANOVA revealed significant differences of walking speed in route lengths ($F(2.458, 31.951) = 141.624$, $p < 0.001$, $\eta_P^2 = 0.916$), indicating a decrease of walking speed over the route lengths. A post hoc analysis revealed significant effects between the route lengths three and four as well as route lengths five and six (both with $p < 0.01$). Also between the route lengths three and five and between the route lengths six and seven significant effects were observed (both with $p < 0.05$). Comparisons of all other route lengths showed highly significant differences with $p < 0.001$. Only the walking speed in the route lengths four and five did not differ among each other (see Fig. 3.7).

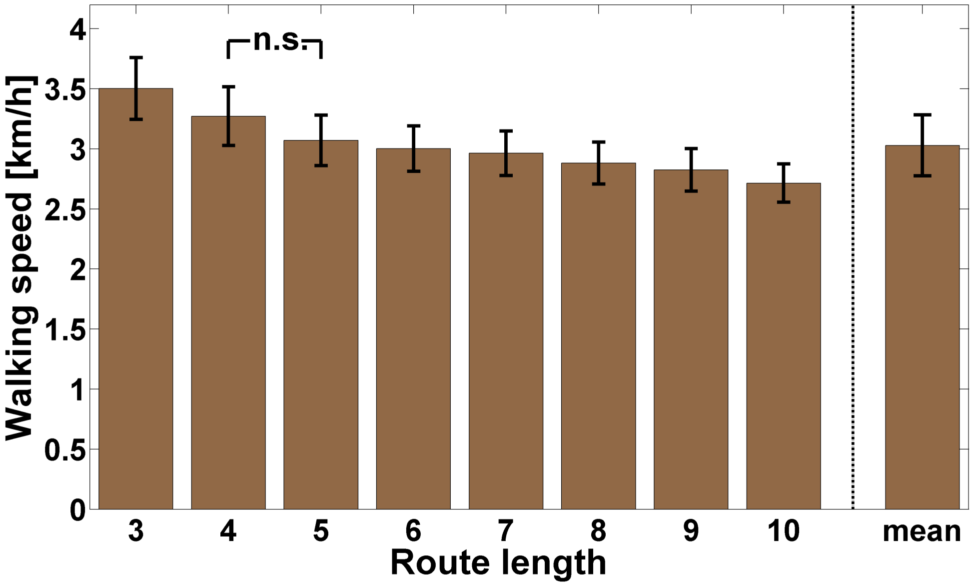

Figure 3.7.: Mean walking speed per route length. Participants' mean walking speed (y-axis) in each route length (x-axis) is depicted. The walking speed decreased from route length three to route length ten. This decrease was significant between all route lengths except between the route lengths four and five. The mean average over all fourteen participants and eight route lengths is depicted on the right. Error bars indicate the standard deviation.

Comparison of walking speed in correct and false trials

Participants' walking speeds were evaluated in detail to check whether there is a difference in walking speed between correctly and falsely walked routes. Therefore, walking speed data were split up in two groups (correct and false, see appendix Fig. A.5, p. 181) and a two-way ANOVA was conducted to analyze main effect differences for the factors route length and performance (here correct and false trials). As described above a significant decrease of walking speed was found for increasing route lengths (F(7, 168) = 23.343, $p < 0.001$, $\eta_P^2 = 0.493$), but there was no difference between the two groups and also no interaction between the factors route length and performance was observed.

Analysis of walking speeds of different route segments

For another analysis of walking speeds, routes were split up in single route distances. Therefore, the square tiles of the pattern configuration as well as the starting positions were numbered (see appendix Fig. A.7, p. 183) and the distances between all square tiles were measured. Due to the usage of the honeycomb pattern underlying the pattern configuration (see Fig. 2.5, p. 16), some of these distances were equal or had almost the same lengths. Distances which differed not more than about ± 5 cm were pooled in one segment (see appendix Tab. A.1, p. 184).

Segments were analyzed with respect to walking speed and in which route length participants walked along the segment. For analysis, only segments that were walked in two or more route lengths and at least by two participants were considered.

Out of the 28 segments 17 were analyzed (the segments 6, 16 and 20 to 28 were excluded due to missing comparable values per route length or no values at all). A conducted one-way ANOVA revealed significant differences in walking speeds between route lengths for six of the 17 analyzed segments (see Fig. 3.8).

In Segment 3 participants' mean walking speed decreased from route length four with 2.84 km/h (SD: ± 0.22) to 2.66 km/h (SD: ± 0.14) in route length eight and remained similar then (F(6, 312) = 5.387, $p < 0.001$, $\eta_P^2 = 0.094$). A post hoc analysis revealed significant differences between route length four with route length six ($p < 0.05$) and route length seven as well as eight (each with $p < 0.01$). Route length four also differed significantly from route length nine ($p < 0.05$) and route length ten ($p < 0.001$). Route length five differed significantly from route length seven and eight (both $p < 0.05$) and also from route length ten ($p < 0.01$).

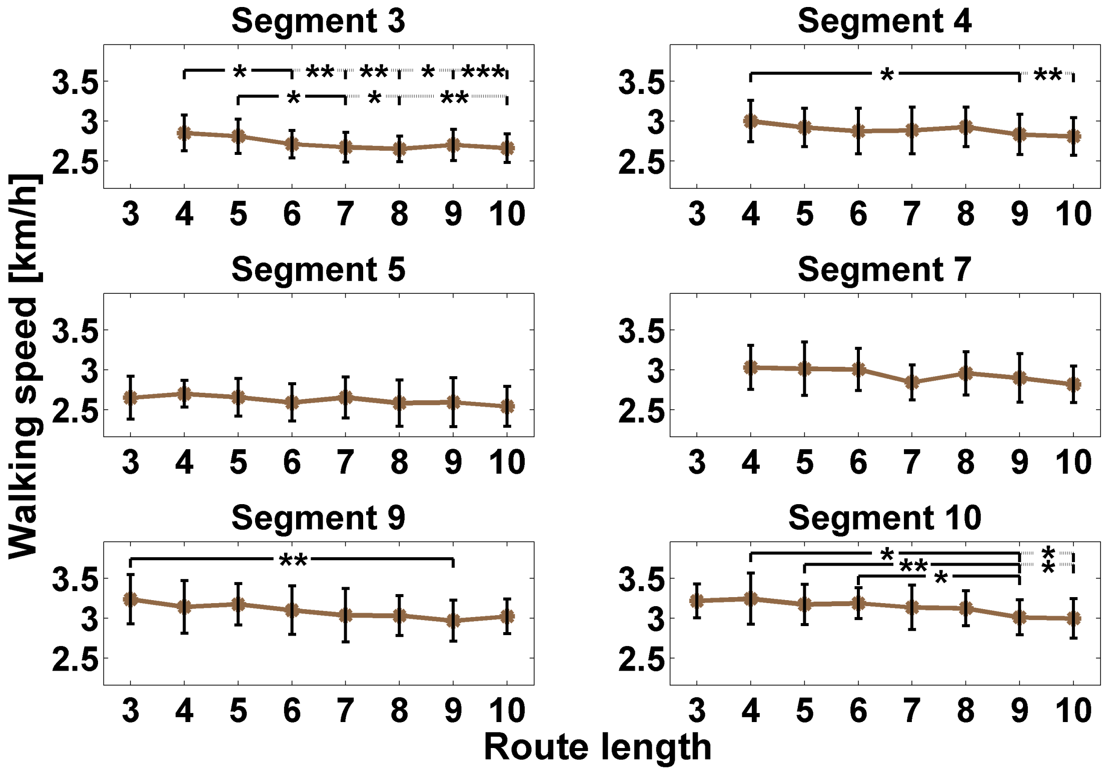

Figure 3.8.: Mean walking speeds of different segments of a route. For each of the six depicted segments (Segment 3 to Segment 10) the mean walking speeds (y-axes) for each route length (x-axes) are depicted with a dot. In route lengths without dot there were no walking speeds for analyzing (e.g. route length three in Segment 3). All of the shown segments had significant differences of walking speeds over the route lengths. The significant differences within each segment are depicted with stars. Note: For reasons of presentation the depiction of significant differences between route lengths are condensed. The dotted lines indicate the extension of the solid lines, e.g. Segment 4: Route length four differed significantly from route length nine ($p < 0.05$) and route length four also differed significantly from route length ten ($p < 0.01$). For Segment 5 and Segment 7 a post hoc analysis showed no difference between single route lengths. In route lengths without dot and error bar participants did not walk this segment. Error bars indicate the standard deviation.

For Segment 4 the mean walking speed decreased significantly from route length four (2.99 km/h (SD: ± 0.25)) to route length ten (2.81 km/h (SD: ± 0.25); F(6, 357) = 3.247, $p < 0.01$, $\eta_P^2 = 0.052$). A post hoc analysis revealed significant differences between route length four and route length nine ($p < 0.05$) and route length four and route length ten ($p < 0.01$). A one-way ANOVA indicated a significant decrease of the mean walking speeds of Segment 5 from route length three to ten ($F(7, 585) = 2.214$, $p < 0.05$, $\eta^2_P = 0.026$). A further post hoc analysis revealed no differences between the route lengths. Similar results were observed for Segment 7, again a one-way ANOVA revealed a significant decrease of mean walking speeds over route lengths four to ten ($F(6, 154) = 2.337$, $p < 0.05$, $\eta^2_P = 0.083$), but a post hoc analysis showed no differences between the single route lengths. In Segments 9 the mean walking speed decreased significantly from 3.24 km/h (SD: ± 0.32) in route length three to 2.95 km/h (SD: ± 0.25) in route length nine ($F(7, 262) = 3.560$, $p < 0.01$, $\eta^2_P = 0.087$). A significant difference between the route lengths three and nine ($p < 0.01$) was revealed by a further post hoc analysis. For Segment 10 a conducted one-way ANOVA showed a significant decrease of walking speed with increasing route length ($F(7, 294) = 4.611$, $p < 0.001$, $\eta^2_P = 0.099$). The mean walking speed decreased from 3.24 km/h (SD: ± 0.32) in route length four to 2.99 km/h (SD: ± 0.25) in route length ten. A post hoc analysis resulted in significant differences between route length four and the route lengths nine and ten (both $p < 0{,}05$). Route length five differed significantly from route length nine ($p < 0.01$) and route length ten ($p < 0.05$). Also a difference between route length six and route length nine ($p < 0.05$) and a trend between route length six and route length ten ($p = 0.053$) was found. All significant differences between the route lengths of the six segments are depicted with stars in Fig. 3.8.

Furthermore, participants' mean walking speeds between two square tiles were plotted against the walked distance between these two squares (see Fig. 3.9). Participants' mean walking speed correlated with the distance between the squares (Pearson: $r = 0.765$, $p < 0.001$), showing that with increasing distance the walking speed increased, too.

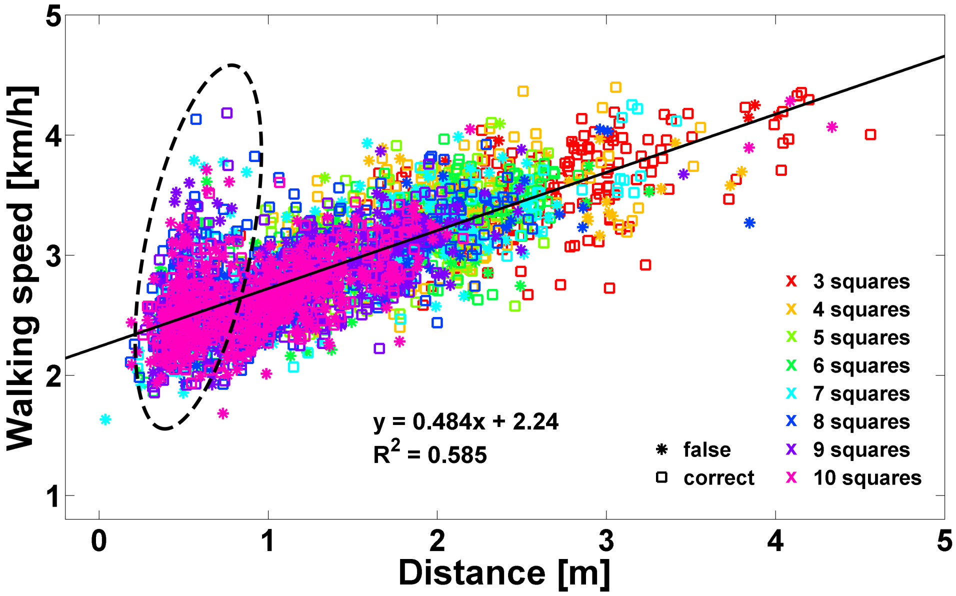

Figure 3.9.: Correlation between the mean walking speed and the distance between two square tiles. The mean walking speed (y-axis) between two square tiles is plotted against the walked distance (x-axis) between these squares for each trial and participant. There was a correlation indicating that with increasing distance the walking speed increased ($R^2 = 0.585$). The dotted ellipse marks the second arm. Correct trials are depicted with squares, false trials with stars and the eight route lengths with different colors.

In Fig. 3.9 a second arm (indicated by a dotted ellipse) can be seen which shows a stronger increase of walking speed for short distances. To analyze this second arm further, correct and false trials were split up and again the walking speed was plotted against the walked distance (cf. appendix Fig. A.6, p. 182). There was no difference between correct and false trials, both showed this second arm.

3.2.4. Analysis of standing time

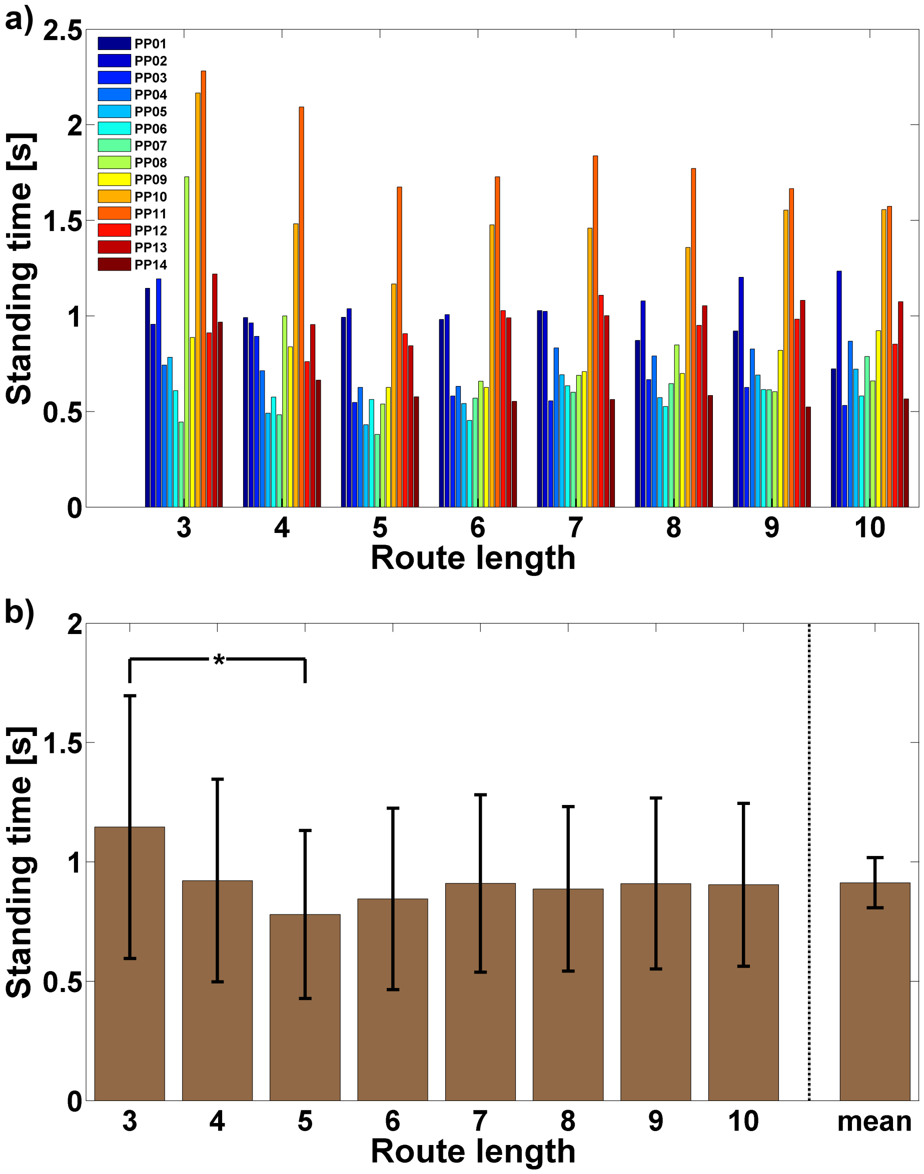

Figure 3.10.: Mean standing time on a single square per route length. a) The mean standing time (y-axis) each participant rested on a single square tile is plotted for each route length (x-axis). The colored bars indicate the fourteen participants. b) The mean standing time (y-axis) of the fourteen participants on a single square tile is depicted for each route length (x-axis). The standing time decreased significantly from route length three to five. For the route lengths six to ten there was no difference between the standing times. Significant differences are depicted with a star. The overall mean over route lengths and participants is shown on the right. Error bars indicate the standard deviation.

Not only walking speed, but also participants' standing time on the square tiles was investigated. For measuring the standing time, the time participants spent on the square tiles was summed up and then divided through the route length (here: the number of squares). The standing times on the starting and ending position were not investigated, only the standing times on the square tiles of the route were evaluated. In Fig. 3.10 a) it can be seen that the individual standing times of the participants differed, some participants only rested about 0.5 s on the square tiles while others stood for about 2 s on the square tiles. Some participants showed a decrease in standing time over the route lengths (Participant 1, 3, 8, 11 and 14). For Participant 2 and 7 the standing time increased over the route lengths.

The mean standing time over all participants (see Fig. 3.10 b)) showed a decrease over the route lengths from 1.15 s (SD: ± 0.55) in route length three over 0.78 s (SD: ± 0.35) in route length five to 0.90 s (SD: ± 0.34) in route length ten. Though, there was no difference in standing time in the longer route lengths seven to ten. The total mean standing time over all route lengths and participants was 0.91 s (SD: ± 0.11).

A Mauchly test was significant ($\chi^2(27) = 94.093$, $p < 0.001$) therefore a Greenhouse-Geisser correction ($\epsilon = 0.252$) was used for further analysis. A one-way repeated measures ANOVA revealed a significant effect for the factor route length ($F(1.761, 22.887) = 6.373$, $p < 0.01$, $\eta_P^2 = 0.329$). A post hoc analysis revealed a significant difference between the route lengths three and five ($p < 0.05$).

In addition to the mean standing time on the square tiles per route length, the mean standing time course of all participants at a given route length was investigated. Therefore, the standing time on each square tile within a route was plotted for each route length (see Fig. 3.11 a)). With standing times between 1.0 and 1.3 s route length three had the longest standing times on the square tiles. The remaining route lengths (four to ten) had standing times between 0.7 and 1.0 s. The shorter route lengths (three to six) tended to have an increase in standing time during the first squares of a route length. At the end of the route the standing time showed a decrease. The route lengths seven to ten had a slight decrease of standing time at the end of the route, but during the first square tiles of a route the standing times showed almost no difference.

For each route length a one-way repeated measures ANOVA was conducted to investigate the factor square number within a route. For the route lengths three and eight no difference between the standing times on the square tiles was found, though for both route lengths there was a trend for shorter standing times on the square tiles which were later in the route (route length three: $p = 0.067$ and route length eight: $p = 0.056$). For route length four a significant decrease of the standing time on the square tiles was found with increasing square number within the route ($F(3, 39) = 4.146$, $p < 0.05$, $\eta_P^2 = 0.242$). A post hoc analysis revealed significant differences between the standing times on the squares three and four ($p < 0.01$). Also for route length five a decrease of standing time with increasing square number was found ($F(4, 52) = 7.440$, $p < 0.001$, $\eta_P^2 = 0.364$). Highly significant differences between the square numbers two and five ($p < 0.01$), three and four ($p < 0.01$), as well as four and five ($p < 0.001$) were found. Also a tendency for differences in standing times between the squares two and three was observed ($p = 0.068$). A conducted one-way repeated measures ANOVA revealed a significant difference for the standing time on the square tiles in route length six, indicating that with a higher square number the standing time on the square tile decreased ($F(5, 65) = 8.954$, $p < 0.001$, $\eta_P^2 = 0.408$). A post hoc analysis revealed significant differences between the square tiles one and three ($p < 0.05$), three and four ($p < 0.05$), three and six ($p < 0.01$), four and five ($p < 0.05$) as well as five and six ($p < 0.05$). Similar results were found for route length seven, again a conducted ANOVA revealed a significant decrease of standing time the later participants were standing on a square within a route (F(6, 78) = 4.627, $p < 0.001$, $\eta_P^2 = 0.263$). In route length seven the square tiles three and six ($p < 0.05$), four and six ($p < 0.001$), four and seven ($p < 0.05$), five and six ($p < 0.01$) and five and seven ($p < 0.05$) differed significantly among each other. Also for route length nine a highly significant decrease of the standing times on the square tiles was found (F(8, 104) = 5.961, $p < 0.001$, $\eta_P^2 = 0.314$). A post hoc analysis showed significant differences between the square numbers one and eight ($p < 0.05$), two and eight ($p < 0.05$), three and six ($p < 0.05$), three and eight ($p < 0.001$), five and eight ($p < 0.001$), six and eight ($p < 0.05$), as well as between the squares seven and eight ($p < 0.05$). For route length ten again a decrease of standing time on square tiles was found with increasing square tile number in the route (F(9, 117) = 2.152, $p < 0.05$, $\eta_P^2 = 0.329$). Significant differences were found between the square tiles five and ten ($p < 0.05$).

For a better comparison of the standing time courses they were aligned with the last square in the route (see Fig. 3.11 b)). All route lengths tend to have a decrease of standing time for the two to three last square tiles. Before, the standing times apparently slightly increased for the lower route lengths (three to six) or showed almost no change for the longer route lengths (seven to ten).

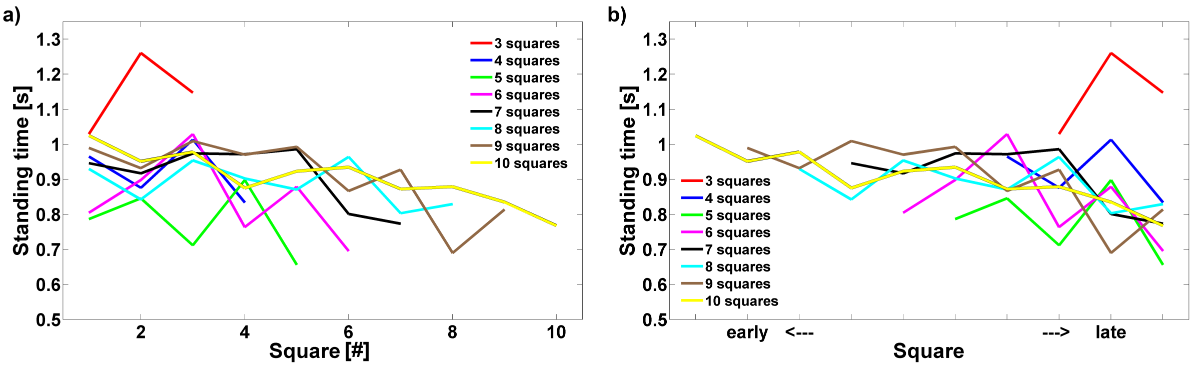

Figure 3.11.: Standing time courses. a) The mean standing time (y-axis) of all fourteen participants is plotted for each square within a route (x-axis) for all eight route lengths. The shorter route lengths (three to six) showed apparently an increase in standing time during the first square tiles of a route length and a decrease of standing time at the end of the route. The longer route lengths (seven to ten) had about the same standing times on the first squares during the route length, though, with a decrease of standing time at the end. No differences between the standing times were found for the route lengths three and eight. b) Again the mean standing times (y-axis) are shown, but this time aligned with the last square tiles (x-axis). It can be seen, that all route lengths tend to have a decrease of standing time for the last two to three squares before the end. The different colored lines show the eight route lengths.

3.2.5. Analysis of routes

During the experiment participants started from two different starting positions (Start 1 and Start 2, cf. Fig. 3.2, p. 21). So it was analyzed whether there was a difference in correctly reproduced routes between the starting positions. Each participant started 16 times from Start 1 and 16 times from Start 2. Starting from Start 1 participants walked in 63.39 % (SD: ±27.96) of the cases the shortest route and from Start 2 in 76.79 % (SD: ±28.63) of the cases. A conducted χ^2-test revealed a significant better performance for Start 2 compared to Start 1 ($\chi^2(1{,}448) = 9.5827$, $p < 0.01$).

In this experiment participants were able to choose their walking direction (beginning left/clockwise or beginning right/counter-clockwise), so it was evaluated if there was a preferred walking direction. Each participant chose both directions at least nine times, just one participant chose the direction to the right 30 times and the direction to the left only twice. Over all 32 trials participants started their route to the left in 43.30 % (SD: ± 15.55) and to the right in 56.70 % (SD: ± 15.55) of the cases. A paired t-test revealed no preference for the left and right direction, respectively. In Fig. 3.12 the directions chosen by the participants are depicted for each route.

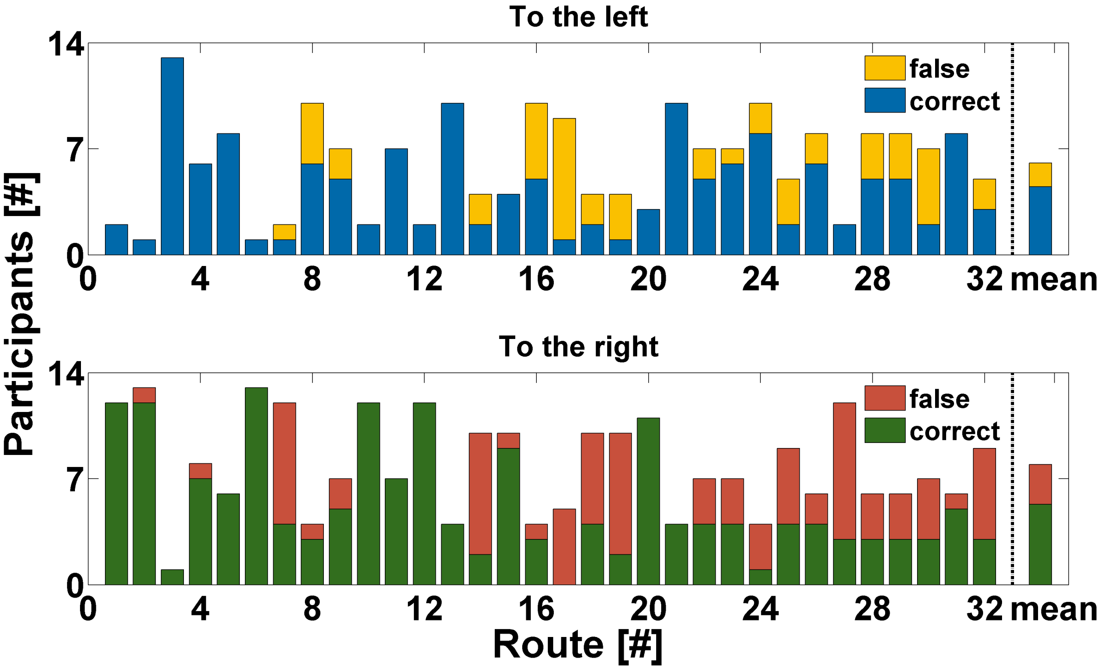

Figure 3.12.: Chosen direction for each route. For each of the 32 routes (x-axis) the number of participants who chose the direction (y-axis) is shown. Top: The direction to the left is depicted. Blue states the number of participants who solved the route correctly, yellow states the number of participants who had an error in their route. Bottom: The number of participants who chose the direction to the right is shown. Green indicates the number of participants who found the shortest route and red states the number of participants who walked a longer route. The mean number of participants for the left and right direction, respectively, is shown on the right. The height of the bars indicates the total number of participants who chose this direction in this route.

3.2.6. Comparison between males and females

For the percentage of correct trials, the walking speed and the standing time on a single square tile, the results were compared between the seven male and seven female participants. For none of these factors a conducted two-way ANOVA showed any differences between the genders. There was only a small tendency for a faster walking speed in the male group compared to the female group ($F(1, 96) = 3.367$, $p = 0.07$, $\eta_P^2 = 0.034$).

3.3. Discussion

In this experiment participants were asked to solve a Traveling Salesman task to investigate the influence of wayfinding while planning a route on working memory resources. The task was designed so that load on working memory for planning the routes was increased; this was accomplished by longer routes which had to be planned. In this task working memory processes were influenced by route planning, spatial updating and costs for walking, e.g. motor control, posture control and so on. Though, the costs for spatial updating and costs for walking could not be distinguished in this experimental design.

Since in this experiment wayfinding while planning a route and potential influences of task difficulties on participants' performance as well as walking itself were investigated, no analysis of participants' potentially applied strategies as mentioned in the general introduction (e.g. nearest neighbor, convex hull or crossing avoidance) for solving the task was made.

All participants were able to solve the task, though with different performances. Most of the participants spontaneously reported early that for finding the shortest route it is useful to avoid crossings. In several studies it has already been shown that routes with crossings did not result in the optimal solution (MacGregor & Ormerod 1996, Graham et al. 2000, Van Rooij et al. 2003) and in the experiment here participants realized this quickly. Van Rooij et al. (2003) concluded in their study that humans avoid crossings when solving a Traveling Salesman task and do not follow the convex hull strategy as proposed by MacGregor & Ormerod (1996), however, this conclusion was rejected by MacGregor et al. (2004).

As predicted, the percentage of correct trials decreased with increasing length of the routes. The best performances were reached in the route lengths three to six. In the route lengths seven to ten a stronger decrease of performance was observed, with the only exception in route length eight, in which performance increased again (cf. Fig. 3.4 b), p. 23). A better performance in shorter route lengths and a poorer performance in longer route lengths was also found in other studies (e.g. Graham et al. 2000 and Tenbrink & Wiener 2009). Overall, participants found the shortest route in 70 % of the trials.
Taking all trials, including the correct ones, participants had a mean deviation of only 1.27 % (SD: ± 1.00) above the shortest route. The deviation in the false trials only, amounted to 4.00 % (SD: ± 3.83; cf. Fig 3.5 b), p. 25). These results are about in line with the results of Dry et al. (2006) and also similar to the deviation of 5.4 % in the navigational task in the study of Blaser & Wilber (2013). Dry et al. (2006) found a deviation of 1 % above the optimal route for tasks with a route length of ten locations. This deviation increased to 11 % above the shortest route for route lengths with 120 locations. Other studies showed also deviations from the optimal route between 3 % and 7 % (e.g. Tenbrink & Wiener 2009, Wiener et al. 2007 and 2009, Blaser & Ginchansky 2012). The small differences in performance in this Traveling Salesman version compared to the other studies could be caused by the chosen target locations which may have allowed an easier finding of the shortest route than the ones chosen in other experiments. Further, the participants did not have to learn the locations before the trial and recall it during the task like e.g. in the study of Wiener et al. (2009). Participants were able to use the dots, which marked the square tiles included in the route, for orientation all the time and did not have to built a spatial map of the locations; this could have facilitated route planning.
In the study of Blaser & Ginchansky (2012) cups with candies were placed at the different lo-

cations and participants collected the candy when they visited the locations. So, participants received more feedback whether they have already visited the location. The participants in the studies of Wiener et al. (2007 and 2009) marked the visited locations with small black markers and again received some information whether the location was already visited. In contrast, the participants here had to keep in mind which locations they had already visited, which could cause an additional demand on spatial working memory compared to the other studies which makes the results not fully comparable.
Though, it has to be admitted that the experiment was carried out in a relatively small experimental room. This enables the participants to find the shortest route by simply stepping on the neighboring square which is next to the square tile they were standing on. Vickers et al. (2003 a) showed that the nearest-neighbor strategy provides good solutions of the Traveling Salesman problem.

During the whole experiment participants' walking speed was measured. As hypothesized the walking speed decreased with increasing route length (cf. Fig. 3.7, p. 27). One reason for this decrease could be the greater load on working memory, caused by longer routes which had to be planned. In several studies it was shown that the load on working memory caused through solving a second task led to a decrease of walking speed (e.g. Yogev et al. 2005, Cho et al. 2008, Lamberg & Muratori 2012, Schabrun et al. 2014, Júnior et al. 2017).

Participants' walking speeds were also analyzed for differences in speed while walking the equal distances in different route lengths. Therefore, 17 out of 28 segments have been analyzed and in about one third of the segments a significant decrease of walking speed with increasing route length was found (cf. Fig. 3.8, p. 28). The six segments with significant differences all had a length of 1.0 to 2.0 m.
Next it was found, that the walking speed was correlated to the distance. With increasing distance the walking speed increased, too (cf. Fig 3.9, p. 29). But besides this correlation also a second arm in the plot was observed, which showed an increase of walking speed in short distances (about 0.5 m). A reason for this increase of walking speed in short distances could be a fast single step on the near next square tile. This quick step enabled participants to focus faster on the next part of the route.

It was shown that walking speed was influenced by additional working memory load, which resulted in a decrease of walking speed in longer route lengths with the same distances. Such a decrease of performance when attention needs to be split between two task was already reported by Barrouillet & Camos (2007). The walking speed was also influenced by the length of the distances. Short distances had a lower walking speed than longer ones.
A possible explanation for the lower walking speed in short distances could be found by having a closer look on the walking profiles of the participants. In Fig. 3.13 an exemplary walking profile of a single participant is shown. The walking profile looks similar to the ones of the other participants; the only difference is the maximum speed which each participant reached, but the course of the walking speed over time was equal. The chosen example is a route with a length of four squares which had to be visited. In Fig. 3.13 there are five peaks because the example started and ended on the starting position. So the five peaks were caused by walking from one square to the other and walking speed slowed down, when the participant was standing on the square tiles. It can be seen that the participant needed about 1 to 2 s each time to accelerate and reach the maximum walking speed.

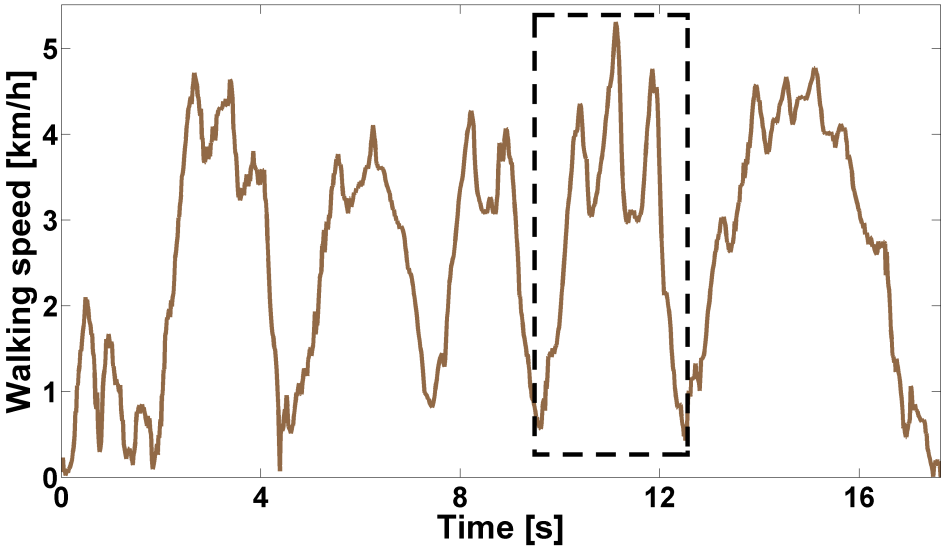

Figure 3.13.: Exemplary walking profile of a single participant. The walking speed (y-axis) is plotted against the time (x-axis) the participant needed to solve the trial (shown is a trial of route length four, as can be seen by the four valleys between 4 and 13 s). It can be seen that the participant always needed 1 to 2 s until he reached his maximum walking speed. There are five peaks because the participant was walking from the starting position to the squares one to four and then back to the starting position. Each time (six times) the participant was standing on a square tile, the walking speed decreased to almost zero (valleys). The little peaks until about 2 s resulted of head movements the participant made at the starting position, probably to check which square tiles were part of the route. The walking speed did not decrease to zero when the participant was standing on the square tiles, because participants' movements were measured with a head target and all participants were moving their heads while standing on the square tiles to look for the upcoming square tile. The black dashed rectangle marks the route segment between two square tiles which is shown in Fig. 3.14 in detail.

The distance between two squares, which is marked with a black dashed rectangle in Fig. 3.13, is analyzed in Fig. 3.14 in more detail for all participants.

In both figures (Fig. 3.13 and Fig. 3.14) it can be seen that all participants accelerate for about the first third of walking time until they reached their maximum walking speed. In the last third of walking time participants slowed down again to stand on the upcoming square tile. Hence, for reaching the maximum walking speed some time is needed and on shorter distances participants had to slow down to stand on the next square tile already before they reached their maximum possible walking speed. Besides the additional demands on working memory in longer route lengths, this could be a further explanation for a lower walking speed in shorter route segments.

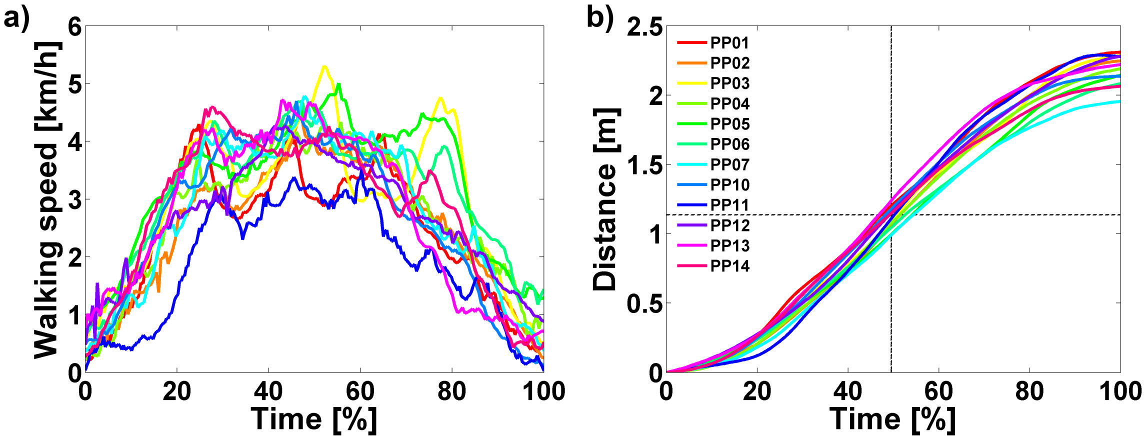

Figure 3.14.: Analysis of walking speed. a) For an exemplary distance (2.3 m) between two square tiles participants' walking speeds (y-axis) are plotted against the percentage of time (x-axis) they needed to walk this distance. Participants accelerated for about the first third of the time, then they reached their maximum walking speed for this distance and slowed down in the last third of the time again. b) The covered distance (y-axis) is plotted against the percentage of time (x-axis). The s-shaped curves describe participants' walking speeds. First, they slowly increased until the maximum speed was reached. Speed was kept constant for a while and slowed down towards the end. The inflection points of the s-shaped curves are at about the half time and the half covered distance (see crossing of dotted lines). The distance chosen here as example is the one of the spike marked with a black dashed rectangle in Fig. 3.13. Note: The time was stated in percent as the participants had individual walking speeds and for a better comparison it was necessary that participants finished the route distance at the same time, therefore the percentage of time was chosen. The horizontal dotted line is at half of the total distance (2.3 m), which is 1.15 m and the vertical time at half of the passed time. The different colored lines indicate the participants. There are only twelve and not fourteen lines, as two participants did not walk this distance at all.

Participants' mean standing time on a single square tile within a route decreased from route length three to route length five and remained constant for the remaining route lengths (cf. Fig. 3.10 b), p. 30). If participants would have used the standing time on the squares for further planning of the route, it would have been expected that the mean standing time increased with increasing route length even further, though, results showed that it decreased and then remained equal. This suggests that participants probably did not only use the standing time for further planning of the route, but were also planning during walking. The longer standing times in route length three could be explained that participants were instructed to stand with both feet on the square tiles. At the beginning of the experiment participants were still more endeavored to follow the instruction straightly. With the ongoing experiment participants concentrated more on the task than on the instruction which could explain why the standing time was highest in sequence length three, then decreased and was constant for the remaining standing times.

The standing time course on the squares within the shorter route lengths (three to six) tend to have an increase in standing time for the first squares and a decrease of standing time in the last squares (cf. Fig. 3.11, p. 32). For the longer route lengths (seven to ten), there was almost no change in the standing times on the first squares of a route, but at the end of the routes the standing times decreased, too. A possible reason for this decrease at the end could be that participants did not have to plan any further steps of the route, but just had go back towards the starting position and hence the standing time on the square tiles decreased.

Participants started their trials to one half at Start 1 and to the other half at Start 2. Their performance was better when they started from Start 2. Beginning at Start 1 participants were facing towards the tracking computer, beginning at Start 2 participants were facing towards the door of the experimental room. A reason for the difference in performance could be that the configuration of the pattern and the chosen routes from Start 2 facilitate the planning of the optimal routes between the square tiles. Possibly present external cues should not be helpful for this kind of task, especially since the square tiles were marked for the whole time of the trial. Therefore the difference in performance between the two starting positions should be a random effect of the configuration and not caused by external cues.

The comparison between male and female participants did not reveal any difference. These results are in line with the results of Wiener et al. (2004, 2007 and 2009), who also found no difference between males and females in performing a Traveling Salesman task. In contrast Cazzato et al. (2010) described differences between males and females in a Traveling Salesman-like task (“Maps test”, in which participants did not have to go back to the starting position). They reported that the initial planning phase did not differ between male and female participants, though, male participants solved the task in a shorter execution time and they were more likely to change their initial plan while solving the task to find the shortest possible path compared to female participants.

For a better analysis of the working memory resources required for walking (including spatial updating, holding posture and so on) it would have been useful to ask the same participants to solve a paper or computerized version of the Traveling Salesman, too. Though, there are several studies which already showed that people are quite good in solving computerized versions of the Traveling Salesman task, e.g. Basso et al. (2001) and Kong & Schunn (2007; for more studies see chapter “Introduction”, p. 7). Blaser & Wilber (2013) compared a paper version to a walking version and found no difference in performance, though they suggested that participants used different strategies in the both tasks. In a study by Haxhimusa et al. (2011) participants had to solve Traveling Salesman tasks on a real and a virtual floor. Another task was made in a “three-dimensional (3D) virtual space”. They found that performance on real and virtual floor are comparable to Traveling Salesman tasks solved at a computer screen. The results of the 3D virtual space were “slightly but systematically worse”. Though, the underlying cognitive processes in visual and walking versions of the Traveling Salesman might not necessarily be identical, even though there are task relevant processes which exist in both tasks (Wiener & Tenbrink 2008).

Conclusion

All participants were able to solve the Traveling Salesman task and were good in finding the shortest route, as most trials were solved correctly and the deviation of the shortest route in false trials was only minimal.
As hypothesized, it could be shown that the lengths of the routes have an influence on the performance, since the percentage of correct trials decreased with increasing route length and therefore additional demands on working memory resources. This additional demands on working memory also affected the working memory resources which were needed for walking, because the resources had to been split up for task solving and walking, which led to a decrease of walking speed in the longer route lengths.

In the next experiment wayfinding of an already known route and its influence on walking will be investigated further.

4. Experiment 2: Walking Corsi task

In Experiment 1 participants' performance in planning a route while walking was examined. The performance decreased with increasing route length and therefore increasing demands on working memory.
In this experiment now wayfinding of an already known route will be investigated further. For route memorization a Corsi sequence will be presented on a computer screen (encoding) and participants have to reproduce this sequence by walking to the squares (recall) in the same square tile configuration already used in Experiment 1. The visuo-spatial and temporal demands on working memory will be changed again by varying the length of the sequences.
It is expected that with increasing sequence length participants' performance will get worse and also that the length of the sequences will affect walking speed. It is also assumed that walking a known route will not require as many working memory demands as planning a route while walking, so participants' performance in this experiment should be better than their performance in Experiment 1 and their walking speed should be faster.

4.1. Material and methods

4.1.1. Participants

The same fourteen participants as in Experiment 1 "Traveling Salesman task" (see subsection 3.1.1 "Participants", p. 19) took part in this experiment; seven males and seven females with a mean age of 26.71 years (SD: ± 3.29). All had normal or corrected to normal vision and gave written informed consent. Participants were paid 8 € per hour.

4.1.2. Experimental setup and design

The experiment was carried out in the experimental room described in subsection 2.1 "Experimental room" (p. 13 f) under dimmed light conditions. The sequence to remember in each trial was presented on the laptop (for description see subsection 2.3 "Computers", p. 15) which was placed at the starting position of the upcoming trial (see Fig. 4.1 and Fig. 4.2). A square tile covered about 2° of visual angle on the laptop screen (100 x 100 pixels). The configuration of the fifteen square tiles presented on the laptop screen and on the floor was identical. The sequence to remember was presented by green dots which appeared for 2 s centered in the respective square tile (two example sequences can be seen in Fig. 4.2).

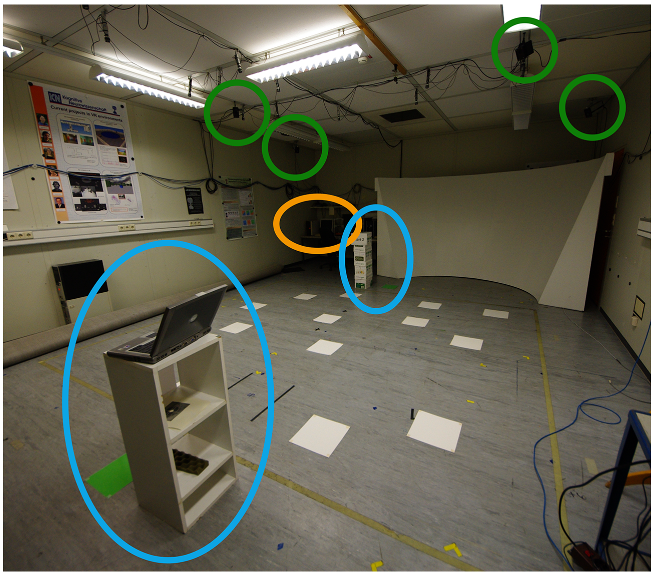

Figure 4.1.: Experimental room. The figure shows the configuration of the fifteen square tiles within a 4 x 4 m frame (yellow tape). The orange circle marks the tracking-computer. The green circles mark four of the six cameras of the tracking system. With the blue circles the two starting positions (Start 1 and Start 2), indicated with green 0.25 x 0.25 m square tiles centered outside the frame, are marked. On the right-hand side of each starting position a rack for the laptop was placed. In front the starting position “Start 1” with the laptop can be seen.

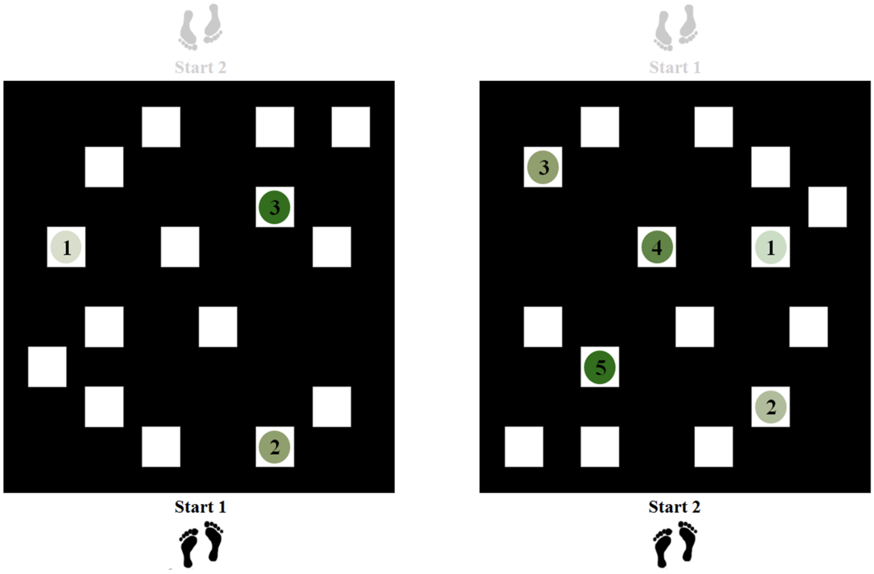

Figure 4.2.: Experimental setup. Configuration of the fifteen squares as potential locations to remember as well as the two different starting positions (Start 1 and Start 2), indicated by the feet which were not visible for the participants. The numbers at the starting positions were also not visible for the participants. Note that the left configuration is identical to the right one, but rotated by 180°. The walking area (frame) had a size of 4 x 4 m. The black feet indicate the starting position of the current trial (left: Start 1, right: Start 2) and the gray ones the other possible starting positions. The orientation of the configuration of squares on the screen was adapted to the viewing direction of the participant in each trial. A sequence length of three squares is shown in the left and a sequence length of five squares is shown in the configuration on the right (green circles). The numbers in the green circles and the color gradient from lightest (first) to darkest (last) green specify the position of this square in the sequence.

There was a delay of 0.5 s until the next square to remember was highlighted to prevent motion effects (interstimulus interval). The configuration of square tiles was not visible during the instructions. Before each trial participants got informed about the length of the upcoming trial. After the sequence was shown, the configuration disappeared again and participants were asked to reproduce the sequence by walking to the square tiles and stepping on them. Participants' position data were recorded with the tracking-computer (see subsection 2.3 "Computers", p. 15). The data recording started when participants started the trial by pressing the space bar and stopped when participants pressed the space bar again after returning to the starting position. Participants received no feedback of their performance between the trials.

4.1.3. General procedure

This experiment took part on the same day as Experiment 3: "Corsi task" (p. 65 ff), but because of measurement reasons it was always carried out before the Corsi task of Experiment 3 (for more details see subsection 5.1.3 "General procedure" of Experiment 3, p. 67). Participants were instructed about the procedure of the two experiments, their questions were answered and they gave written informed consent.

Before the actual experiment started, participants were asked to memorize one practice trial with a sequence length of five squares (which corresponds to an average sequence length) and reproduce it by walking around and stepping on the shown square tiles. All participants had to solve the same practice trial. This practice trial was used to familiarize participants with the procedure of watching a sequence on the laptop screen (screen-encoding) and to reproduce it on the floor (floor-recall).

Participants began the experiment at Start 1 by pressing the space bar. On the screen the length of the next sequence to remember appeared. Participants started with a sequence length of three squares. After each fourth trial the sequence length increased by one up to a sequence length of ten squares. Overall, 32 sequences had to be solved (4 repetitions x 8 sequence lengths; for all used sequences see appendix Fig. B.1 to Fig. B.4, p. 185 ff).

Right after a sequence was presented on the screen (screen-encoding) participants had to walk to the memorized squares in the correct order and step on the square tiles with both feet (floor-recall). They should not stand longer than 2 s on the square tiles and they also should not stop while walking between the squares. When participants had visited all squares of the sequence, they walked back to the starting position and pressed the space bar again to complete the current trial. On the screen the starting position for the next trial appeared. Participants moved to the next starting position and pressed the space bar to start the next trial when they were ready. The laptop was carried over to the other starting position by the participants themselves or by the experimenter.

The 32 sequences had lengths between 10 m and 15 m with a mean distance length of 12.5 m (SD: ± 1.07).

4.1.4. Analysis[1]

As first analysis a) participants' correct performance of the sequence recall was analyzed. For evaluating the performance the data of the tracking system were used. With the partici-

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[1] Some parts of this subchapter have been used and were published in the paper Röser et al. (2016) and were adopted here almost one to one. The final publication is available at link.springer.com/article/10.1007%2Fs00221-016-4582-z.

pants' performance the individual Corsi span of each participant was calculated (see below). Not only the number of correctly reproduced trials, but also b) the length of the correctly reproduced initial sequence of each trial was evaluated. Therefore, the number of correctly reproduced square tiles from start to the first wrong square tile were counted. Besides the correct initial sequence length, also c) the number of partial set correct square tiles was counted. This means that all square tiles which were shown in the sequence to be remembered and visited by the participant were counted, regardless if the participant visited these squares in the correct order shown in the sequence or in a different order - they just had to visit the squares at all. This method was also used by Zimmer et al. (2003).

The analysis of the length of the correct initial sequence was used as an alternative measurement of Corsi performance. The additional analysis of partial set correct is presented to differentiate between memories representing sequence information and memories representing only the spatial location of squares included in the sequence.

Again, like in Experiment 1 only participants' d) pure walking speed between the square tiles was measured. Finally, e) participants' standing time on the square tiles was analyzed.

To determine participants' Corsi span the procedure used by Smyth & Scholey (1992), as well as Lépine et al. (2005) was adopted. For all sequence lengths the number of correctly recalled trials was summed up and divided by 4 (the number of trials per sequence length). It was started with a sequence length of three, since it was assumed that all participants were able to solve trials with a sequence length of one or two correctly; for the Corsi span these trials were counted as correct. For example, consider a participant who solved the sequence lengths three, four and five correctly, in sequence length six the participant performed three correct trials (out of four), in sequence length seven two trials and only one correct trial in the sequence length of eight squares. In sequence length nine the participant again had one correct trial and in sequence length ten none. Also, the sequence lengths with one and two squares were assumed to be correct. Consequently, this participant would have a Corsi span of $([4 + 4] + 4 + 4 + 4 + 3 + 2 + 1 + 1 + 0) / 4 = 6.75$.

The difficulty of the shown sequences depended on the number of crossings and the rotation angles and of course the total lengths. Therefore, for each sequence the minimal rotation angle, occurring when solving the sequence correctly, was calculated. For the calculation of the rotation angles the first and the last angle were neglected, that is the angle from the starting position to the first square and also the angle from the last square back to the starting position. This was done because only the rotations while solving the task should be considered.

Similar to the minimal rotation angles also the minimal number of crossings in each sequence was counted. "Crossings" were defined as intersections with the already traveled route, excluding intersections that occurred on the way back from the last target to the starting position. Also a turn of 180° at one square and consequently a coincidence of segments was counted as crossing (see Fig. 4.3).

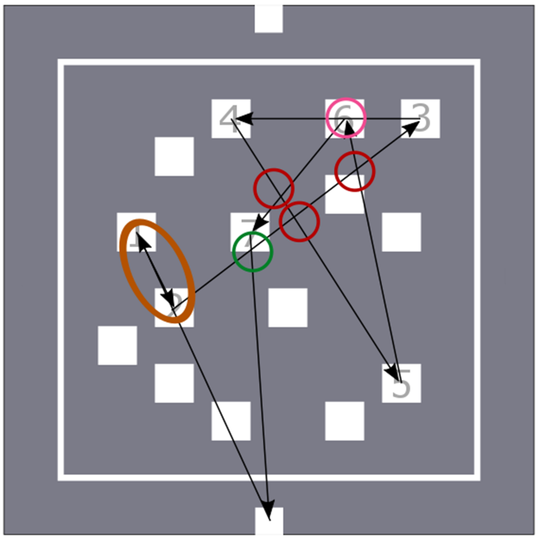

Figure 4.3.: Exemplary sequence illustrating the different crossing types. The sequence length is seven. Black arrows indicate the walking trajectory and directions. Red circles indicate the crossing of the already traveled route. The green circle shows a "crossing" from the last square back to the starting position which was not considered for the analysis since the sequence was already completed. The orange oval shows a turnaround of 180° and was counted as a crossing. The pink circle marks a touching of an already traveled route. This was also counted as a crossing. Here, the sequence contains five relevant crossings

4.2. Results

Again, participants' walking trajectories were measured and used for further analyses. By way of example two walking trajectories of this experiment are shown in Fig. 4.4.

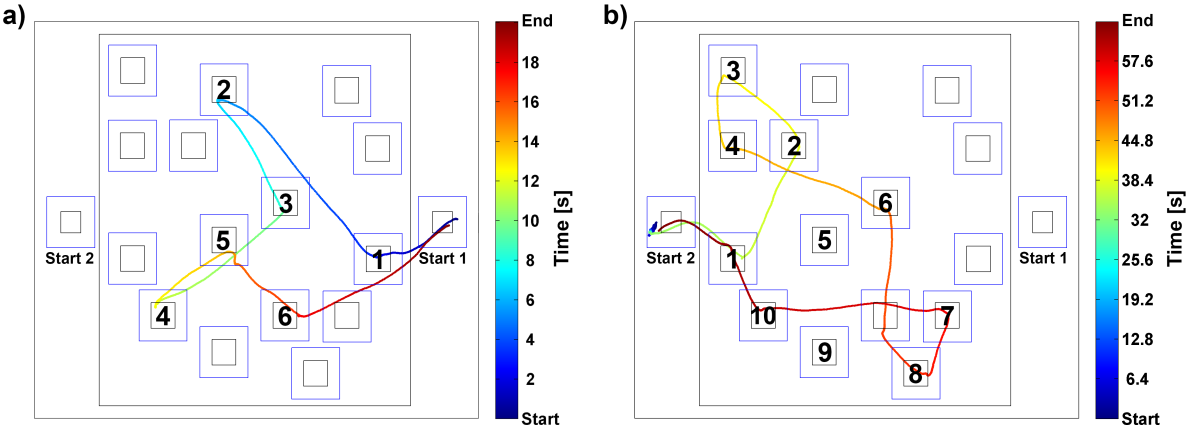

Figure 4.4.: Walking trajectories. a) A walking trajectory of a middle sequence (six squares) is shown. The start of the sequence was at Start 1. The sequence was remembered correctly by the participant. b) A long sequence (ten squares), beginning at Start 2, is shown. The sequence was not reproduced correctly (missed square 5 and 9). In both figures the numbers in the squares mark the order of the squares in the shown sequence. The time [s] participants needed to solve the sequence is indicated by the color gradient from blue (early) to red (late).

4.2.1. Analysis of correct trials

The first analyses of this experiment were participants' performance (see Fig. 4.5) and their Corsi span. The mean Corsi span of all participants was 3.98 (SD: ± 0.74). The individual Corsi spans of the participants lay between 2.75 and 5.25 (see Tab. 4.1).

Table 4.1.: Participants' individual Corsi span and the mean Corsi span over all participants with standard deviation.

P 1	**P 2**	**P 3**	**P 4**	**P 5**	**P 6**	**P 7**	
4.50	3.25	3.00	3.75	4.25	3.25	4.50	
P 8	**P 9**	**P 10**	**P 11**	**P 12**	**P 13**	**P 14**	**mean**
2.75	4.25	3.50	4.75	5.25	4.25	4.50	3.98 (SD: ±0.74)

For participants' performance the percentage of correct trials was evaluated. Participants mean performance in all trials lay between 9 % and 40 % (see Fig. 4.5 a)).

The mean performance of the participants (see Fig. 4.5 b)) decreased with increasing sequence length. In sequence length three and four participants reached 60.71 % (SD: ± 21.29) and 58.93 % (SD: ± 30.39), respectively. In sequence length five the percentage of correct trials was 35.71 % (SD: ± 27.24) and in sequence length six 14.29 % (SD: ± 12.84). In the higher sequence lengths seven to ten the performance lay between 5% and 10%. The overall mean over all participants and sequence lengths was 24.78 % (SD: ± 23.76).

A one-way repeated measures ANOVA was conducted to analyze main effects for the factor sequence length. A Mauchly test indicated a violation of sphericity ($\chi^2(27) = 62.275$, $p < 0.001$), therefore Greenhouse-Geisser ($\epsilon = 0.51$) corrected values were used further on. The percentage of correct trials decreased significantly with increasing sequence length ($F(3.57, 46.41) = 24.801$, $p < 0.001$, $\eta_P^2 = 0.656$). A post hoc analysis showed highly significant differences between sequence length three and the sequence lengths six to ten (all $p < 0.001$). Significant differences were also found between the sequence lengths four and six to ten, all with $p < 0.01$, except of the comparison between sequence lengths four and ten ($p < 0.001$). Sequence length five had significant differences to sequence lengths six and the sequence lengths eight to ten (all $p < 0.05$; see also depicted stars in Fig. 4.5 b)). No differences were found between the sequence lengths three to five and between the sequence lengths six to ten.

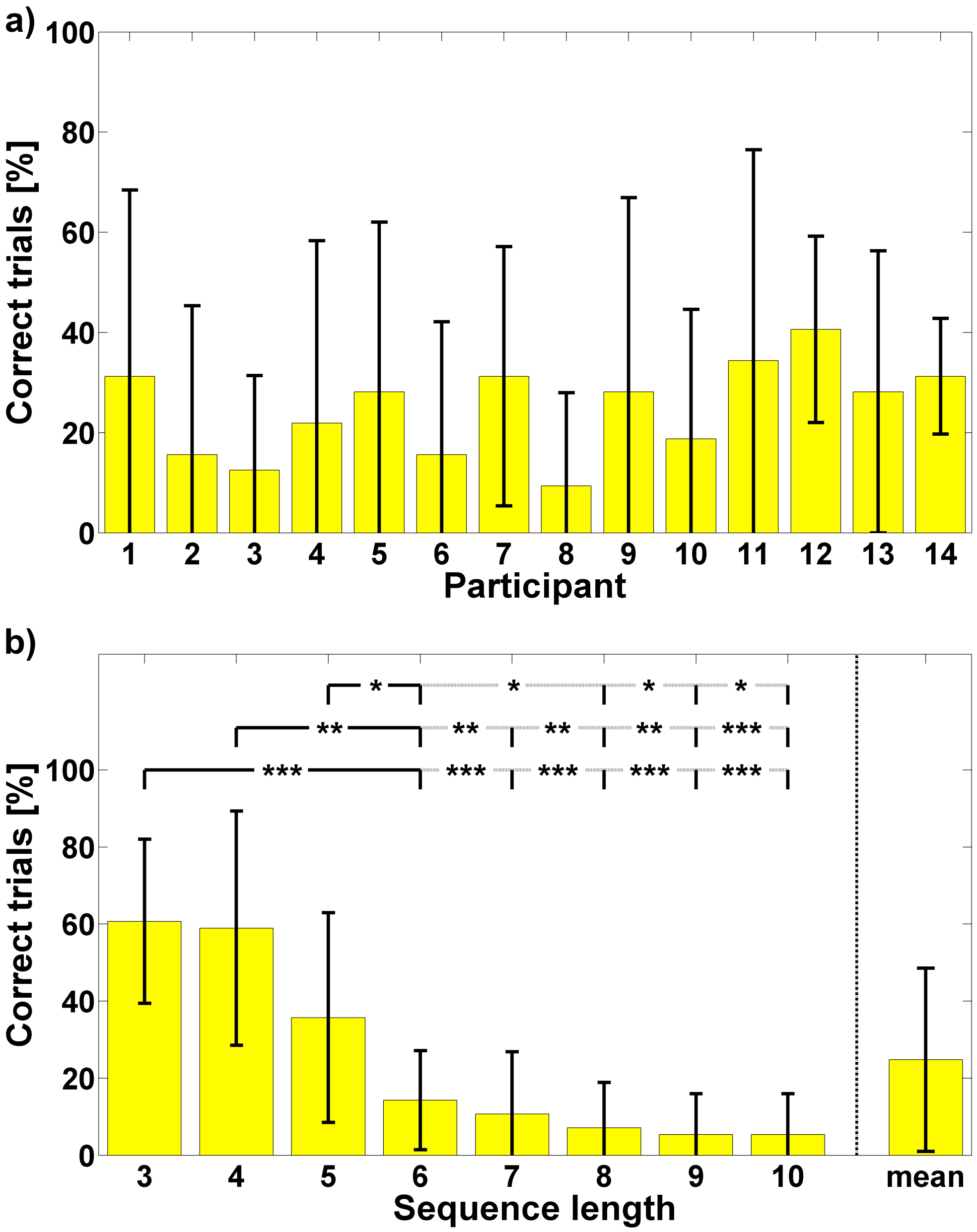

Figure 4.5.: Percentage of correct trials. a) For each participant (x-axis) the mean percentage of correct trials (y-axis) over all 32 trials is depicted. b) The mean percentage of correct trials over all fourteen participants (y-axis) is shown per sequence length (x-axis). The percentage of correct trials decreased rapidly with increasing sequence length. The sequence lengths three, four and five all differed significantly from the sequence lengths six to ten; except of sequence length five which did not differ from sequence length seven. The longer sequence lengths (six to ten) did not differ between each other in the percentage of correct trials. The mean over all sequence lengths and participants is shown in the right bar. Significant differences are depicted with stars. Note: For reasons of presentation the depiction of significant differences between sequence lengths are condensed. The dotted lines indicate the extension of the solid lines, e.g. sequence length three differed significantly from sequence length six, but differed also significantly from sequence lengths seven, eight, nine and ten. Error bars indicate the standard deviation.

4.2.2. Analysis of correct initial sequence length

As second variable the length of the correct initial sequence was evaluated by counting the number of correct square tiles from the starting position to the first error (see Fig. 4.6). In all eight sequence lengths the correct initial sequence length remained at about three. The average over all sequence lengths and participants was 2.91 (SD: ±0.26). A one-way repeated measures ANOVA was conducted; no differences between the sequence lengths was found for the factor initial sequence length ($F(7, 91) = 0.865$, $p = 0.54$, $\eta_P^2 = 0.062$).

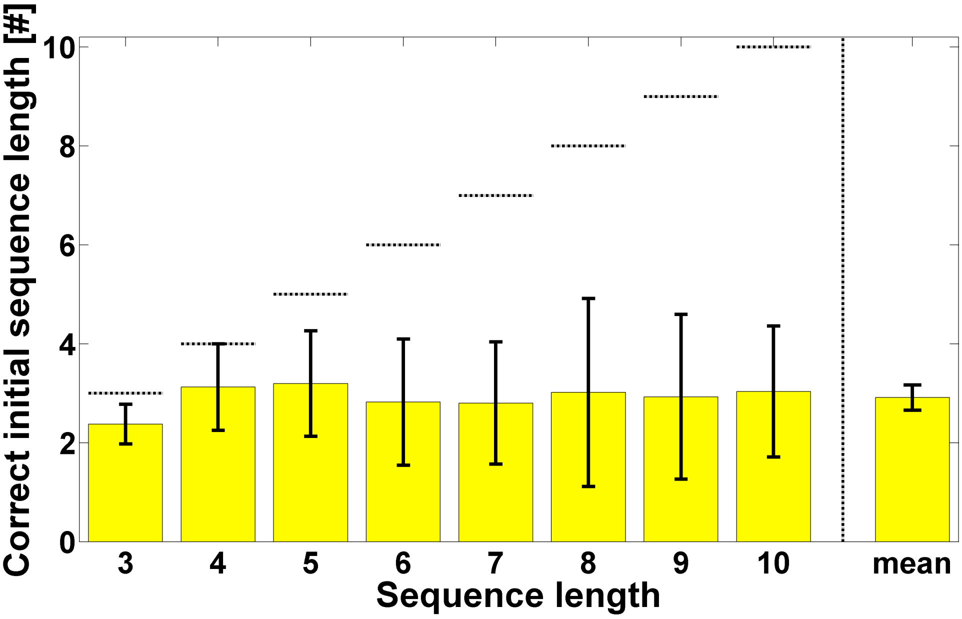

Figure 4.6.: Length of correct initial sequence. The length of the correct initial sequence over all fourteen participants (y-axis) is depicted for each sequence length (x-axis). The correct initial sequence lengths stayed at about the same level with increasing sequence lengths. On the right the mean over all trials and participants is shown. The horizontal lines denote the maximum reachable number for each sequence length. Error bars indicate the standard deviation.

4.2.3. Analysis of partial set correct

Not only the length of the correct initial sequence was evaluated, but also the number of squares, which were shown in the sequence and remembered by the participants regardless in which order, was counted (partial set correct; see Fig. 4.7). This partial set correct number was 2.55 (SD: ±0.31) in sequence length three. The value increased to 3.48 (SD: ±0.49) in sequence length four, reached 5.68 (SD: ±0.65) in sequence length seven and 8.21 (SD: ±0.54) in sequence length ten. Over all sequence lengths the average was 5.30 (SD: ±1.94).
A one-way repeated measures ANOVA revealed a highly significant increase of partial set correctly remembered square tiles over the sequence lengths ($F(7, 91) = 229.325$, $p < 0.001$, $\eta_P^2 = 0.946$). A post hoc analysis revealed highly significant differences between most of the sequence lengths with $p < 0.001$. The sequence lengths three and four showed a difference with $p < 0.01$ and the sequence lengths six and seven with $p < 0.05$. No difference was found between the sequence lengths four and five, as well as five and six and between the sequence lengths seven and eight (see Fig. 4.7).

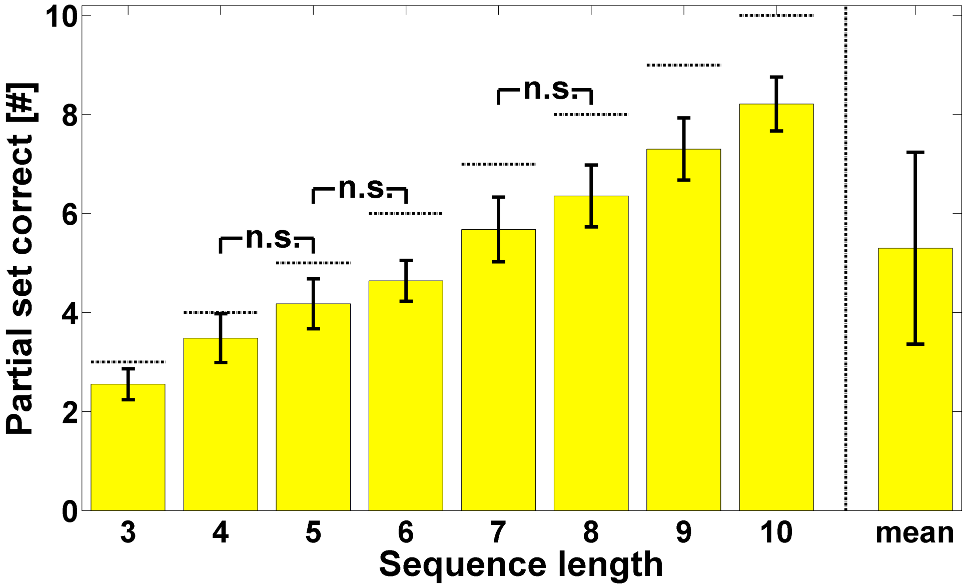

Figure 4.7.: Number of partial set correct. The number of partial set correctly reproduced square tiles averaged over the fourteen participants (y-axis) is shown for each sequence length (x-axis). The number of partial set correct square tiles increased over the sequence lengths. This increase was significant for all sequence lengths except for the sequence lengths four and five, the sequence lengths five and six, as well as the sequence lengths seven and eight. The right bar shows the mean over all sequence lengths and participants. The horizontal lines denote the maximum possible partial set correct squares. Error bars indicate the standard deviation.

4.2.4. Analysis of walking speed

Like in Experiment 1: "Traveling Salesman task" participants' walking speed was analyzed (see Fig. 4.8). The walking speed decreased with increasing sequence length. In sequence length three participants had a mean walking speed of 3.53 km/h (SD: ± 0.26), in sequence length six the average was 2.99 km/h (SD: ± 0.21) and in sequence length ten a mean walking speed of 2.70 km/h (SD: ± 0.13) was reached. The mean walking speed over all participants and sequence lengths amounted to 3.02 km/h (SD: ± 0.28).

For analyzing the main effects in the factor sequence length a one-way repeated measures ANOVA was conducted. A Mauchly test indicated a violation of sphericity ($\chi^2(27) = 67.069$, $p < 0.001$), so for further analysis a Greenhouse-Geisser correction ($\epsilon = 0.316$) was used. A highly significant decrease of walking speed with increasing sequence length was found ($F(2.214, 28.778) = 115.102$, $p < 0.001$, $\eta_P^2 = 0.899$). A post hoc analysis revealed no difference between the sequence lengths six and seven, seven and eight as well as nine and ten (see Fig. 4.8). Significant differences were found between the sequence lengths five and six, six and eight as well as eight and nine ($p < 0.05$). The sequence lengths four and five, six and nine, seven and nine as well as the sequence lengths eight and ten differed also significantly ($p < 0.01$). All other comparisons between the sequence lengths showed highly significant differences ($p < 0.001$).

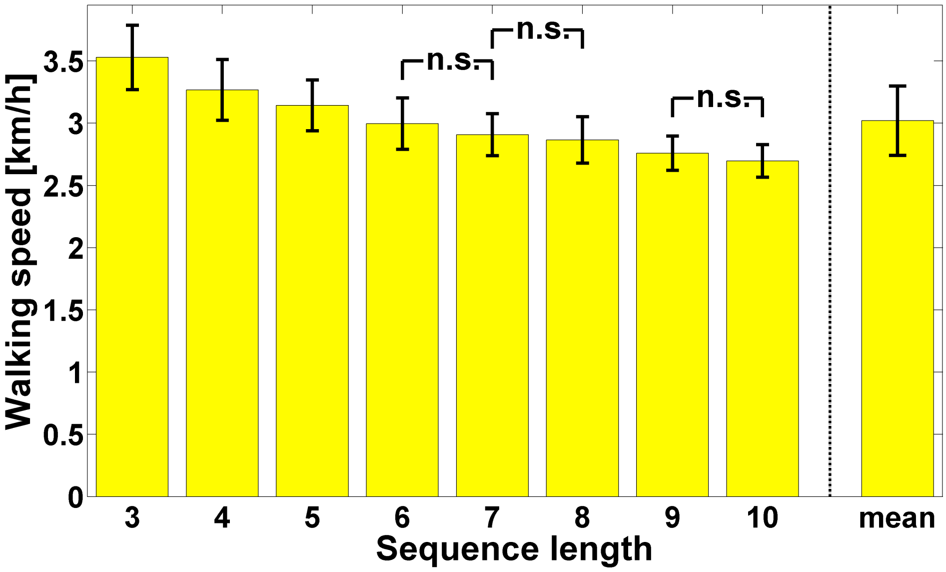

Figure 4.8.: Mean walking speed per sequence length. For each sequence length (x-axis) the mean walking speed of all fourteen participants (y-axis) is shown. The walking speed decreased with increasing sequence lengths. All sequence lengths differed significantly from each other, except of the sequence lengths six and seven, the sequence lengths seven and eight as well as the sequence lengths nine and ten. On the right the mean average over all fourteen participants and all eight sequence lengths is depicted. Error bars indicate the standard deviation.

Comparison of walking speed in correct and false trials

For a second analysis of walking speed the walking speeds were separated into a group of correctly remembered sequences and into a group of falsely reproduced sequences (see appendix Fig. B.5, p. 189). For analyzing main effect differences for the factors sequence length and performance (correct and false trials) a two-way ANOVA was carried out. As already found before, again a highly significant decrease of walking speed with increasing sequence length was found (F(7, 153) = 29.921, $p < 0.001$, $\eta_P^2 = 0.578$). For the factor performance no difference between correct and false trials was found and there was no interaction between the factors sequence length and performance.

Analysis of walking speeds of different route segments

Again, walking speeds were analyzed further and evaluated for each segment of a route. For classification of the different segments see Experiment 1: “Traveling Salesman task” chapter 3.2.3 “Analysis of walking speeds of different route segments” (p. 27) as well as appendix Fig. A.7 (p. 183) and Tab. A.1 (p. 184).
In this experiment 18 out of the 28 segments were analyzed for walking speed differences in the eight sequence lengths. The segments which were not evaluated were Segment 6, Segment 18 and the segments 21 to 28 because of not enough walking speed values for the different sequence lengths (only segments which were walked in at least two different sequence lengths and by more than two participants per sequence length were evaluated). Six of the remaining 18 segments had significant differences in walking speed over the sequence lengths (see Fig. 4.9).

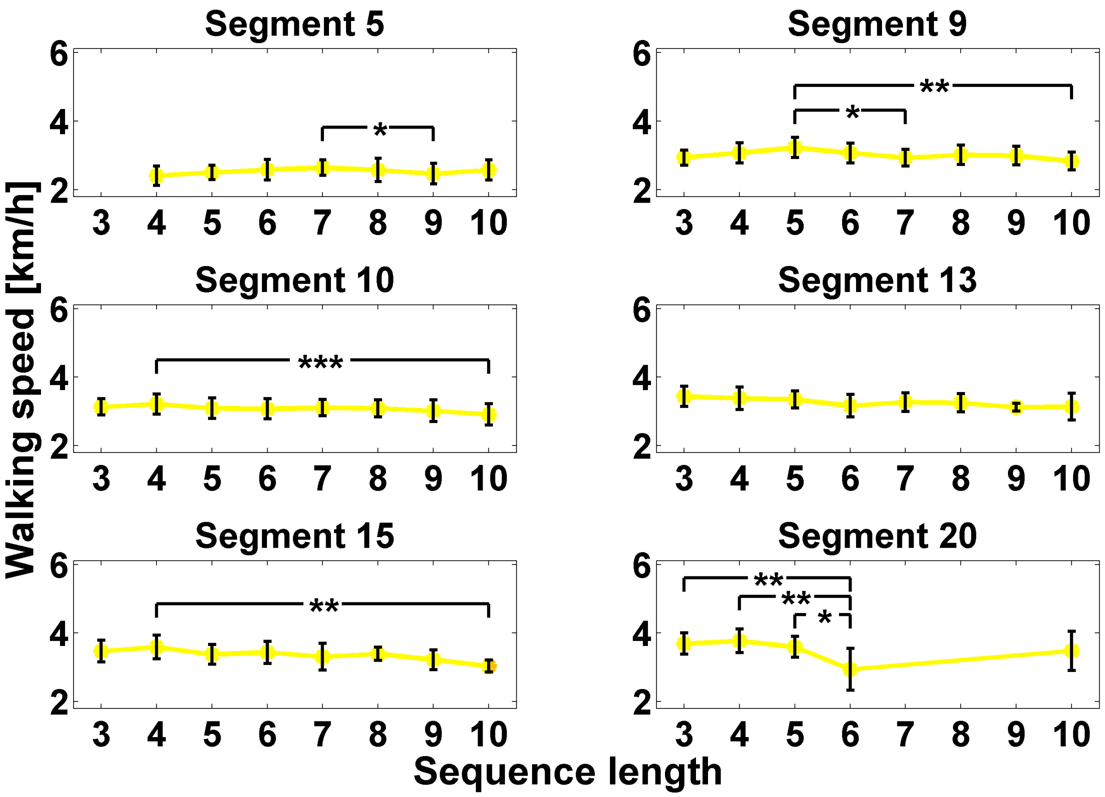

Figure 4.9.: Mean walking speeds of different segments of a sequence. The mean walking speeds (y-axes) are depicted with a dot for each of the eight sequence lengths (x-axes) for six different segments (Segment 5 to Segment 20). For sequence lengths without dot no walking speeds for analyzing existed (e.g. Segment 20: Participants were only walking the distances of Segment 20 in the sequence lengths three to six and ten, but not in the sequence lengths seven to nine). All of these six segments had significant differences in walking speeds over the sequence lengths. The significant differences among the sequence lengths are depicted with stars. For Segment 13 a post hoc analysis revealed no differences between the single sequence lengths. Error bars indicate the standard deviation.

For Segment 5 a conducted one-way ANOVA revealed a significant difference of walking speed with increasing sequence length ($F(6, 372) = 2.511$, $p < 0.05$, $\eta_P^2 = 0.039$). A further post hoc analysis showed a significant difference between sequence length seven and sequence length nine ($p < 0.05$). For Segment 9 a one-way ANOVA revealed also significant differences between the walking speeds ($F(7, 202) = 2.948$, $p < 0.01$, $\eta_P^2 = 0.093$). A post hoc analysis showed a significant decrease between sequence length five and sequence length seven ($p < 0.05$) and a decrease between sequence length five and ten ($p < 0.01$). For Segment 10 a decrease of mean walking speed with increasing sequence length was observed ($F(7, 213) = 3.341$, $p < 0.01$, $\eta_P^2 = 0.099$). Sequence length four differed highly significant from sequence length ten ($p < 0.001$) as shown by a post hoc analysis. For Segment 13 a decrease of mean walking speed over the sequence lengths was observed ($F(7, 123) = 2.235$, $p < 0.05$, $\eta_P^2 = 0.113$). There was no difference between the single sequence lengths. Also for Segment 15 a conducted one-way ANOVA revealed a decrease of mean walking speed with increasing sequence length ($F(7, 133) = 3.064$, $p < 0.01$, $\eta_P^2 = 0.139$). A post hoc analysis showed a highly significant decrease between sequence length four and sequence length ten ($p < 0.01$). For Segment 20 a decrease of mean walking speed from sequence length three to sequence length six was observed (F(4, 89) = 4.605, $p < 0.01$, $\eta_P^2 = 0.171$). A post hoc analysis resulted in significant differences between the sequence lengths three and four with sequence length six (both $p < 0.01$). Sequence length five had also a higher walking speed than sequence length six ($p < 0.05$). The mean walking speed of sequence length ten showed no difference to the walking speeds of the other sequence lengths. All significant differences of the six segments are depicted with stars in Fig. 4.9.

Next, participants' mean walking speed between two square tiles of a sequence was plotted against the distance between the two squares (see Fig. 4.10). There was a correlation indicating that with increasing distance the walking speed increased, too (Pearson: $r = 0.736$, $p < 0.001$).
Like in Experiment 1: "Traveling Salesman task" again a second arm with a higher increase of walking speed in short distances was found (see Fig. 4.10). Therefore, the trials were split up again in false and correct trials and walking speed was plotted once more against the walked distance. The second arm reappeared for correct as well as for false trials (see appendix Fig. B.6, p. 190).

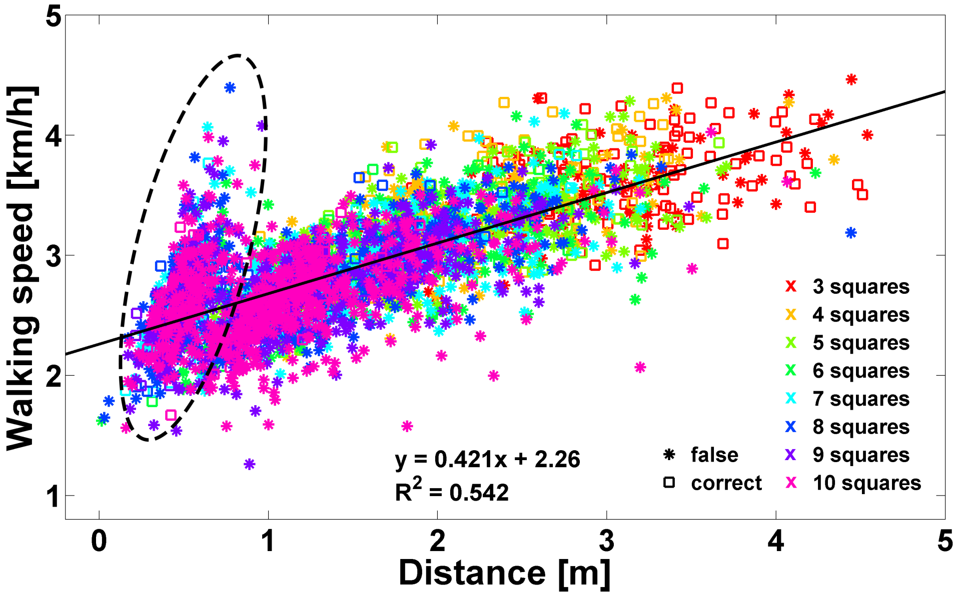

Figure 4.10.: Correlation between the mean walking speed and the distance between two square tiles. For each trial and participant the mean walking speed (y-axis) between two square tiles is plotted against the walked distance (x-axis) between these squares. There was a correlation showing that with increasing distance the walking speed increased ($R^2 = 0.542$). The dotted ellipse marks the second arm. Correct trials are depicted with squares, false trials with stars and the sequence lengths with different colors.

4.2.5. Analysis of standing time

After the analysis of walking speeds participants' mean standing times on a square tile was evaluated for each sequence length (see Fig. 4.11). The standing time on the starting and ending position was not evaluated.
The individual standing time of each participant is shown in Fig. 4.11 a). The time participants stood on the square tiles in each sequence length varied between 0.65 and 2.87 s. Participant 1 and Participant 7 had mostly the shortest standing times over the sequence

lengths. Participant 14 had short standing times on the square tiles for the sequence lengths three to six, but in the longer sequences (seven to ten) the standing time increased rapidly compared to the other participants.

The mean standing time on a square tile per sequence length is depicted in Fig. 4.11 b). Averaged over the fourteen participants the standing time was between 1.33 and 1.78 s in all eight sequence lengths. The total mean over all participants and sequence lengths amounted to 1.55 s (SD: ± 0.16).

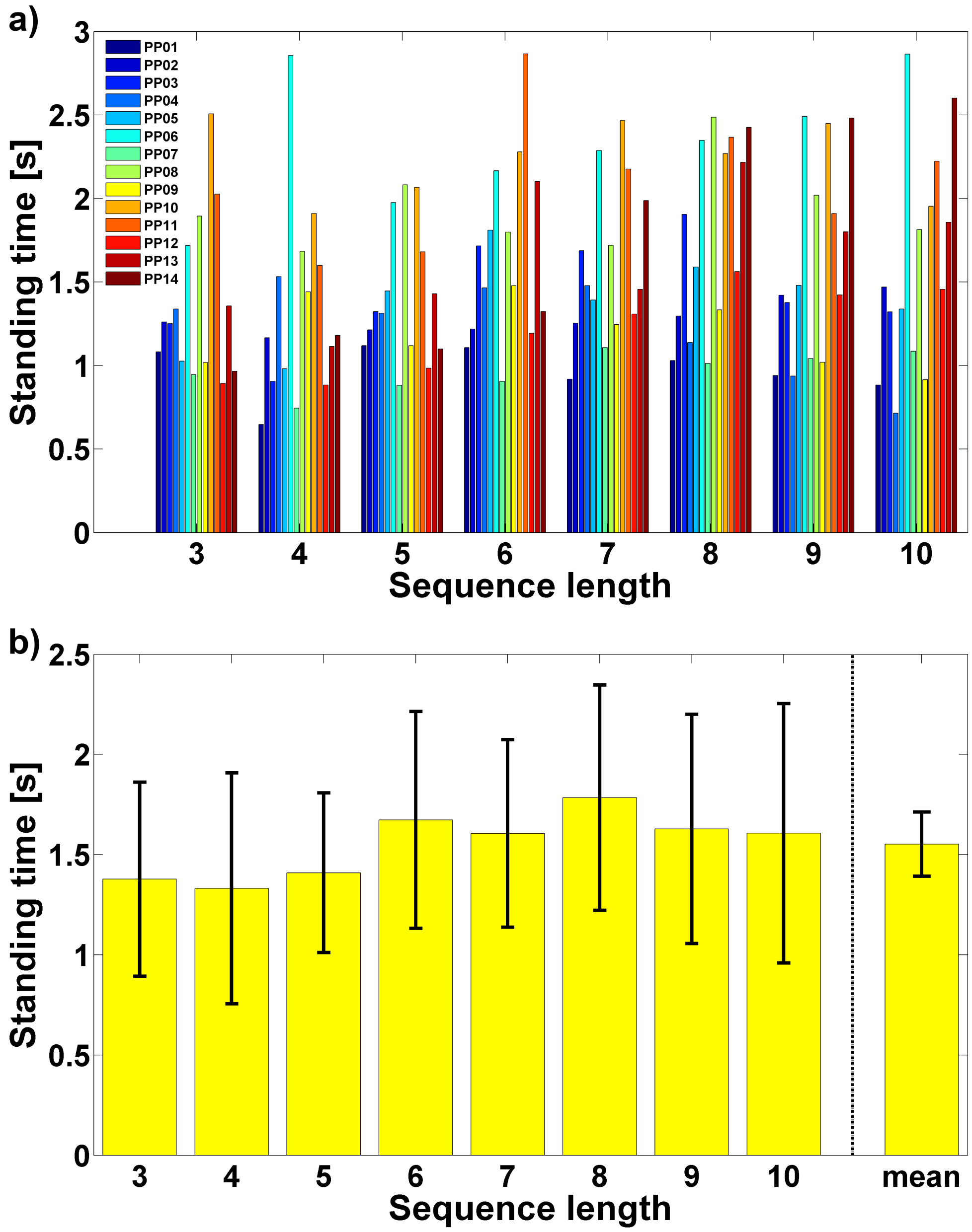

Figure 4.11.: Mean standing time on a single square per sequence length. a) The mean standing time (y-axis) each participant stood on a single square tile is plotted for the eight sequence lengths (x-axis). The colored bars indicate the fourteen participants. b) The mean standing time of the fourteen participants on a single square tile (y-axis) is depicted for each sequence length (x-axis). The standing time on the square tiles increased with increasing sequence length. The right bar shows the mean standing time over all sequence lengths and participants. Error bars indicate the standard deviation.

A one-way repeated measures ANOVA was conducted to analyze main effect differences for the factor sequence length. A Mauchly test indicated a violation of sphericity ($\chi^2(27) = 53.527$, $p < 0.01$), so for further analysis a Greenhouse-Geisser correction ($\epsilon = 0.426$) was used. The standing time on a single square tile increased significantly with increasing sequence length ($F(2.981, 38.759) = 4.102$, $p < 0.05$, $\eta_P^2 = 0.24$). A post hoc analysis revealed no differences between the single sequence lengths.

Not only the average standing time on a square tile per sequence length was evaluated but also the course of the standing times on the squares at a given sequence length (see Fig. 4.12 a)). In the sequence lengths three and four participants had similar standing times between 1.2 and 1.5 s on the square tiles. The standing times on a square tile in sequence length five were between 1.0 and 1.7 s. At the remaining five sequence lengths (six to ten) participants had standing times between 1.2 and 2.6 s. Though, all of the eight sequence lengths tended to have an increase in standing time on the first square tiles and a decrease in standing time for about the three last square tiles of a sequence (see Fig. 4.12 a) and b)).

For all sequence lengths a one-way ANOVA with repeated measures was conducted to investigate whether there was a change in standing time on a single square tile during a sequence. No difference between the standing times was found for the sequence lengths three and nine. For sequence length four a conducted one-way ANOVA revealed a significant difference of the standing times within a sequence ($F(3, 39) = 3.869$, $p < 0.05$, $\eta_P^2 = 0.229$). A following post hoc test did not show a difference of the standing times for the four squares. For sequence length five a Mauchly test indicated a violation of sphericity ($\chi^2(9) = 17.645$, $p < 0.05$). Greenhouse-Geisser corrected values ($\epsilon = 0.579$) revealed a highly significant difference between the standing times on the square tiles ($F(2.317, 30.126) = 9.399$, $p < 0.001$, $\eta_P^2 = 0.420$). A post hoc analysis showed highly significant differences between the squares one and three ($p < 0.01$), three and five ($p < 0.001$), as well as between the squares four and five ($p < 0.01$). Also for sequence length six highly significant differences between the standing times were found ($F(5, 65) = 5.787$, $p < 0.001$, $\eta_P^2 = 0.308$). Square two differed significantly from square four ($p < 0.05$), square four differed highly significant from square six ($p < 0.001$) and square five from square six ($p < 0.01$). A tendency for different standing times was found between the squares one and six ($p = 0.054$). For sequence length seven a Mauchly test indicated a violation of sphericity ($\chi^2(20) = 49.052$, $p < 0.001$), hence a Greenhouse-Geisser correction ($\epsilon = 0.467$) was used for further analyses. Significant differences were found for the standing times on a square ($F(2.804, 36.450) = 3.441$, $p < 0.05$, $\eta_P^2 = 0.209$). A further post hoc analysis did not reveal any differences between the square numbers. Once more for sequence length eight a Mauchly test indicated a violation of sphericity ($\chi^2(27) = 54.105$, $p < 0.01$), hence Greenhouse-Geisser corrected values ($\epsilon = 0.442$) were used for further analyses and highly significant differences for the factor square number were found ($F(3.095, 40.231) = 6.413$, $p < 0.01$, $\eta_P^2 = 0.330$). Significant differences between the squares five and eight ($p < 0.05$) and between the squares six and eight ($p < 0.01$) were found. Also there were tendencies for different standing times between the squares one and six ($p = 0.055$) and the squares seven and eight ($p = 0.056$).

In sequence length ten one participant only walked to nine and not to ten squares in a sequence, therefore a one-way ANOVA with repeated measures was conducted only for the remaining thirteen participants. A violation of sphericity was indicated by a Mauchly test ($\chi^2(44) = 87.441$, $p < 0.001$) and further on Greenhouse-Geisser ($\epsilon = 0.394$) corrected values were used. Again a significant difference between the standing times on the squares was observed ($F(3.544, 42.526) = 2.831$, $p < 0.05$, $\eta_P^2 = 0.191$). A following post hoc test showed no differences between the square numbers.

Again for better comparison the mean standing times were aligned with the last square tile of the sequence (see Fig. 4.12 b)). All sequence lengths showed apparently an increase of the mean standing times for the first squares of a sequence. About three squares before the end the standing times tend to decrease for all sequence lengths.

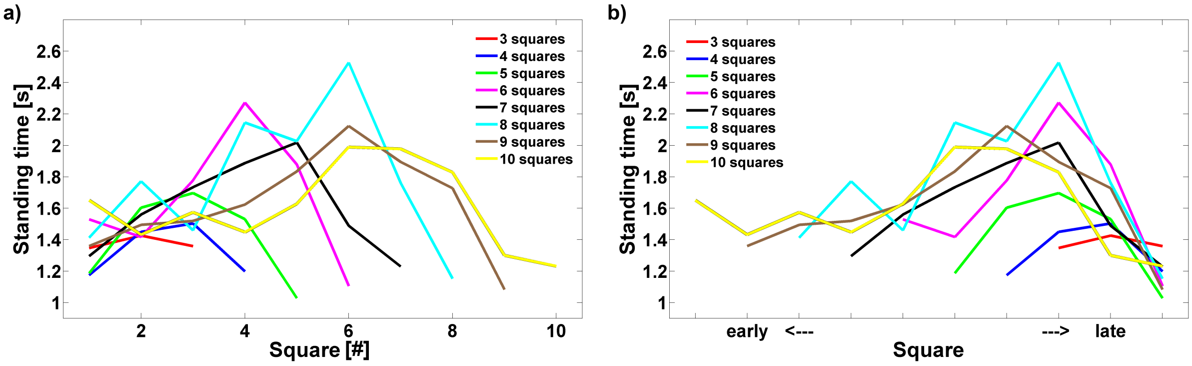

Figure 4.12.: Standing time courses. a) The mean standing time (y-axis) of the fourteen participants on each square tile (x-axis) in a sequence is shown. All sequence lengths showed apparently an increase in standing time during the first square tiles of a sequence. At the end of a sequence the standing time decreased again. The sequence lengths three and nine had no difference in standing times within a sequence. b) The mean standing time (y-axis) was aligned with the last square (x-axis) for comparison reasons. All sequence lengths had apparently an increase of the standing time over the first squares. The standing time decrease started about three squares before the end of a sequence, this was about the same for most sequence lengths. Note: For square number 10 in sequence length ten the average is only over thirteen participants as one participants walked only to nine than to ten squares. The eight sequence lengths are depicted with different colored lines.

4.2.6. Analysis of sequences

Again the more detailed analyses of the sequences started with evaluating the two different starting positions participants started off in this experiment. Each starting position was used as beginning of a sequence for 16 times for each participant. Starting from Start 1 participants remembered 21.88 % (SD: ± 20.28) of the sequences correctly. Beginning at Start 2 27.68 % (SD: ± 29.26) of the 224 total trials of all participants were solved properly. No difference of performance was found between the two starting positions as a χ^2-test revealed.

For each sequence the minimal rotation angle and the minimal number of crossings in the correct sequence were evaluated. For all trials the percentage of correct trials was analyzed for possible correlations with the number of minimal crossings (see Fig. 4.13 a)) and the minimal rotation angles (see Fig. 4.13 b)). No correlation was found for the percentage of correct trials and the number of minimal crossings (Spearman: r_s = -0.264, p = 0.145) but there was a correlation between the percentage of correct trials and the minimal rotation angles (Pearson: r = -0.828, p < 0.001), showing that with increasing rotation angles the percentage of correct trials decreased.

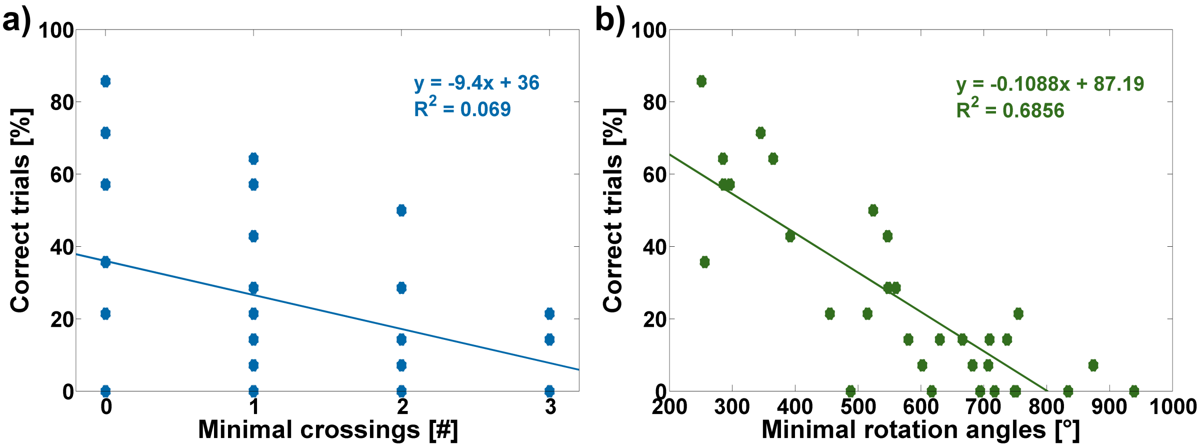

Figure 4.13.: Correlations between the mean percentage of correctly reproduced sequences and minimal crossings or rotations. a) Correlation between the percentage of correct trials (y-axis) and the number of minimal crossings (x-axis) for each trial. There was no correlation between the two factors ($R^2 = 0.069$). b) Correlation between the percentage of correct trials (y-axis) and the minimal rotation angles (x-axis) for each trial. There was a correlation showing that with increasing rotation angles the percentage of correct trials decreased ($R^2 = 0.686$). Note: Some dots are overlapping, therefore not all 32 dots are visible.

4.2.7. Comparison between males and females

Again participants' results were compared between males and females. The factors percentage of correct trials, the length of the correct initial sequence as well as the number of partial set correctly reproduced square tiles did not show any differences between genders. In contrast to Experiment 1: "Traveling Salesman task" in which the factor walking speed showed a tendency for male participants walking faster than female participants, in this experiment a two-way ANOVA revealed a significant difference between male and female participants for the factor walking speed ($F(1, 7) = 10.827$, $p < 0.01$, $\eta_P^2 = 0.101$) showing that the male participants had a higher walking speed than the female participants (see appendix Fig. B.7, p. 191). There was no interaction between the factors gender and sequence length. Similar results were found for the factor standing time on a single square tile. A two-way ANOVA showed significant differences between males and females ($F(1, 7) = 11.117$, $p < 0.01$, $\eta_P^2 = 0.104$). Females had a longer standing time on the square tiles compared to males (see appendix Fig. B.8, p. 191). Like for the factor walking speed there was no interaction between gender and sequence length for the factor standing time.

4.2.8. Comparison with Traveling Salesman task

The results of this experiment were compared to the results of Experiment 1: "Traveling Salesman task" (p. 19 ff). Comparisons were made for the percentage of correct trials, the walking speed in the two experiments and for the mean standing time on a square for the eight route and sequence lengths, respectively.

Correct trials

The percentage of correct trials decreased in both experiments with increasing route and sequence length, respectively. Though, the percentage of correct trials was better in Experiment 1: "Traveling Salesman task" than in Experiment 2: "Walking Corsi task" (see Fig. 4.14). In the Traveling Salesman experiment participants reached about 95 % of correct trials in the route lengths three and five and about 70 % in the route lengths four and six. In the Walking Corsi task the percentage of correct trials was at about 60 % in the sequence lengths three and four, in sequence length five only 35.71 % (SD: ± 27.24) and in sequence length six 14.29 % (SD: ± 12.84) were reached.

The mean average over all eight route and sequence lengths was 70.09 % (SD: ± 18.92) in the Traveling Salesman experiment and 24.78 % (SD: ± 23.76) in the Walking Corsi task, respectively.

A two-way repeated measures ANOVA revealed a highly significant effect for the factor route and sequence length ($F(7, 91) = 29.923$, $p < 0.001$, $\eta_P^2 = 0.697$), showing that with increasing route and sequence length the percentage of correct trials decreased. There was also a highly significant difference between the two experiments ($F(1, 13) = 447.55$, $p < 0.001$, $\eta_P^2 = 0.972$; see Fig. 4.14) and an interaction between the factors route and sequence length and experiment ($F(7, 91) = 5.180$, $p < 0.001$, $\eta_P^2 = 0.285$) was observed.

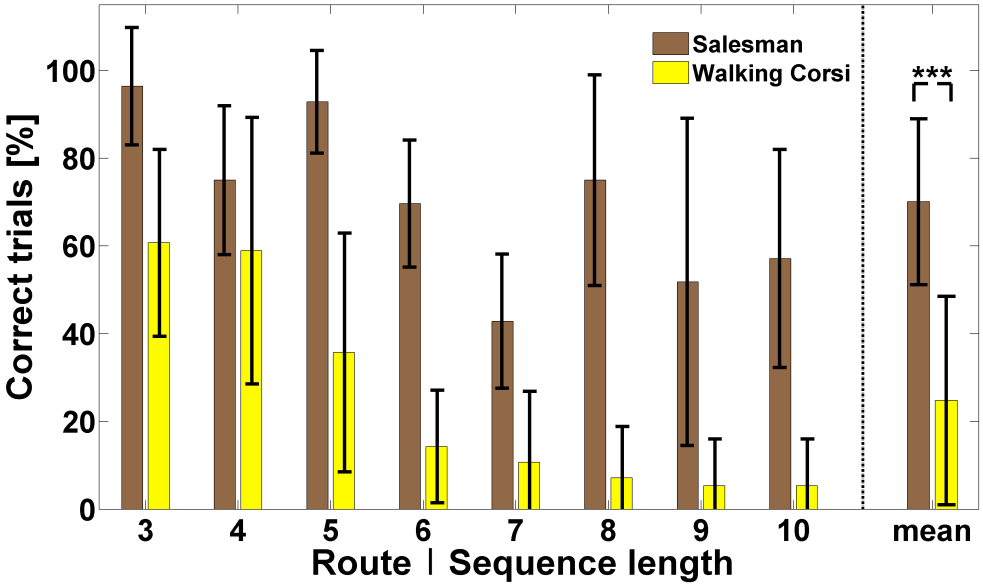

Figure 4.14.: Comparison between Traveling Salesman task and Walking Corsi task in percentage of correct trials. The mean percentage of correct trials averaged over the fourteen participants (y-axis) is shown for each route and sequence length, respectively (x-axis). In both experiments the percentage of correct trials decreased with increasing route and sequence length. On the right the mean percentage averaged over all fourteen participants and over all route and sequence lengths is shown for both experiments. The percentage of correct trials was significantly different between the Traveling Salesman task and the Walking Corsi task (depicted with stars above the means) and there was an interaction between the experiments and the route and sequence lengths. Brown bars depict the percentages of correct trials of the Traveling Salesman task and the yellow bars the percentages of correct trials of the Walking Corsi task. Error bars indicate the standard deviation.

Walking speed

After the percentage of correct trials the walking speed of both experiments was compared. The mean walking speed of the fourteen participants decreased with increasing route and sequence length in the Traveling Salesman task and in the Walking Corsi task, respectively (see Fig. 4.15) from about 3.5 km/h in route and sequence length three to about 2.7 km/h in route and sequence length ten. In the Traveling Salesman task participants had an averaged walking speed over all route lengths of 3.03 km/h (SD: ± 0.25) and in the Walking Corsi task an averaged walking speed over all sequence lengths of 3.02 km/h (SD: ± 0.28) was reached. There was no difference between walking speeds in both experiments.

A Mauchly test indicated a violation of sphericity ($\chi^2(27) = 86.933$, $p < 0.001$) for the factors route and sequence length, hence, for further analysis of effects in the factors route and sequence length a Greenhouse-Geisser correction ($\epsilon = 0.299$) was used. A two-way repeated measures ANOVA revealed a highly significant effect in route and sequence length ($F(2.096, 27.254) = 195.264$, $p < 0.001$, $\eta_P^2 = 0.938$), indicating that with increasing route and sequence length the walking speed decreased. There was no difference of walking speed between the two experiments, but an interaction between the factors route and sequence length and experiment ($F(7, 91) = 2.377$, $p < 0.05$, $\eta_P^2 = 0.155$) was found.

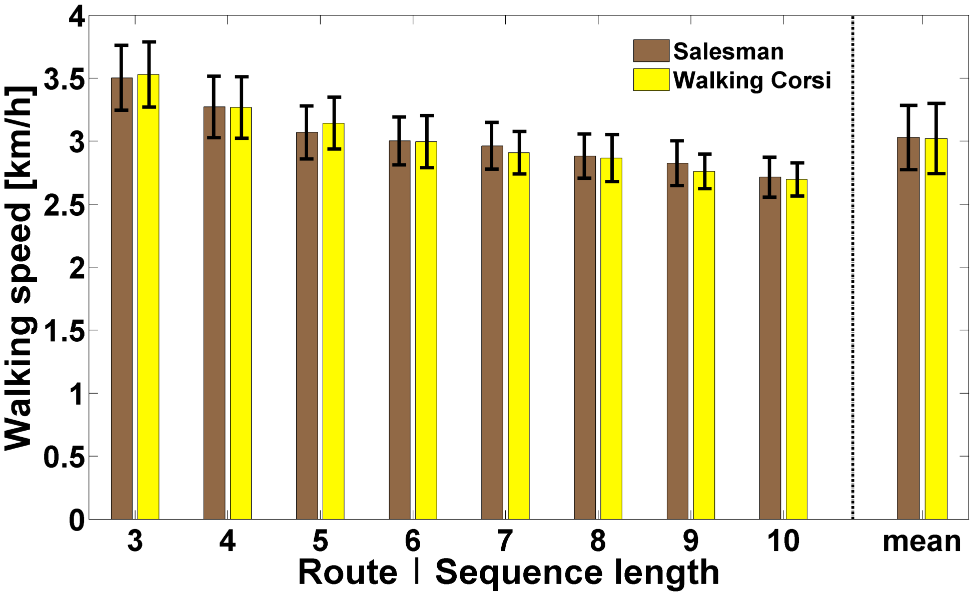

Figure 4.15.: Comparison between Traveling Salesman task and Walking Corsi task in walking speed. For both experiments the mean walking speed (y-axis) of the fourteen participants is shown for each route and sequence length (x-axis) and also the two means over all route and sequence lengths and participants are depicted. In both experiments the walking speed decreased with increasing route and sequence length. There was no difference in walking speeds between Traveling Salesman task and Walking Corsi task, but there was an interaction between the experiments and the route and sequence lengths. Brown bars depict the walking speeds of the Traveling Salesman task and the yellow ones the walking speeds of the Walking Corsi task. Error bars indicate the standard deviation.

Standing time

The standing time in Experiment 1: “Traveling Salesman task” decreased for the route lengths three to five; for the route lengths six to ten there was no difference in standing time. The mean standing time on a single square tile amounted to 0.91 s (SD: ± 0.11). The standing time in Experiment 2: “Walking Corsi task” slightly increased with increasing sequence lengths (see Fig. 4.16) and had an overall mean of 1.55 s (SD: ± 0.16).
A two-way repeated measures ANOVA was conducted to analyze the main effects for the factors route and sequence length and experiment. For the factors route and sequence length the assumption of sphericity had been violated as Mauchly’s test indicated ($\chi^2(27) = 44.801$, $p < 0.05$), for following analysis a Greenhouse-Geisser correction ($\epsilon = 0.487$) was used. There was a significant effect for the factors route and sequence length ($F(3.412, 44.353) = 3.257$, $p < 0.05$, $\eta_P^2 = 0.20$). There was a highly significant difference in standing time between the two experiments ($F(1, 3) = 27.390$, $p < 0.001$, $\eta_P^2 = 0.678$), showing that the standing times in the Walking Corsi task were longer than in the Traveling Salesman experiment. For the analysis of the factors experiment and route and sequence length a Mauchly test indicated a violation of sphericity ($\chi^2(27) = 64.564$, $p < 0.001$) and a Greenhouse-Geisser correction ($\epsilon = 0.40$) was used further on. There was an interaction between the factors route and sequence length and experiment ($F(2.797, 36.356) = 5.895$, $p < 0.01$, $\eta_P^2 = 0.312$).

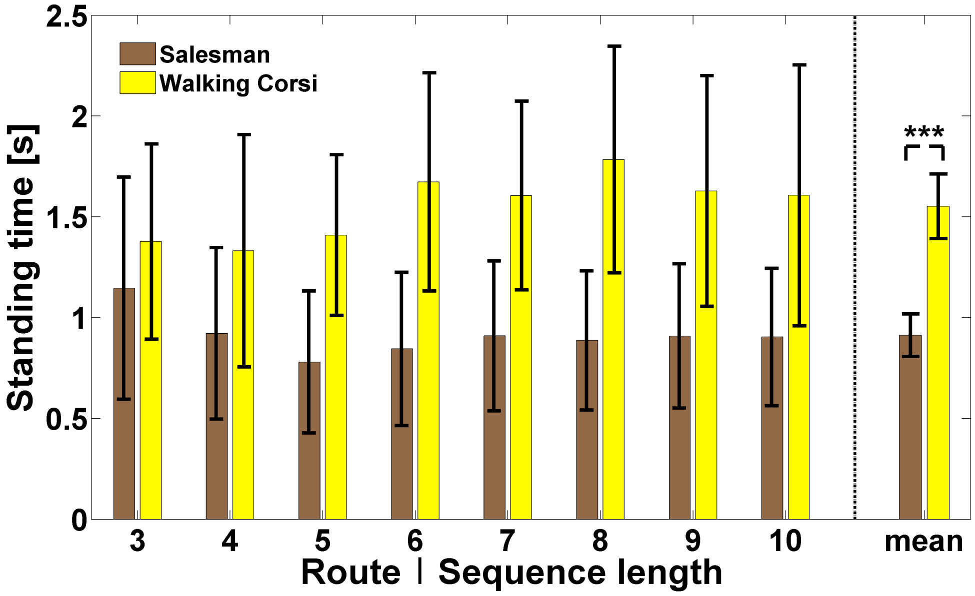

Figure 4.16.: Comparison between Traveling Salesman task and Walking Corsi task in standing time. The mean standing time on a single square tile (y-axis) averaged over the fourteen participants is shown for each route and sequence length (x-axis). For the Traveling Salesman task the standing time decreased in the route lengths three to five; the standing time in the route lengths six to ten was similar. For the Walking Corsi task the mean standing time on a single square tile increased with increasing sequence length. Both experiments differed highly significant in the standing time (depicted with stars above the means). An interaction between the factors experiment and route and sequence length was found. Brown bars depict the standing times of the Traveling Salesman task and the yellow bars the standing times of the Walking Corsi task. Error bars indicate the standard deviation.

4.3. Discussion

In this experiment wayfinding while recalling a known route and the influencing demands on working memory load were investigated, therefore participants solved a walking version of the Corsi task. Solving a Corsi task includes, but is not limited to, visuo-spatial and also temporal working memory load because the shown sequence has to be reproduced in the given order. A walking version furthermore includes working memory processes for spatial updating and for processes which are related to walking itself. In this experiment, due to the type of sequence presentation, additional working memory load was caused by reference frame transformation from screen to floor, too. The visuo-spatial and temporal load on working memory was varied by increasing the length of the sequences participants had to memorize.

In the Walking Corsi task participants had more difficulties to solve the task than in Experiment 1: “Traveling Salesman task”, though all participants were able to solve the experiment. As predicted the percentage of correctly solved trials decreased with increasing sequence length (cf. Fig. 4.5 b), p. 45). The performance was similar in the sequence lengths three and four and decreased rapidly in sequence length five. Another rapid decrease was observed in sequence length six; for the remaining sequence lengths performance stayed at the same level. A performance decrease with increasing sequence length in classical or computerized Corsi tasks was also observed by e.g. Fischer (2001), Busch et al. (2005) and Cornoldi & Mammarella (2008). Overall, participants solved 24 % of the trials correctly.
An explanation for the performance decrease is the limited capacity of the working memory, which makes it difficult to reproduce sequences with a length of six to ten correctly, since the short-term memory capacity is limited to three to five (Cowan 2000). Another reason for the performance decrease could be that participants watched the sequences on a screen and had to transfer the sequences to the floor and thus into another reference frame. This means the pattern had to be transferred from a small scale of space, i.e. a figural space (Montello 1993, Jiang & Won 2015), to a large scale of space, i.e. vista space (Montello 1993) and it is known that the space of scale influences spatial coding (Wolbers & Wiener 2014, Jiang & Won 2015). This reference frame transformation and also the continuous spatial updating while walking require additionally working memory resources which were not available for sequence recall and might have a stronger influence on rehearsal and recall of longer sequences.

The mean Corsi span reached by the participants was about four (cf. Tab. 4.1, p. 44). Orsini et al. (1987) mentioned a Corsi span of about five for a test group aged between 20 and 30 years and also Corsi (1972) reported a Corsi span of five. Hence, the participants in Corsi’s and Orsini et al.’s experiments reached slightly better values, though, in their Corsi tasks participants solved a classical version with nine wooden blocks in front of them. Since there were no reference frame transformations necessary in their experiments this might be an easier design and maybe led to a better performance. Further, the calculation of the Corsi span was different compared to the one used here because in their classical version the maximum number of blocks correctly reproduced was taken. The lower Corsi span of the participants could be caused by the working memory resources which were required for walking in the reproduction phase. A Corsi span of almost five was also shown by Piccardi et al. (2010) in a walking version of the Corsi task. Piccardi et al. as well as Orsini et al. used sequences up to a length of nine. The sequence lengths were increased if at least two out of three (Piccardi et al. 2010) and three out of five (Orsini et al. 1987), respectively, trials were correctly reproduced. The Corsi span resulted of the longest correctly reproduced sequence. Here, sequence lengths up to ten were used without ending the experiment prematurely and all trials were used to calculate the Corsi span including short sequence lengths which were solved wrong. Piccardi et al. (2010) further used a different presentation type of the sequences: An experimenter was walking the sequence on the floor. In contrast, the participants in this experiment watched the sequences on a screen. Watching an examiner walking the sequence might facilitate the encoding of the sequence in contrast to watching it on the screen because participants could encode the examiner's trajectory with body turns, gait and viewing directions. These facts, as well as different chosen sequences and a different pattern configuration, could be reasons that participants reached a Corsi span of four in this experiment and thus a slightly poorer value than reported in the other studies.

Since it seemed to be more difficult to remember the correct squares at the end of a sequence, the square tiles from beginning to the first error were counted, too (i.e. correct initial sequence length) for having another measurement of participants' performance. In this experiment participants' mean correct initial sequence length remained equal at about three over all sequence lengths (cf. Fig. 4.6, p. 46).
While carrying out the measurements of this experiment it was observed that participants sometimes mixed-up the order of two squares within a sequence. Thus, for another analysis the temporal factor of the sequence was ignored and only the recalled square tiles regardless of their order in the sequence were counted (i.e. partial set correct). The same analysis method was applied by Zimmer et al. (2003). They used the method to check if their secondary task has only impaired the temporal information of the Corsi sequence but not the spatial one.
Using the partial set correct analysis method participants performance increased up to eight correctly remembered square tiles in sequence length ten (cf. Fig. 4.7, p. 47) and thus, without the temporal factor performance was above the mentioned capacity limit of working memory. Though, it has to be conceded that e.g. in sequence length ten the chance level to step on one of ten correct square tiles out of fifteen is 66.7 %. So there is a good chance to step on a correct square tile without knowing at all if this square tile was part of the sequence or not. The better performance in partial set correct was contrary to the findings of Zimmer et al. (2003), who found no difference between the standard analysis of performance and such a partial set correct method. Though, in their experiment participants were presented with a secondary task (finger tapping or visual noise task) and they checked whether the secondary task impaired performance in the Corsi task.

Similar to Experiment 1: "Traveling Salesman task", again participants' walking speeds were measured and, as expected, the walking speed decreased with increasing sequence length (cf. Fig. 4.8, p. 48) in this task, too. This should be again caused by the increased additional working memory load in longer sequences, because more locations had to be remembered and recalled. To check for this possibility again the walked distances with equal length were analyzed for differences in walking speed in different sequence lengths.
18 out of 28 segments were analyzed and in one third of the segments significant decreases of walking speeds in some of the sequence lengths were found (cf. Fig. 4.9, p. 49). Five of the six segments had distances between 2.0 and 3.5 m, the sixth segment had a distance of 1.1 m. In contrast to Experiment 1, this time significant differences in walking speed were found for longer distances. This could be an evidence for different working memory processes which are involved in the both tasks. Working memory components included in planning a route while walking seemed to have a larger effect on short distances, whereas working memory components required for recalling a known route might affect longer distances stronger. The decrease of walking speed in longer sequence lengths shows that the additional load on

working memory has an influence on walking speed.

Again, the walking speed was correlated to the distance of the distance traveled (cf. Fig. 4.10, p. 50). The longer the traveled distance the faster the walking speed was. Similar to Experiment 1 a second arm of increasing walking speeds was observed for distances of about 0.5 m, which probably was caused again through quick steps to nearby square tiles.
Participants' walking profiles were analyzed in this experiment, too. They looked quite similar to the example shown for the Traveling Salesman task (cf. Fig. 3.13, p. 36).
So again it was shown that the length of a sequence had an influence on walking speed due to additional demands on working memory. A second explanation for the decrease of walking speed with increasing sequence length could again be the length of the walked distance between two squares. In the longer sequence lengths the distances between the square tiles were often shorter than in the short sequence lengths and participants needed some time for acceleration and also deceleration, so that they might not reach their maximum walking speed on the shorter distances in the longer sequence lengths. Since it was shown that the same distances were walked with different walking speeds in different sequence lengths, the shorter distances in the longer sequence lengths were not the only reason for the decrease of walking speed in the longer sequence lengths but it was also caused by additional working memory demands.

The analysis of the standing time revealed an increase of the standing time on a single square tile with increasing sequence length (cf. Fig. 4.11 b), p. 51). This increase might be caused by the fact that participants (mentally) rehearsed the sequence to be sure about the next square while they were standing on the squares and not only while walking between the square tiles. In the shorter sequence lengths there were not as many squares to keep in mind and reproduce during the task and therefore participants' standing time on the squares was shorter. In longer sequence lengths the rehearsal phase of the next square needed longer due to a longer sequence and this could result in increased standing times in longer sequence lengths.
Not only differences in standing time between the sequence lengths were found, but also differences in the standing times on the squares within a sequence length, showing that the standing times tended to increase at the beginning and to decrease at the end of a sequence (cf. Fig. 4.12, p. 53). A possible explanation for this standing time course could be that participants were endeavored to memorize the beginning of the sequence exceptionally well during the encoding phase, which makes it easier to reproduce the first squares in the recall phase. In case participants were using the standing times on the squares to rehearse the sequence this could explain why the standing time was shorter for the first squares. With ongoing sequence participants had to rehearse the sequence more often than at the beginning to be aware of the next square. At the end of a sequence participants did not have to remember so many squares since they just had to go back towards the starting position. Hence, the standing time on the square tiles decreased again. Since this decrease of standing times already started about three squares before the end it could be assumed that participants recalled the sequence not square by square, but that they group two to three squares together and recall them as chunks. This would mean that they did not have to recall any further squares of the sequence towards the end of the sequence and so did not have to rest longer on the square tiles. This could be an explanation for the standing time decrease at the end of a sequence.

In Experiment 1 a difference in performance was found for the two starting positions, indicating a better performance with beginning from Start 2. In contrast to this finding there

was no difference between the starting positions in the Walking Corsi task. This result was expected since there should not be any present external cues which could help to solve the task.
The sequences used in this task were not only analyzed for their starting positions but also for their minimal number of crossings and their minimal rotation angles (cf. Fig 4.13, p. 54). This means the number of crossings included in the correct sequence and the rotation angle of the correctly walked sequence. No correlation between the number of crossings and participants' performance was found. In contrast to this result, dependencies on the number of crossings in solving a Corsi task were found by e.g. Orsini et al. (2001) and Parmentier & Andrés (2006). For the minimal rotation angle a correlation to the percentage of correct trials was found; with increasing rotation angle the performance decreased. This correlation can be explained with the greater load on working memory through spatial updating with increasing rotations. The more turnings participants made during walking, the more they had to update their positions and mentally adjust the pattern configuration to their new orientation. This additional working memory load required working memory resources which could not be used any longer for purposes such as recalling the sequence.

The comparison between males and females revealed no differences in performance (including percentage of correct trials, length of correct initial sequence and partial set correctly reproduced square tiles). These results are in line with the findings of Kessels et al. (2000). In contrast, Piccardi et al. (2008 and 2013) found a larger Corsi span of males compared to females. Also Nori et al. (2015) found a better performance of males compared to females in a virtual walking Corsi task, whereas women were better than men in a walking Corsi task.
For walking speed (cf. Fig. B.7, p. 191) as well as for standing time (cf. Fig. B.8, p. 191) a difference between the genders was found. Male participants had a faster walking speed than female participants. This difference could be caused by physical characteristics (e.g. males are taller) which enable males to walk faster than females. In some studies it has already been shown that males walk faster than females (e.g. Himann et al. 1988, Öberg et al. 1993). For the standing time a conversely result was found. The standing time of males on a square tile was shorter than the standing time of females. The longer standing times of females could be explained by weaker mental rotation capabilities of females. In several studies a weaker performance of females in mental rotation was reported (Linn & Petersen 1985, Richardson 1994, Voyer et al. 1995, also see Masters & Sanders 1993 for an overview). Because males had a shorter standing time and also a faster walking speed, the differences in walking speed between the genders might not only be caused by physical characteristics but also by advantages in mental rotation processes of males.

Comparison with Traveling Salesman task

In this experiment participants should recall a sequence and walk a known route. Whereas in the Traveling Salesman task participants had to plan their route while walking. It was assumed that walking a known route needs less working memory resources than planning a route while walking. Therefore, the performances in the Walking Corsi task were expected to be better than the results of the Traveling Salesman experiment.
In both experiments the percentage of correct trials decreased with increasing route and sequence length, though, participants' performance was better in the Traveling Salesman experiment compared to the Walking Corsi task (cf. Fig. 4.14, p. 55). There was also an interaction between the experiments and the route and sequence lengths indicating that the decrease of performance was larger in the Walking Corsi task.

For the factor walking speed no difference between the experiments was found (cf. Fig. 4.15, p. 56). The walking speed decreased with increasing route and sequence lengths in both experiments, though, the walking speeds in the experiments were equal.
The standing times in the two experiments had contrary courses and there was an interaction between the experiments and the route and sequence lengths. For the Traveling Salesman task the standing time decreased in the first route lengths and remained similar then. For the Walking Corsi task the standing times increased with increasing sequence length (cf. Fig. 4.16, p. 57) and they were longer than in the Traveling Salesman task.

For the percentage of correct trials, the walking speed and the standing time an interaction between the experiments was found. Further, the walking speed in the Walking Corsi task seemed to be a bit faster in the shorter sequence lengths and a bit slower in the longer sequence lengths compared to the Traveling Salesman task. So for a more detailed analysis the mean of the two shortest route and sequence lengths (three and four) was compared to the mean of the two longest route and sequence lengths (nine and ten). This was done for each of the three factors (see Fig. 4.17).

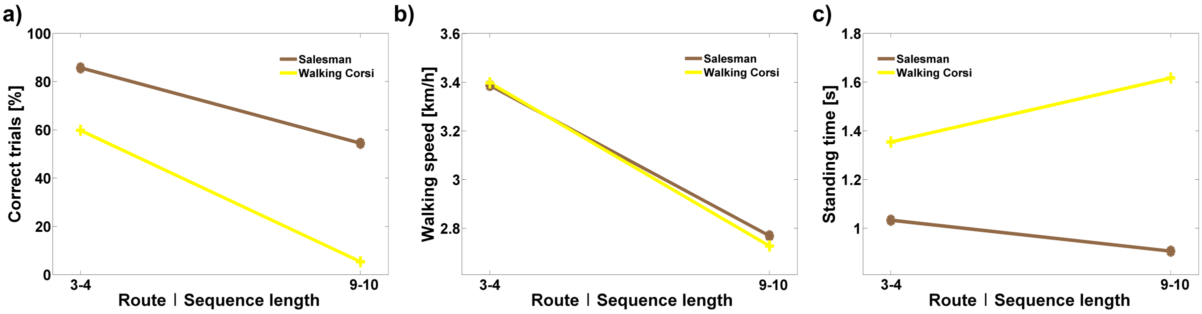

Figure 4.17.: Interaction plots for the percentage of correct trials (a), the walking speed (b) and the standing time (c). The mean performance (y-axis) of all fourteen participants in the route and sequence lengths three and four and nine and ten, respectively, (y-axis) is depicted for the Traveling Salesman task (brown lines) and the Walking Corsi task (yellow lines). In a) participants' performance in the Walking Corsi task showed a larger decrease than in the Traveling Salesman task. In b) the walking speed was equal in the route and sequence lengths three and four. In both experiments the walking speed decreased towards the higher route and sequence lengths but the walking speed in the Traveling Salesman experiment seemed to be slightly higher than the one in the Walking Corsi task in the route and sequence lengths nine and ten. Though, there was no interaction between the two experiments in this case. In contrast to a) and b) where both experiments showed a decrease, the standing time decreased in the Traveling Salesman task but increased in the Walking Corsi task.

For the percentage of correct trials there was a performance decrease in both experiments (see Fig 4.17 a)), but in the Walking Corsi task the decrease was stronger than in the Traveling Salesman task. The walking speed in the route and sequence lengths three and four was almost similar in both experiments (see Fig. 4.17 b)). In route and sequence length nine and ten the walking speed of the Traveling Salesman experiment was slightly higher than in the Walking Corsi task. In Fig. 4.17 b) a crossing of the two lines can be seen, though there was no interaction between the two experiments. For the factor standing time a different course of performance was found in the two experiments (see Fig. 4.17 c)), whereas the standing time in the Traveling Salesman task apparently decreased slightly with increasing route length. The standing time in the Walking Corsi task increased with increasing sequence length. These different standing time courses might be the result of different working memory processes which were necessary for solving each of the two tasks. Recalling a sequence required more time than finding the next square of the shortest route and this might cause the longer standing times in the Walking Corsi task compared to the standing times in the Traveling Salesman task.

The findings of the percentage of correct trials, as well as the findings of the standing times in the Traveling Salesman task and Walking Corsi task are not in line with the hypothesis that planning a route requires more working memory resources than recalling a known route. Though, the different decreases of performance and the contrary standing times indicate that at least some different working memory processes are involved while solving the two tasks.

Conclusion

The performance in the Walking Corsi task decreased with increasing sequence length due to additional working memory loads caused by longer sequences and reference frame transformations from screen (small space) to floor (large space). Also spatial updating as well as the costs caused by walking itself require working memory resources which had an influence on participants' performance in solving the task. Further, the walking speed was affected through additional working memory loads because equal distances were walked slower in longer sequence lengths.
It was predicted that participants would reach a better performance in the Walking Corsi task compared to the Traveling Salesman task - this could not be confirmed. In contrast, participants had a better performance in the Traveling Salesman task. Thus, there should be different working memory processes needed for solving the two tasks because of the different performance decreases and the contrary standing times in the experiments. A reason why participants reached a better performance while planning the route might be the chosen setup for the Traveling Salesman task. The targets of the routes were visible for the whole trial and therefore might have facilitated the task, whereas in the Walking Corsi task no cues were present while walking. Therefore, planning a route while walking could result in the better performance compared to walking a known route in the Walking Corsi task.

Ignoring the temporal factor of the sequences in the analysis participants reached much better results. In the next experiment the working memory costs caused by walking will be investigated further. Therefore, participants had to solve a “more classical” version of the Corsi task without walking but seated in front of a screen. Their performance should be better in the seated version since no additional working memory load caused by reference frame transformations and spatial updating processes, including walking, were needed.

5. Experiment 3: Corsi task

In Experiment 2 participants' performance got worse with increasing sequence length. The walking version of the Corsi task requires not only working memory demands for remembering the Corsi sequence and reference frame transformation from screen to floor but also additional costs for spatial updating and walking, such as body turns, posture control, gait, etc. in the reproduction phase (recall).

In this experiment the same method of task presentation (encoding) like in Experiment 2 was chosen, but this time the same participants were asked to solve the task seated in front of a computer screen. This allows to compare the experiments in a within-subject design but excludes most of the additional working memory loads caused by reference frame transformations, spatial updating and walking itself and minimize it to the costs which results of finger tapping and posture control as well as the visuo-spatial and temporal demands required for memorizing and recalling the sequence. Again, the length of the shown sequences will be increased and hence the visuo-spatial and temporal demands for memorizing the sequence will be changed.

Since the additional working memory requirements are lower compared to Experiment 2, it is expected that participants' performance in this experiment will be better than in the previous one.

5.1. Material and methods

5.1.1. Participants

The same male and female volunteers as in Experiment 1: "Traveling Salesman task" (p. 19 ff) and Experiment 2: "Walking Corsi task" (p. 39 ff) participated in this experiment. One of the female participants had to be excluded due to measurement and recording errors, therefore only thirteen participants took part in this experiment. For further information see subsections 3.1.1 "Participants" (p. 19) and 4.1.1 "Participants" (p. 39).

5.1.2. Experimental setup and design

The computer (see subsection 2.3 "Computers", p. 15) for presenting the Corsi sequences in this experiment was placed next to the tracking-computer in the experimental room (which was not needed in this experiment, see Fig. 2.1 (p. 13) and Fig. 7.1 (p. 109) for overview of the room). The experiment was again carried out under dimmed light conditions. The squares of the pattern on the computer screen had a size of 80 x 80 pixels each and covered about 2.5° of visual angle. The different sequence lengths were presented with green circles which appeared for 2 s centered inside the squares one after another (see Fig. 5.1). Between two circles a delay of 0.5 s was introduced (interstimulus interval). This delay was chosen to prevent motion effects which could facilitate the memorization of the sequence. After presenting the sequence on the screen (screen-encoding) participants were asked to reproduce the sequence by clicking with the computer mouse on the squares in the correct order (screen-recall). When participants clicked on a square the mouse cursor disappeared from the screen as long as participants would have needed to walk the respective distance from the previous square to the next one in reality, in order to adjust the timing in this task. To calculate this time delay the mean individual walking speed of each participant measured during the Walking Corsi task in Experiment 2 was used. For each sequence length a separate time delay was calculated by using the mean walking speeds of the four trials of each sequence length. This adjustment should prevent participants from reaching a better performance in the Corsi task than in the Walking Corsi task because of different timings. After the time delay the mouse cursor reappeared and participants were able to click in the next square. The pattern configuration was visible during the time delay, but it was not visible between trials when participants were instructed about the length of the sequence of the upcoming trial. Also, the configuration was not visible after the sequence was presented and participants were instructed to reproduce the sequence by clicking in the squares. It was visible again in the recall phase.

In this experiment participants received feedback whether they clicked in the correct square or not. When participants clicked into the correct square a green circle appeared in this square. When participants clicked into a wrong square or not in a square at all a red circle appeared in the square, which would have been the next correct one in the sequence.

The data recording for each trial started when participants pressed the space bar after the practice trial and the right mouse button between trials. Thus, participants were able to have a break between each trial if needed. The data recording stopped when the number of mouse clicks was equal to the sequence length of the trial.

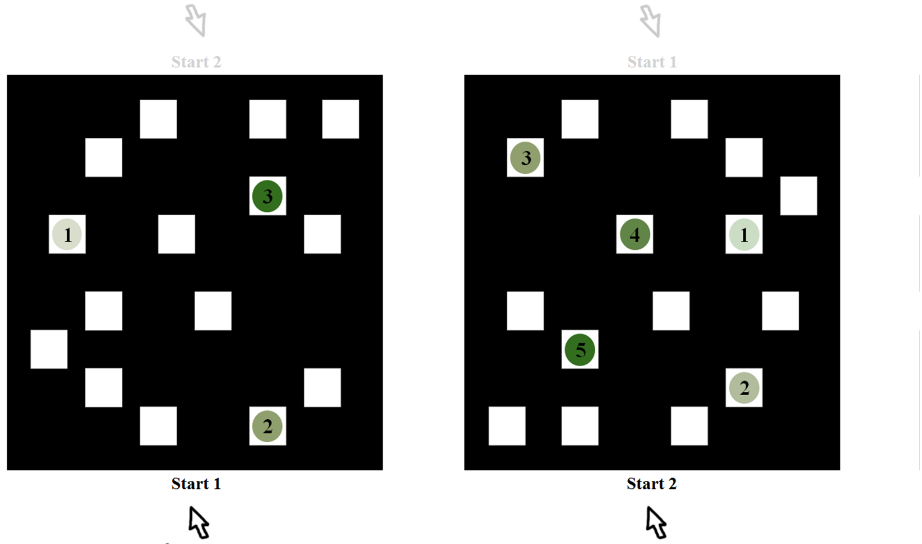

Figure 5.1.: Experimental setup. Configuration of the fifteen squares as potential locations to memorize as well as the two different starting positions (Start 1 and Start 2) indicated by the mouse cursor. Numbers at the starting positions and the mouse cursors were not visible for the participants. The left configuration is identical to the right one but rotated by 180°. The squares covered about 2.5° of visual angle (80 x 80 pixels). The black mouse cursor indicates the starting positions of the current trial (left: Start 1, right: Start 2) and the gray ones the remaining possible starting positions. A sequence length of three squares (green circles) is shown on the left and a sequence length of five squares is shown in the configuration on the right side. The numbers in the green circles and the color gradient from lightest (first) to darkest (last) green specify the position of this square in the sequence.

5.1.3. General procedure

The experiment was conducted always with a short break after Experiment 2: "Walking Corsi task" (p. 39 ff). Participants started with a practice trial with a sequence length of three squares by pressing the space bar. On the black screen the information "practice trial" was presented for 2 s, after that the configuration of the squares appeared and the sequence of the three squares was shown. Then the configuration of squares disappeared and participants were requested by a notice on the screen to reproduce the sequence. This notice was presented for 2 s, after that the configuration with the squares reappeared. Participants were asked to use the practice trial to familiarize with the procedure. They were also encouraged to click into a wrong square to see that the next correct square was lit up red in this case. The practice trial ended when participants have clicked three times, whether in squares or not. The experiment started when participants pressed the space bar. They could ask any questions or take a short break before starting.

During the experiment two different configurations of the square tiles were used. They were rotated by 180° (see Fig. 5.1) and similar to the two different starting positions in Experiment 2: "Walking Corsi task". Before each trial the number of the upcoming sequence length was shown on the screen. Participants started with a sequence length of three and ended with a sequence length of ten. For each sequence length they had to perform four repetitions, leading to a total number of 32 trials that had to be solved like in the other experiments. After each shown sequence the information to reproduce the sequence by clicking into the squares (screen-recall) appeared on the screen. The reproduction phase stopped when participants reached the number of the shown sequence length with mouse clicks. Participants continued the experiment by pressing the right mouse button and again the length of the next sequence was shown. After the fourth trial in sequence length ten the information "Experiment finished" was shown on the screen.

The sequences to reproduce were the same sequences participants also had to solve in Experiment 2: "Walking Corsi task" (see appendix Fig. B.1 to Fig. B.4, p. 185 ff).

5.1.4. Analysis

For data analyses the mouse clicks of the participants were evaluated. Like in Experiment 2: "Walking Corsi task" the evaluated variables were a) the number of correctly reproduced trials, b) the length of the correct initial sequence and c) the number of partial set correct square tiles. Participants' Corsi span was calculated with the same method described in Experiment 2 subsection 4.1.4 "Analysis" (p. 41 f).

5.2. Results

In this experiment participants solved the task by clicking into the squares with a mouse. Two of such click patterns are depicted in Fig. 5.2.

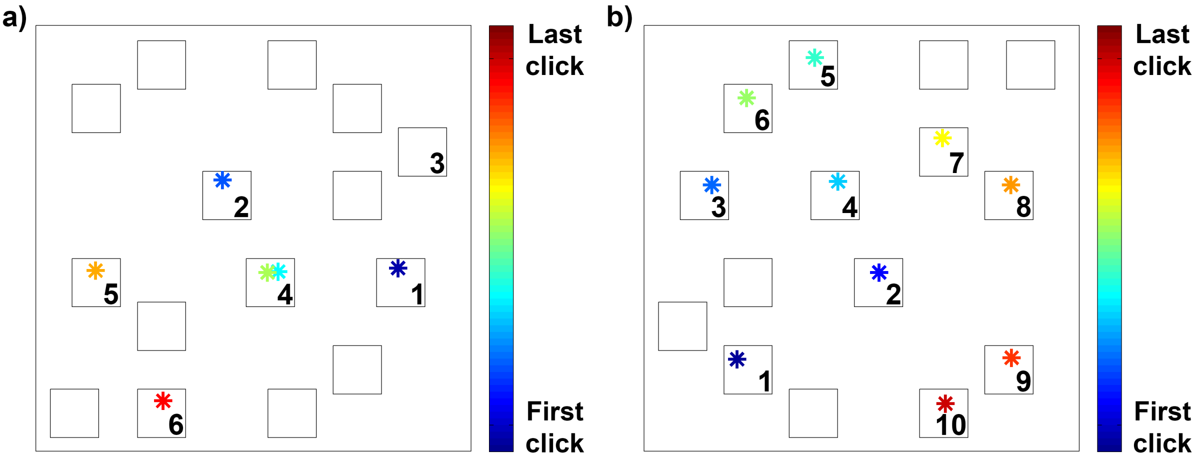

Figure 5.2.: Click patterns. a) A click pattern of a sequence with an average length (six squares) is shown. The orientation of the squares was identical to trials beginning at Start 2 in the experiments 1 and 2. The sequence was not reproduced correctly as there is no click into Square 3 of the sequence but two clicks into Square 4 of the sequence. b) A long sequence (ten squares) is shown. The orientation of the squares was identical to Start 1 in the experiments 1 and 2. This sequence was remembered correctly. In both figures the numbers in the squares indicate the order of the squares in the shown sequence. The color gradient indicates the order of the clicks, blue stars mark early clicks and red stars late clicks.

5.2.1. Analysis of correct trials

Like in Experiment 2: "Walking Corsi task" participants' Corsi spans were evaluated. This time the individual Corsi spans lay between 5.50 and 8.00 with an overall average of 6.75 (SD: ±0.78; see Tab. 5.1).

Table 5.1.: Participants' individual Corsi span and the mean Corsi span over all participants with standard deviation. Note: Participant 12 was excluded due to a failure in data recording.

P 1	**P 2**	**P 3**	**P 4**	**P 5**	**P 6**	**P 7**	
7.25	8.00	6.00	6.00	7.50	5.50	6.50	
P 8	**P 9**	**P 10**	**P 11**		**P 13**	**P 14**	**mean**
6.00	6.25	6.75	7.00		7.25	7.75	6.75 (SD: ±0.78)

As second analysis the percentage of correct trials of each participant was evaluated. In this experiment participants reached between 43 % and 75 % of correctly solved trials (see Fig. 5.3 a)).
Participants' mean performance in each sequence length decreased with increasing sequence length (see Fig. 5.3 b)). In the sequence lengths three and four 98.08 % (SD: each ±6.93) of correct trials were reached. In sequence length six still 76.92 % (SD: ±29.69) of the trials were reproduced correctly. In the higher sequence lengths (eight to ten) between 19 % and 23 % of the trials were solved properly. The overall mean over the thirteen participants and the 32 trials was 59.38 % (SD: ±34.82).

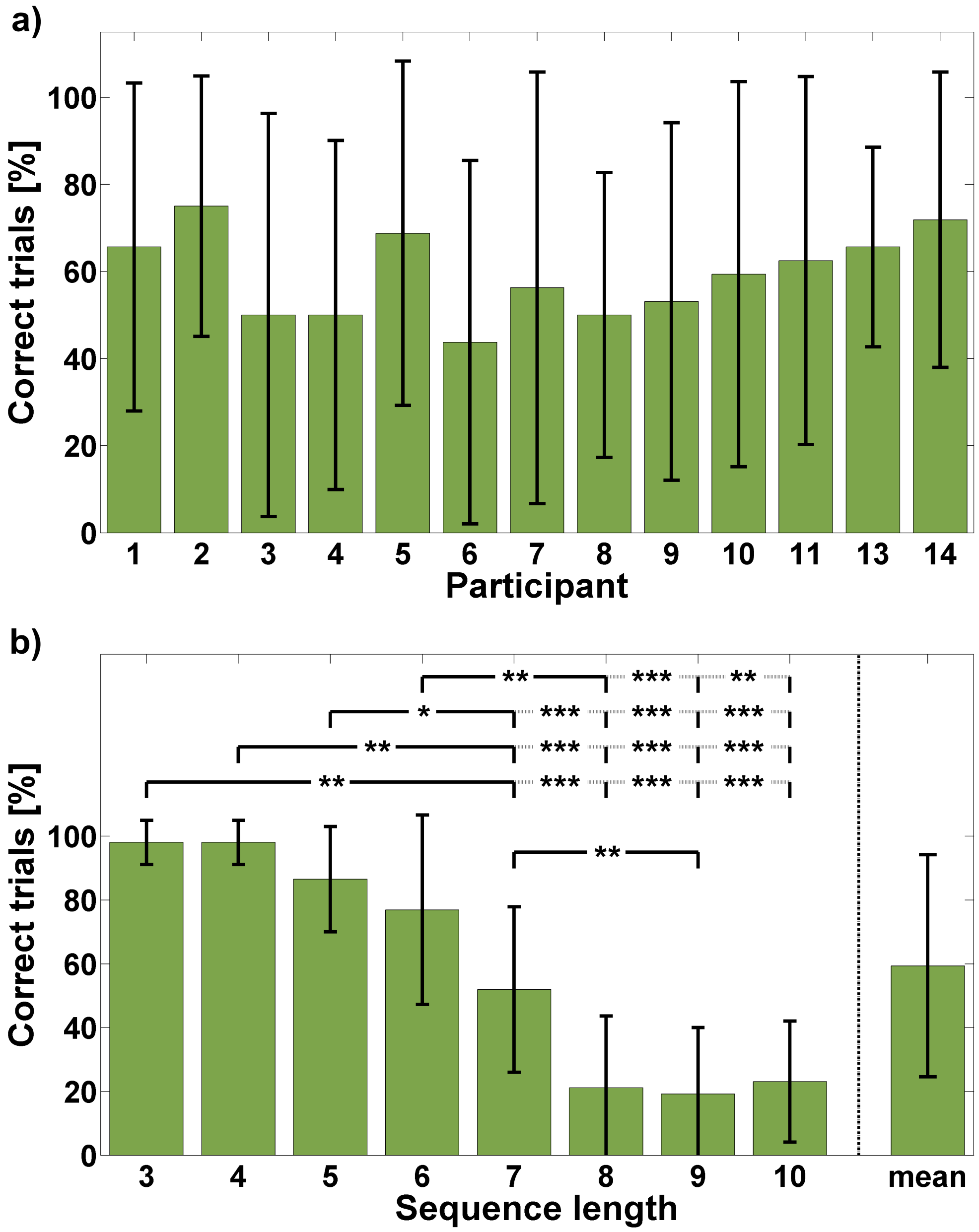

Figure 5.3.: Percentage of correct trials. a) For each of the thirteen participant (x-axis) the mean percentage of correct trials (y-axis) over all 32 trials is depicted. b) The mean percentage of correct trials over all thirteen participants (y-axis) is depicted for each sequence length (x-axis). With increasing sequence length the percentage of correct trials decreased. The shorter sequence lengths three to six differed significantly from the longer sequence lengths seven to ten, though there was no difference between the shorter sequence lengths and between the longer sequence lengths. The right bar depicts the overall mean over the thirteen participants and over the eight sequence lengths. Significant differences are depicted with stars. Note: For reasons of presentation the depiction of significant differences between sequence lengths are condensed. The dotted lines indicate the extension of the solid lines, e.g. sequence length three differed significantly from sequence length seven but differed also from the sequence lengths eight, nine and ten. Error bars indicate the standard deviation.

A one-way repeated measures ANOVA revealed a highly significant effect for the factor sequence length, showing that the percentage of correct trials decreased with increasing sequence length ($F(7, 84) = 44.742$, $p < 0.001$, $\eta_P^2 = 0.789$). A post hoc analysis showed highly significant differences between the sequence lengths three and eight to ten, four and eight to ten, five and eight to ten as well as between the sequence lengths six and nine (all $p < 0.001$). The sequence lengths three and seven, four and seven, six and eight, six and ten as well as seven and nine differed also significantly from each other ($p < 0.01$). Also for the comparison of sequence length five and seven a significant difference was found ($p < 0.05$; significant differences are depicted with stars in Fig. 5.3 b)). Between the other sequence lengths no differences were found.

5.2.2. Analysis of correct initial sequence length

After the percentage of correct trials the length of the correct initial sequence was evaluated. In this experiments participants' mean correct initial sequence length increased slightly with increasing sequence length from 2.98 (SD: ±0.07) in sequence length three to 5.31 (SD: ±1.11) in sequence length seven and remained similar then (see Fig. 5.4). The average over all eight sequence lengths amounted to 4.47 (SD: ±0.77) correctly reproduced square tiles from the beginning to the first error.

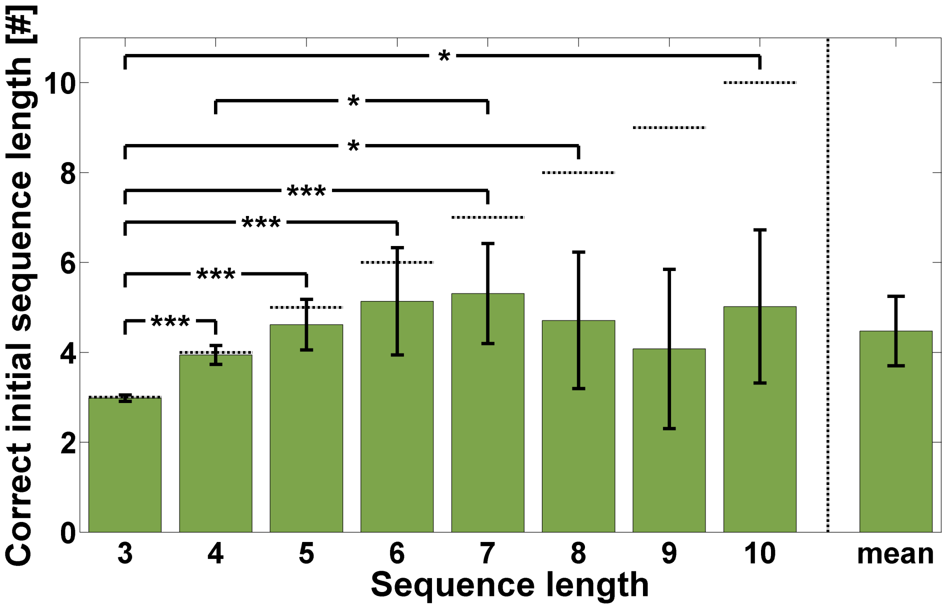

Figure 5.4.: Length of correct initial sequence. The length of the correct initial sequence averaged over all thirteen participants (y-axis) is depicted for each sequence length (x-axis). The correct initial sequence length increased slightly with increasing sequence length. The right bar shows the mean over all trials and participants. The horizontal lines indicate the maximum reachable number of correct initial sequence length. Significant differences are depicted with stars. Error bars indicate the standard deviation.

A one-way repeated measures ANOVA was conducted to analyze main effects for the factor sequence length. A violation of sphericity was indicated by a Mauchly test ($\chi^2(27) = 65.728$, $p < 0.001$), so a Greenhouse-Geisser correction ($\epsilon = 0.552$) was used for the residual analysis. The correct initial sequence length increased highly significant with increasing sequence length ($F(3.866, 43.395) = 6.60$, $p < 0.001$, $\eta_P^2 = 0.355$). A conducted post hoc analysis revealed highly significant differences between sequence length three and the sequence lengths four, five, six and seven (all $p < 0.001$; depicted with stars in Fig. 5.4). Sequence length three was also significantly different from sequence length eight and ten ($p < 0.05$). Sequence length four was significantly different from sequence length seven ($p < 0.05$). No differences between the other sequence lengths were observed.

5.2.3. Analysis of partial set correct

Next for this experiment the number of partial set correctly reproduced square tiles within a sequence was analyzed. The number of correctly recalled square tiles of the sequence, regardless of their order, increased from 2.98 (SD: ±0.07) square tiles in sequence length three to 8.42 (SD: ±0.54) square tiles in sequence length ten. Averaged over the 32 trials participants reproduced 5.67 (SD: ±1.77) partial set square tiles correctly (see Fig. 5.5).
A one-way repeated measures ANOVA was conducted and a Mauchly test indicated a violation of sphericity ($\chi^2(27) = 73.667$, $p < 0.001$), therefore Greenhouse-Geisser corrected values ($\epsilon = 0.465$) were used further on. The number of partial set correctly reproduced square tiles increased with increasing sequence length ($F(3.252, 39.019) = 236.844$, $p < 0.001$, $\eta_P^2 = 0.952$). Significant differences were found between sequence length six and seven, as well as six and eight (both $p < 0.05$), also the comparison between the sequence lengths seven and nine showed a significant difference ($p < 0.01$). All other sequence lengths differed highly significant from each other with $p < 0.001$. Only for the sequence lengths seven and eight and the sequence length eight and nine no differences were found.

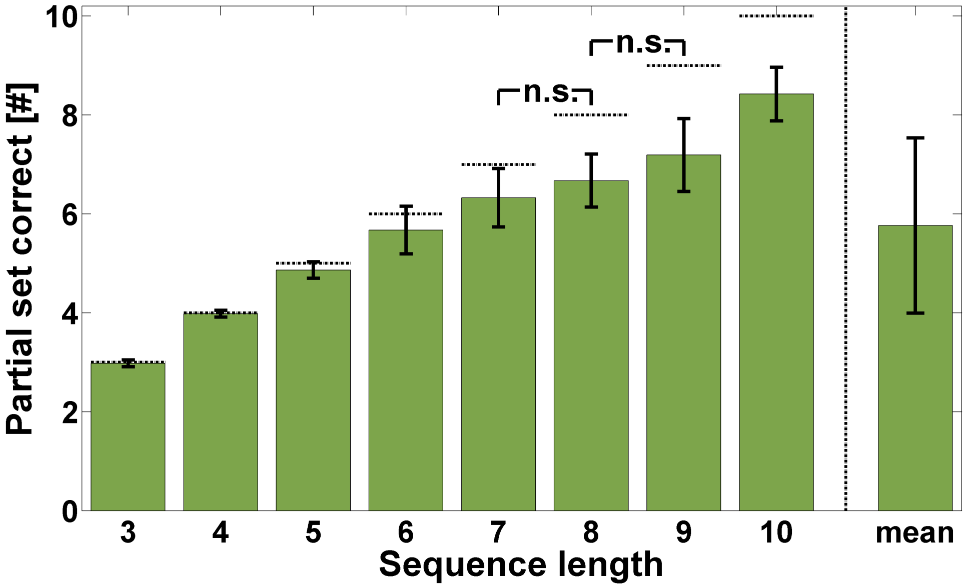

Figure 5.5.: Number of partial set correct. The number of partial set correctly reproduced square tiles averaged over the thirteen participants (y-axis) is shown for each sequence length (x-axis). The number of partial set correct square tiles increased over the sequence lengths. This increase was significant for all sequence lengths except for the sequence lengths seven and eight as well as the sequence lengths eight and nine. The right bar shows the mean over all sequence lengths and participants. The horizontal lines denote the maximum possible partial set correct squares. Error bars indicate the standard deviation.

5.2.4. Analysis of sequences

Again the sequences were evaluated for potential differences in pattern orientation, this means the orientation similar to the two starting positions in the former experiments. The sequences were orientated like Start 1 for 16 times and also for Start 2 for 16 times. With an orientation similar to Start 1 participants solved 57.21 % (SD: ± 36.73) of the trials correctly and with an orientation similar to Start 2 61.54 % (SD: ± 34.40) of the trials were solved properly. A conducted χ^2-test revealed no differences between the two pattern orientations.

5.2.5. Comparison between males and females

Once more the performance in this experiment was analyzed for gender differences. This was made for the factors percentage of correct trials, correct initial sequence length and partial set correctly reproduced square tiles. Like in Experiment 2: “Walking Corsi task” no difference between the genders was found for the three factors.

5.2.6. Comparison with Walking Corsi task

The results of this experiment were compared with the results of the percentage of correct trials, the correct initial sequence length and the number of partial set correct square tiles in Experiment 2: “Walking Corsi task” (p. 39 ff).
Since only thirteen participants were evaluated in the Corsi task, the comparisons between the two experiments were also done only for these thirteen participants; Participant 12 was excluded in the results of Experiment 2: “Walking Corsi task” for these comparisons, too.

Correct trials

The mean percentage of correct trials decreased in both experiments with increasing sequence length (see Fig. 5.6). In contrast to Experiment 2: “Walking Corsi task” participants reached in Experiment 3: “Corsi task” 98.08 % (SD: ± 6.93) in sequence lengths three and four and still 51.92 % (SD: ± 25.94) in sequence length seven. In contrast, in the Walking Corsi task about 60 % were reached in sequence lengths three and four and in sequence length seven the percentage of correct trials already decreased to 10.71 % (SD: ± 16.16). The sequence lengths eight to ten stayed about the same in both experiments but amounted to about 20 % in the Corsi task and about 10 % in the Walking Corsi task. The mean over all participants and sequence lengths was 23.56 % (SD: ± 24.43) in the Walking Corsi task and 59.38 % (SD: ± 34.82) in the Corsi task (see Fig. 5.6).
A conducted two-way repeated measures ANOVA showed a highly significant effect for the factor sequence length, which indicated a decrease of performance with increasing sequence length ($F(7, 84) = 58.043$, $p < 0.001$, $\eta_P^2 = 0.829$). The two experiments differed highly significant from each other with a better performance in the Corsi task ($F(1, 12) = 187.614$, $p < 0.001$, $\eta_P^2 = 0.94$) and an interaction between the factors experiment and sequence length was found ($F(7, 84) = 6.647$, $p < 0.001$, $\eta_P^2 = 0.356$).

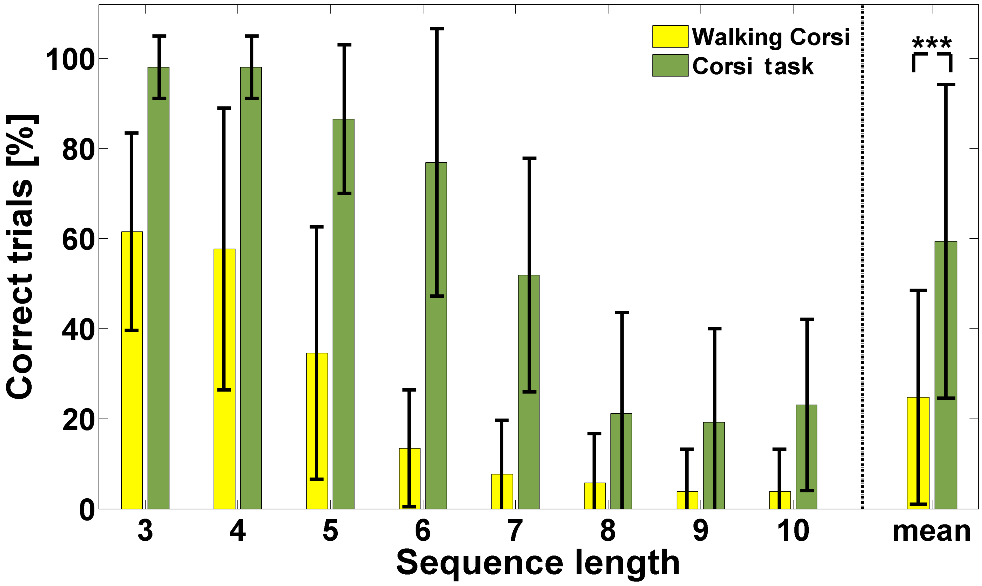

Figure 5.6.: Comparison between Walking Corsi task and Corsi task in percentage of correct trials. The mean percentage of correct trials averaged over the thirteen participants (y-axis) is shown for each sequence length (x-axis). For the Walking Corsi task as well as for the Corsi task the percentage of correct trials decreased with increasing sequence length. On the right the mean percentage averaged over thirteen participants and over all sequence lengths is depicted for both experiments. The percentage of correct trials was significantly different between the Walking Corsi task and the Corsi task (depicted with stars above the means) and there was an interaction between the two experiments and the sequence lengths. The percentages of correct trials of the Walking Corsi task are shown with yellow bars and the percentages of correct trials of the Corsi task are depicted with green bars. Error bars indicate the standard deviation.

Correct initial sequence length

Next, the number of the correctly recalled square tiles until the first error occurred, that is the length of the correct initial sequence, was compared. In the Walking Corsi task the mean length of the correct initial sequence (yellow bars in Fig. 5.7) remained equal at about three correctly reproduced square tiles in all eight sequence lengths. In contrast, the mean correct initial sequence length increased in the Corsi task to about five correctly recalled square tiles (green bars in Fig. 5.7). The overall mean in the Walking Corsi task was 2.91 (SD: ± 0.26) square tiles and in the Corsi task the total average amounted to 4.48 (SD: ± 0.77) square tiles (see Fig. 5.7).

A two-way repeated measures ANOVA was conducted to analyze the main effects for the factors sequence length and experiment. A Mauchly test indicated a violation of sphericity ($\chi^2(27) = 45.851$, $p < 0.05$) for the factor sequence length. Greenhouse-Geisser corrected ($\epsilon = 0.556$) values revealed a significant effect for the factor sequence length ($F(3.890, 46.678) = 3.733$, $p < 0.05$, $\eta_P^2 = 0.237$). A highly significant effect was found for the factor experiment ($F(1, 12) = 108.754$, $p < 0.001$, $\eta_P^2 = 0.901$) as well as an interaction between the factors experiment and sequence length was observed ($F(7, 84) = 4.115$, $p < 0.001$, $\eta_P^2 = 0.255$).

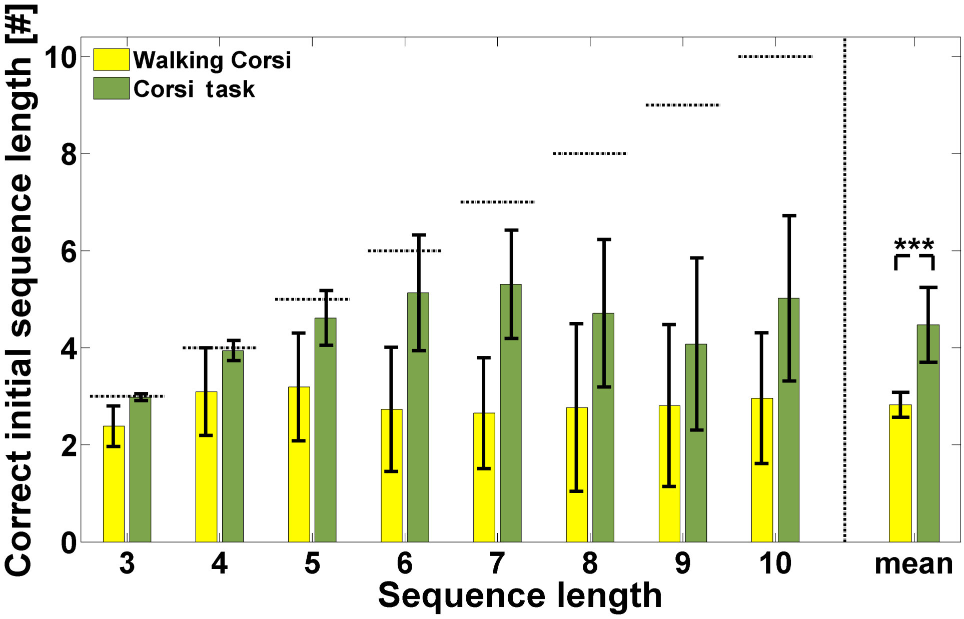

Figure 5.7.: Comparison between Walking Corsi task and Corsi task in correct initial sequence length. The average length of the correct initial sequence (y-axis) over thirteen participants is depicted for the eight sequence lengths (x-axis) for both experiments. In the Walking Corsi task the length of the correctly reproduced initial sequence stayed about the same for all sequence lengths (yellow bars). In the Corsi task (green bars) the length of the correct initial sequence increased slightly with increasing sequence length. For both experiments the overall mean over all participants and sequence lengths is shown by the right bars. The length of the correct initial sequence differed significantly between the Walking Corsi task and the Corsi task (depicted with stars above the means) and there was an interaction between the experiments and the sequence lengths. The horizontal lines denote the maximum possible number of correct initial sequence length. Significant differences are depicted with stars. Error bars indicate the standard deviation.

Partial set correct

As last comparison between the two experiments the number of partial set correct square tiles was investigated. In both experiments the mean number of partial set correct square tiles increased with increasing sequence length (see Fig. 5.8). In the Walking Corsi task the mean partial set correct number of the thirteen participants started with 2.55 (SD: ± 0.31) in sequence length three and increased over 4.64 (SD: ± 0.41) square tiles in sequence length six to 8.21 (SD: ± 0.54) partial set correct square tiles in sequence length ten. In the Corsi task participants started with a mean number of 2.98 (SD: ± 0.07) square tiles in sequence length three over 5.67 (SD: ± 0.48) square tiles in sequence length six to 8.42 (SD: ± 0.54) correctly reproduced square tiles regardless of their order in sequence length ten. The mean over all participants and sequence lengths amounted to 5.30 (SD: ± 1.94) in the Walking Corsi task and 5.76 (SD: ± 1.77) square tiles in the Corsi task.

Highly significant differences between the two experiments were revealed by a two-way repeated measures ANOVA ($F(1, 12) = 42.357$, $p < 0.001$, $\eta_P^2 = 0.779$). It revealed also a highly significant effect for the factor sequence length ($F(7, 84) = 349.092$, $p < 0.001$, $\eta_P^2 = 0.967$) and an interaction between the factors experiment and sequence length was found ($F(7, 84) = 4.876$, $p < 0.001$, $\eta_P^2 = 0.289$).

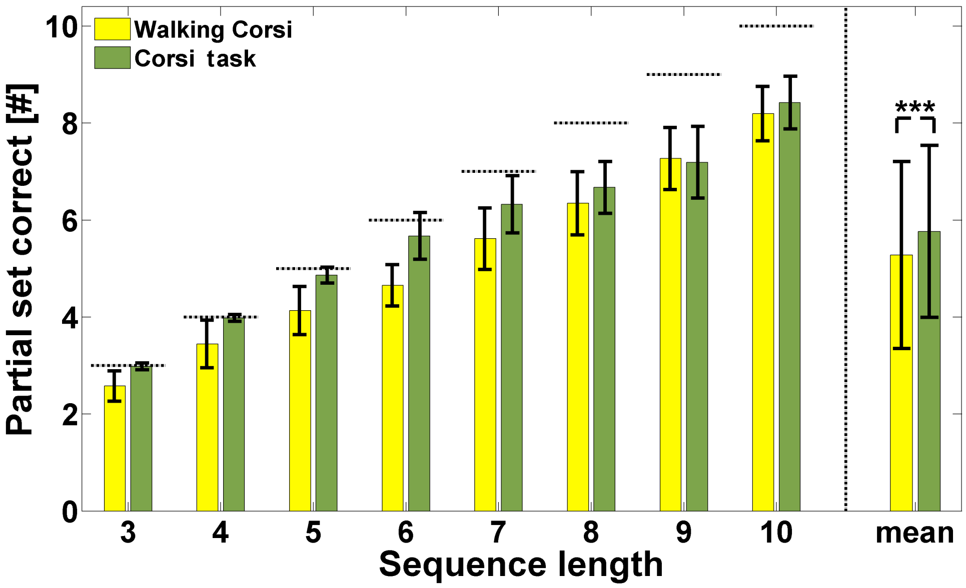

Figure 5.8.: Comparison between Walking Corsi task and Corsi task in number of partial set correct. For both experiments the mean number of partial set correctly reproduced square tiles (y-axis) increased with increasing sequence length (x-axis). The overall means over the thirteen participants and eight sequence lengths are depicted on the right. There was a significant difference between the mean number of partial set correctly reproduced square tiles in the Walking Corsi task and in the Corsi task (depicted with stars above the means). Also an interaction between the experiments and the sequence lengths was found. The yellow bars indicate the results of the Walking Corsi task, the green bars the results of the Corsi task. The horizontal lines denote the maximum possible number of partial set correct squares. Error bars indicate the standard deviation.

5.3. Discussion

In this experiment participants' performance in recalling a sequence was investigated, therefore, participants had to solve a computerized version of a Corsi task. This requires among others visuo-spatial and temporal working memory processes because the shown sequence had to be reproduced in the correct order. Also costs for finger tapping and holding posture will affect working memory capacity, though, this could not be distinguished from the costs required for the visuo-spatial and temporal working memory processes in this experimental design. Similar to the experiment before the visuo-spatial and temporal load on working memory was varied by increasing the length of the sequences participants had to memorize.

All participants were able to solve this version of a Corsi task. Again, the predicted decrease of performance with increasing sequence length was found (cf. Fig. 5.3 b), p. 69). Up to sequence length six the performance only slightly decreased, then a stronger decrease was found. In the higher sequence length (eight to ten) there was no difference in performance anymore. Participants had an overall performance of about 60 % of correctly solved trials. Once more this decrease of performance can be explained with the limited capacity of the working memory with three to five items (Cowan 2000) and therefore a loss of performance in higher sequence lengths. Similar results were also found in the studies of Fischer (2001), Cornoldi & Mammarella (2008) and Busch et al. (2005), though for the latter one not in a

computerized but a classical version of the Corsi task.
The Corsi span reached by the participants in this experiment amounted to 6.75. This value was better than the Corsi span of about four which was reached in the Walking Corsi task in the previous experiment and it was also better than the Corsi span of about five which Corsi (1972) and Orsini et al. (1987) described in their studies. A reason for this difference could be that in their studies a classical version was used, meaning the sequence was shown by an experimenter on wooden blocks. In contrast to this 3D-presentation, here, the sequences were shown on a screen, which means in 2D and without further spatial (depth) information. Though, Monaco et al. (2013) reported in their study with a classical version of the Corsi task a Corsi span of almost six for participants aged between 20 and 40 years. Kessels et al. (2000) found a Corsi span of about six for a classical Corsi version, too. Again, the differences to these studies could be the result of different experimental designs, this means the pattern configuration as well as the used sequences and the different methods of calculating the Corsi span.

Like for the Walking Corsi task the correct initial sequence length was evaluated in this experiment, too. An increase of the correct initial sequence length was found up to a sequence length of six, for the longer sequence lengths the length of the correct initial sequence remained the same with a length of about five (cf. Fig 5.4, p. 70). This value is in line with the limited working memory capacity of three to five items (Cowan 2000).
In the analysis of the partial set correctly reproduced square tiles the temporal factor of the task was eliminated. The number of partial set correct square tiles increased up to about eight remembered squares in sequence length ten (cf. Fig. 5.5, p. 71). Similar to Experiment 2, the possibility to click randomly on one square which was included in the sequence was 66.7 % in sequence length ten. So again participants had a good chance to select a square tile randomly if they were not completely sure, which was the next square of the sequence. Equally to Experiment 2 the result of partial set correct squares is contrary to the results reported by Zimmer et al. (2003).

Similar to the two starting positions in Experiment 1 and Experiment 2, in this experiment the two orientations of the pattern configuration were evaluated for potential differences. Like in Experiment 2 no difference between the pattern orientations similar to Start 1 and Start 2 was found. Since the pattern configurations were presented on a screen no external cues, which could facilitate the one or the other pattern configuration should be present and therefore it was not expected to find any differences between the two pattern orientations.

Like in Experiment 2 the comparison between male and female participants revealed no differences between the genders for the three factors percentage of correct trials, length of the correct initial sequence as well as for partial set correctly reproduced square tiles. This is in line with the findings of e.g. Kessels et al. (2000), Pagulayan et al. (2006) and Monaco et al. (2013); they also found no difference between genders in a classical version of the Corsi task.

Comparison with Walking Corsi task

In this experiment participants were asked to solve a computerized version of the Corsi task, whereas in Experiment 2 participants were asked to solve a walking version of the Corsi task. It was hypothesized that participants would have a better performance in the computerized version compared to the walking version since most of the working memory loads caused by reference frame transformations (from screen to floor) and walking (e.g. spatial updating, mental rotation, walking itself) were eliminated in the experimental design and most of the available working memory resources can be used for solving the task. Though, some additional working memory loads caused by, among others, finger tapping and posture control were still existing in this experiment.

The percentage of correct trials decreased in both experiments with increasing sequence length (cf. Fig. 5.6, p. 73). Furthermore, a difference of performance between the experiments and an interaction between the experiments was found. As predicted the performance in the Corsi task was better than in the Walking Corsi task. The interaction between the two experiments should be caused by the faster decrease in the shorter sequence lengths in the Walking Corsi task compared to the Corsi task. The better performance in the Corsi task is not unexpected because there were less additional working memory loads compared to the walking version and so more working memory resources were available for solving the task.
Though, it has to be admitted that participants always solved the walking version before the computerized version because of measuring reasons. Since the same sequences were used in both tasks it cannot be ruled out that participants reached a better performance in the computerized version because of an advantage of solving the sequences a second time. However, later in Experiment 5 (p. 107 ff) a randomized order between the walking and the computerized versions was chosen and they showed the same results found here.

In the Walking Corsi task participants reached a Corsi span of about four and in the Corsi task a span of 6.75. This result is contrary to Piccardi et al. (2010). In their study no difference between the Corsi spans of healthy adults in a classical version (not a computerized one) and a walking version of a Corsi task was found. Though, in another study of 2008 Piccardi et al. could show that participants had a higher Corsi span and also a better total performance in the walking version of the Corsi task compared to a classical version. Both of these studies have different results than the results found here. Piccardi et al. described in their study of 2008 that participants reported they were "joining the squares covered by the examiner", while the examiner walked the sequence to remember on a carpet and "visualizing a pathway on the carpet" (Piccardi et al. 2008). No such visualization was done in the classical Corsi task, but this visualization could facilitate solving the walking version. In the Walking Corsi task used in this experiment no experimenter walked the sequence but it was shown on a screen and was presented the same way as the computer version. Therefore, unlike in Piccardi et al.'s experiment, no advantage of presentation for one version, which could have helped to memorize the sequence was provided here.
In a study by Perrochon et al. (2014) participants solved an electronic version of a Corsi task (but not a computerized one), in which the sequences were presented by illuminating blocks of a Corsi board and a walking version of the Corsi task. They found a Corsi span of 6.2 in the electronic version and a Corsi span of 5.3 in the walking version. The Corsi span in the electronic version was slightly lower than the one found for the Corsi task in this experiment (Corsi span: 6.75), though, the Corsi span of 5.3 in their walking version was better than the Corsi span of about four in the Walking Corsi task. Nevertheless, Perrochon et al. also reported a poorer performance in the walking version, similar to the results found here for the comparison between the Corsi task and the Walking Corsi task.

The comparison of the length of the correct initial sequence revealed a highly significant difference between the two experiments (cf. Fig. 5.7, p. 74). For the Walking Corsi task the length remained about the same over all sequence lengths, whereas the length of

the correct initial sequence in the Corsi task increased in the lower sequences to a length of about five squares, which is once more in line with the capacity limit of the working memory. Not only a difference between the experiments but also an interaction between the factors experiment and sequence length was found. The interaction could be a result of the different courses of the initial sequence length over the sequence lengths.
The last comparison between the experiments was made for the partial set correctly reproduced square tiles. In both experiments the number of partial set correctly reproduced square tiles increased with increasing sequence length (cf. Fig. 5.8, p. 75), though, a highly significant difference between the experiments and also an interaction between the factors experiment and sequence length was found. In the lower sequence lengths the number of partial set correct square tiles was higher in the Corsi task, but in the longer sequence lengths both experiments had about the same number, which can also be seen in Fig. 5.9 c).

For analyzing possible interactions between the short and the long sequence lengths similar to Experiment 2 the means of the shortest (three and four) and the longest (nine and ten) sequence lengths were investigated further. This was done for the percentage of correct trials and also for the length of the correct initial sequence as well as for partial set correctly reproduced square tiles (see Fig. 5.9). For the correct initial sequence length and also the number of partial set correct squares this analysis was made in percent, too, for having better comparisons.
For the percentage of correct trials in both experiments a decrease was found (see Fig. 5.9 a)). In the Corsi task participants had a better performance than in the Walking Corsi task, but the decrease between the short and the long sequence lengths was larger in the Corsi task.
The decrease of the correct initial sequence length is about parallel in both experiments but with a better performance in the Corsi task (see Fig. 5.9 b)).
For the number of partial set correct square tiles participants reached a performance of 100 % in the short sequence lengths of the Corsi task. This performance decreased to about 85 % in the long sequence lengths. In contrast, participants had a performance of about 85 % in the Walking Corsi task, this value was the same for the short and the long sequence lengths (see Fig. 5.9 c)).

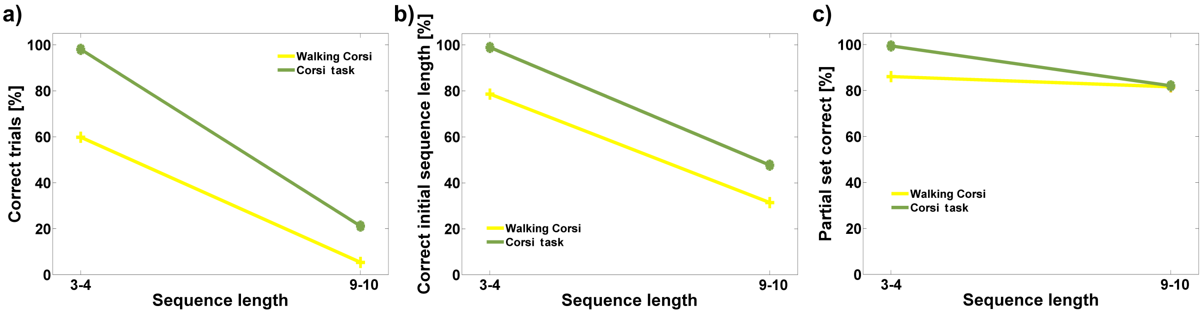

Figure 5.9.: Interaction plots for the percentage of correct trials (a), the correct initial sequence length (b) and partial set correct remembered square tiles (c). For all subplots the mean performance in percent (y-axis) of thirteen participants in the sequence lengths three and four and nine and ten (y-axis) is shown for the Walking Corsi task (yellow lines) and the Corsi task (green lines). In a) both experiments showed a decrease in performance, though the Corsi task had a stronger decrease than the Walking Corsi task. Nevertheless, the performance in the Corsi task was always better than in the Walking Corsi task. In b) both experiments had a similar decrease of performance (almost parallel lines), again with a better performance in the Corsi task. c) The Walking Corsi task had almost no change in performance. The Corsi task showed a decrease in performance over the sequence lengths. Here for none of the shown factors an interaction between the experiments was found.

The results of the percentage of correct trials, the length of the correct initial sequence as well as the number of partial set correct square tiles are all in line with the hypothesis that participants' performance is better in the Corsi task compared to the Walking Corsi task. They also showed that the available resources of working memory had to be split up between the different requirements for task solving, e.g. reproducing the sequence in both tasks, as well as spatial updating, reference frame transformation and walking itself in the walking version, and finger tapping and holding posture in the computerized version. In the walking version more additional demands required working memory resources and thus this splitting between the available resources resulted in a poorer performance in the Walking Corsi task compared to the Corsi task.

Conclusion

Again, the results of the Corsi task revealed a decrease of performance with increasing sequence length which was caused by additional working memory load in the longer sequences. With the last two experiments, it could be shown that reference frame transformations, spatial updating and walking itself cause additional demands on working memory because participants' performance in the walking version of the Corsi task was lower than in the computerized version. Though, the respective amounts of the factors could not be differentiated with these two experiments and will be addressed further in Experiment 5: "Corsi task in different modality conditions" (p. 107 ff). Nevertheless, the results show that walking is not a completely automated process but requires working memory resources.

Since the shown sequences have to be reproduced in the correct order in a Corsi task the temporal demands on working memory play a role in this task. To get a better understanding of the influence of the temporal factor on the working memory resources this factor will be investigated further in the next experiment with a Pattern Copying task.

6. Experiment 4: Pattern Copying task

In Experiment 3 it was shown once more that the performance decreased with increasing sequence length and therefore additionally required visuo-spatial and temporal resources of working memory.
In this experiment the temporal factor of memorizing a sequence should be eliminated. For that purpose the squares to memorize will not be shown one by one to the participants on a computer screen in the encoding phase, but all squares will be shown at the same time (Pattern Copying task). Presenting the squares of the sequence or pattern simultaneously would lead to an advantage in time, because the squares would have to be kept in mind shorter compared to presenting the squares one after another and therefore should require less working memory resources for e.g. rehearsal processes. To rule out such an advantage the squares of the sequence will be shown as long as it would be needed to present the squares one by one.
For having a within-subject setup again, participants have to solve a Pattern Copying task and also a Corsi task equally to Experiment 3. The working memory costs will be again varied by increasing the number of squares which have to be memorized.
It is supposed that the performance in the Copying task will be better than in the Corsi task, since there is no additional temporal factor which requires working memory resources, but the visuo-spatial demands on working memory should be similar to the ones of the Corsi task. Further it is presumed that the performance will decrease with increasing sequence length but will increase again in the longest sequences due to a possible strategy change in solving the task. Since the capacity of the working memory is limited to about five items, in the longer sequence lengths it should be easier to memorize the squares, which were not part of the pattern, instead of memorizing the squares included in the pattern. This should result in an increase of performance in the longer sequence lengths.

6.1. Material and methods

6.1.1. Participants

In this experiment fifteen participants took part, however, one of them had to be excluded due to measurement errors. Thus, the data of fourteen participants, eight males and six females, were evaluated. All of the participants were bachelor or master students who attended the practical course “Spatial Cognition” which was hold at the chair of “Cognitive Neuroscience”. The participants’ age was estimated to be between 20 and 30 years.

6.1.2. Experimental setup and design

The experiment was carried out in the seminar room of the chair “Cognitive Neuroscience” by all fourteen participants at the same time. In contrast to the other experiments, this experiment was not carried out under dimmed light conditions. Participants had to solve a Corsi task and a Pattern Copying task (also called Copying task; see Fig. 6.1). The presentation of the sequences in the Corsi task was identical to Experiment 3: “Corsi task” (p. 65 ff). In contrast to Experiment 3 participants did not get feedback in this experiment. After each mouse click into a square a green circle appeared in this square whether it was the correct one or not. If participants did not click into a square but next to one on the black background the whole pattern configuration was lit up red for 1.5 s. For pattern presentation in the Copying task the same configuration of the square tiles as in the previous experiments was used, though, the presentation of the squares was not one by one but all squares were presented simultaneously (see Fig. 6.1 right).

Most of the participants solved the tasks on the personal computers of the seminar room with MATLAB version 2013a and Psychtoolbox 3 running on it. Some of the participants used their own laptops.

The configuration of the fifteen squares was the same as in the other experiments. On the personal computers the squares covered a visual angle of 2.5° and had a size of 80 x 80 pixels. On the laptop screens they covered about 2° of visual angle and had a size of 100 x 100 pixels because of a different screen resolution.

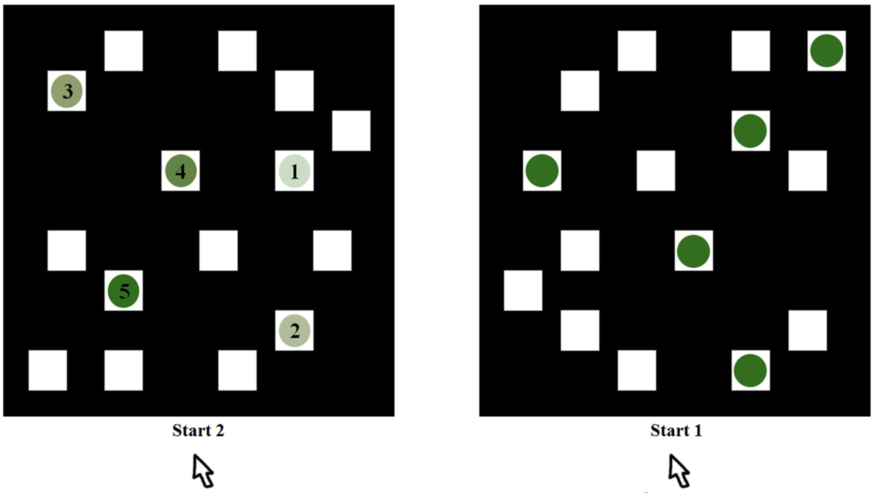

Figure 6.1.: Experimental setup. Configuration of the fifteen square tiles. Both configurations are identical but rotated by 180°. The squares covered a visual angle of 2.5° (80 x 80 pixels) on the computer screen and 2° of visual angle (100 x 100 pixels) on the laptop screen. Left: An example sequence with a length of five squares is depicted for the Corsi task. The numbers in the green circles and the color gradient from lightest (first) to darkest (last) green specify the position of the squares in the sequence. Right: An example sequence with a sequence length of five (green circles) for the Pattern Copying task is shown. All five squares were highlighted at the same time for 10 s (2 s per square). The mouse cursors indicate the starting position, but were, just like the numbers at the starting positions, not visible for the participants.

6.1.3. General procedure

The experiment took place within the frame of the practical course “Spatial Cognition” within the topic spatial working memory. Half of the participants started with the Corsi task, the other half with the Pattern Copying task. For analyses participants’ mouse clicks were recorded. In both conditions participants started with a sequence length of three and ended with a sequence length of ten. The sequence lengths increased after each fourth trial and like in the other experiments 32 trials had to be solved.

Corsi task. Participants started with a practice trial of three squares to remember. After they reproduced the sequence by clicking with the mouse cursor in the squares they started the experiment by pressing the space bar. Before each trial the length of the upcoming sequence was shown on the screen. Each trial ended when the number of mouse clicks was equal to the length of the sequence. Like in Experiment 3 a time delay between two consecutive mouse clicks was implemented. In contrast to Experiment 3, in this experiment the time delay was not calculated by the individual walking speed of each participant in each sequence length because there was not enough time to measure all individual walking speeds within the practical course. Hence, for the separate time delays in the different sequence lengths the averaged walking speeds of all participants of Experiment 3 in the respective sequence lengths were used. After each trial participants had to click with the right mouse button to continue the experiment; so they were able to have a break between two trials whenever they wanted. Participants received no feedback about their performance. The sequences participants had to reproduce were the same as in Experiment 3 (see appendix Fig. B.1 to Fig. B.4, p. 185 ff). The end of the task was indicated by a notice on the screen. For more detailed information on the procedure see Experiment 3: “Corsi task”, subsection 5.1.3 “General procedure” (p. 67).

Pattern Copying task. In contrast to the Corsi task, here, the squares were not marked one after another but all squares to remember were highlighted at the same time. The task started with a practice trial of three squares, all three squares were marked with a green circle centered in the squares at the same time for 6 s. The display duration depended on the number of squares which were highlighted at once. For each shown circle the duration was increased by 2 s. Thus, in sequence length three the squares were marked for 6 s and in sequence length ten for 20 s. After that the screen went black and the instruction to click into the marked squares was shown. This instruction was shown for 2 s. After that, the configuration of squares reappeared and participants were able to click into the squares. Like in the Corsi task the mouse cursor here also disappeared for the time participants would have needed to walk the distance between the starting position to the first square or from a square to the next one. The time delay for each sequence length was calculated with the averaged walking speed of the participants from Experiment 3 in this sequence length. Each trial ended when the number of mouse clicks was identical to the shown sequence length. The next trial was started by pressing on the right mouse button. The task was finished after 32 trials (4 repetitions x 8 sequence lengths). The highlighted squares in this task were the same squares which were also used for the sequences in the Corsi task, though, the order of the trials in each sequence length was changed.

6.1.4. Analysis

The analyses of the Corsi task were identical to the analyses of Experiment 3: “Corsi task” (p. 65 ff). This means a) the number of correct trials and the Corsi span, b) the correct initial sequence length and c) the number of partial set correct square tiles were evaluated. Likewise for the Pattern Copying task a) the number of correct trials and the Copy span (see below), b) the length of the correct initial sequence and c) the number of partial set correct square tiles were analyzed, too.

6.2. Results

Corsi task

Again, participants' mouse clicks were measured in this experiment, two of these click patterns are shown in Fig. 6.2.

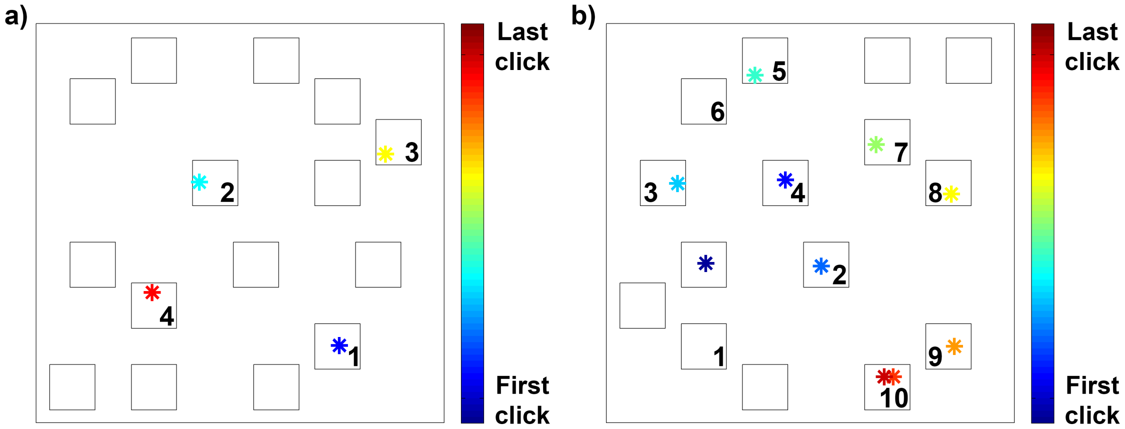

Figure 6.2.: Click patterns. a) A correctly solved click pattern of a short sequence (four squares) is shown. The orientation of the squares is identical to trials beginning at Start 2 in the experiments 1 and 2. b) A long sequence (ten squares) is depicted. This sequence was not reproduced correctly. The orientation of the squares is identical to Start 1 in the previous experiments. In both figures the numbers in the squares tag the order of the squares in the shown sequence. The color gradient indicates the order of the clicks, blue stars mark early clicks and red stars late clicks.

6.2.1. Analysis of correct trials

As in the previous experiments the analysis began with investigating participants' Corsi spans (see Tab. 6.1). The fourteen participants had Corsi spans between 5.50 and 8.75, which resulted in an average Corsi span of 6.71 (SD: ± 0.99).

Table 6.1.: Participants' Corsi spans and the mean Corsi span over all participants with standard deviation.

P 1	P 2	P 3	P 4	P 5	P 6	P 7
5.75	6.00	6.75	7.50	7.50	5.75	6.25

P 8	P 9	P 10	P 11	P 12	P 13	P 14	mean
6.25	5.75	5.50	7.50	6.75	8.00	8.75	6.71 (SD: ±0.99)

The individual percentage of correct trials was between 43.75 % (SD: ± 43.81) and 84.38 % (SD: ± 26.52) for the fourteen participants (see Fig. 6.3 a)). The mean performance of the participants (see Fig. 6.3 b)) decreased with increasing sequence length from 94.64 % (SD: ± 10.65) in sequence length three over 78.57 % (SD: ± 21.61) and 55.36 % (SD: ± 29.71) in the sequence lengths six and seven to 17.86 % (SD: ± 28.47) in sequence length ten. The total average amounted to 58.93 % (SD: ± 33.75; see Fig. 6.3 b)) of correctly solved trials.

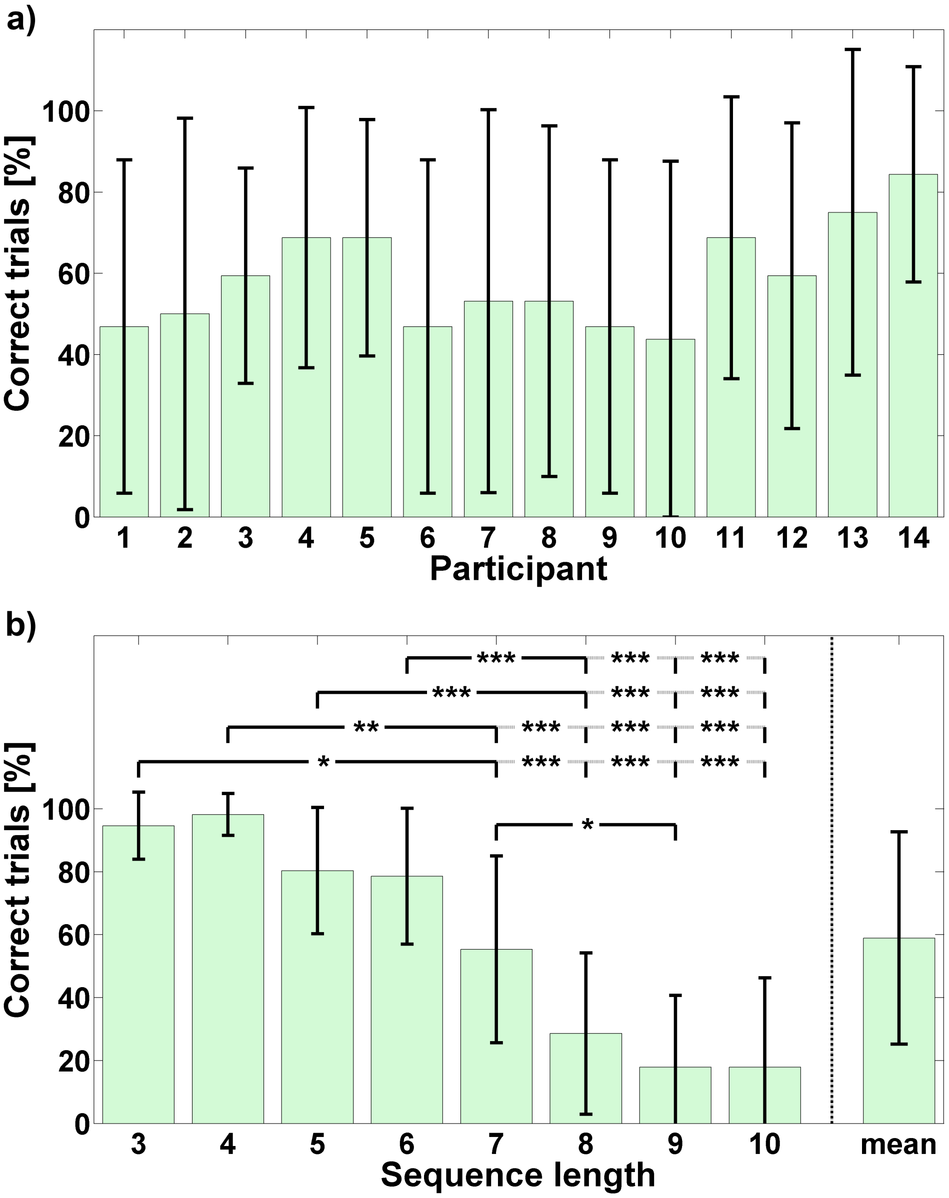

Figure 6.3.: Percentage of correct trials. a) For each of the fourteen participants (x-axis) the mean percentage of correct trials (y-axis) over all 32 trials is depicted. b) The mean percentage of correct trials over all fourteen participants (y-axis) per sequence length (x-axis) is shown. With increasing sequence length the percentage of correct trials decreased. The shorter sequence lengths three to six showed significant differences to the longer sequence lengths seven to ten. There was no difference between the shorter sequence lengths and also the longer sequence lengths did not differ among each other. The right bar depicts the percentage of correct trials averaged over participants and trials. Significant differences are depicted with stars. Note: For reasons of presentation the depiction of significant differences between sequence lengths are condensed. The dotted lines indicate the extension of the solid lines, e.g. sequence length three differed significantly from sequence length seven but differed also from sequence lengths eight, nine and ten. Error bars indicate the standard deviation.

A one-way repeated measures ANOVA revealed a highly significant effect for the factor sequence length (F(7, 91) = 41.881, $p < 0.001$, $\eta_P^2 = 0.763$). The percentage of correct trials decreased with increasing sequence length. A conducted post-hoc analysis revealed a significant difference between sequence length three and sequence length seven ($p < 0.05$). Sequence length three also differed from the sequence lengths eight to ten (all $p < 0.001$; see depicted stars in Fig. 6.3 b)). For sequence length four significant differences were found with sequence length seven ($p < 0.01$) and also with the sequence lengths eight to ten (all $p < 0.001$). Sequence lengths five and six both showed highly significant differences to the sequence lengths eight, nine and ten (all $p < 0.001$). Further, sequence length seven differed significantly from sequence length nine ($p < 0.05$). No differences between the shorter sequence lengths (three to six) as well as between the longer sequence lengths (eight to ten) were found.

6.2.2. Analysis of correct initial sequence length

After the percentage of correct trials the correctly reproduced square tiles from first click to first error were evaluated (that is “correct initial sequence length”; see Fig. 6.4). In sequence length three participants had a mean correct initial sequence length of 2.91 (SD: ± 0.21) squares. The correct initial sequence length increased from sequence length three to six in which participants reached 5.84 (SD: ± 0.55) correctly recalled square tiles. Overall an average of 4.30 (SD: ± 0.76) correctly reproduced square tiles for the initial sequence length was reached by the fourteen participants in 32 trials (see Fig. 6.4 right bar).

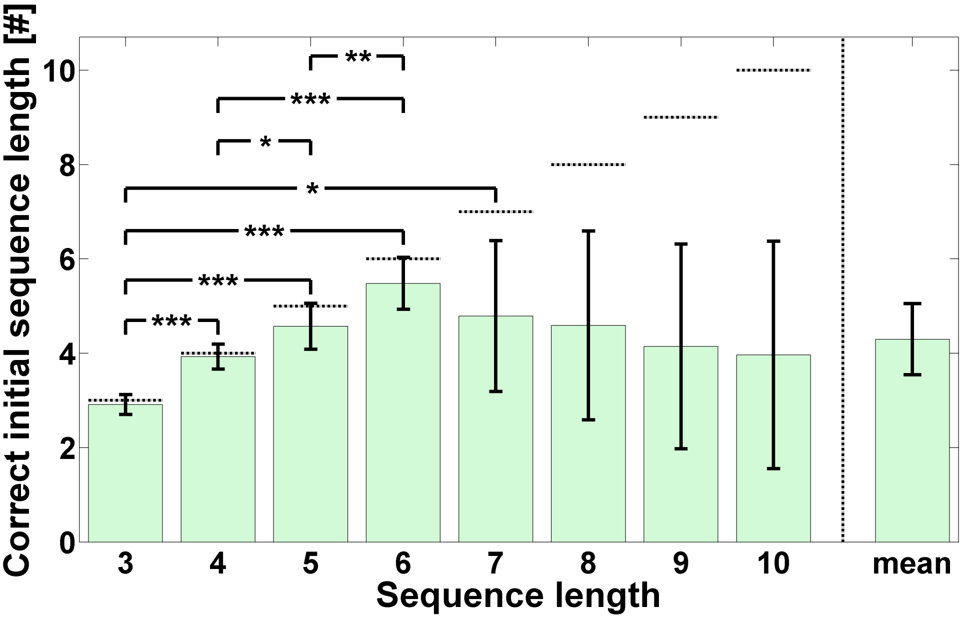

Figure 6.4.: Length of the correct initial sequence. The length of the correct initial sequence averaged over all fourteen participants (y-axis) is depicted for each of the eight sequence lengths (x-axis). The correct initial sequence length increased with increasing sequence length up to sequence length six. The higher sequence lengths (seven to ten) showed no difference between each other. The right bar shows the mean over all trials and participants. The horizontal lines indicate the maximum possible length of the correct initial sequence. Significant differences are depicted with stars. Error bars indicate the standard deviation.

A one-way repeated measures ANOVA was conducted. A Mauchly test indicated a violation of sphericity ($\chi^2(27) = 84.064$, $p < 0.001$) so Greenhouse-Geisser ($\epsilon = 0.432$) corrected values were applied for further analysis. A significant effect was found for the factor sequence length ($F(3.024, 39.306) = 4.340$, $p < 0.05$, $\eta_P^2 = 0.250$). A post-hoc analysis showed highly significant differences between sequence length three with the sequence lengths four to six (all $p < 0.001$; see also depicted stars in Fig. 6.4). Sequence length three also differed from sequence length seven ($p < 0.05$). Sequence length four differed from sequence length five ($p < 0.05$) and sequence length six ($p < 0.001$). A significant difference was also found between the sequence lengths five and six ($p < 0.01$). There was no difference between the other sequence lengths.

6.2.3. Analysis of partial set correct

The next analysis of this experiment was the evaluation of the partial set correctly recalled square tiles. With increasing sequence length the number of square tiles, which were reproduced correctly regardless of their order, increased (see Fig. 6.5). In sequence length three an average of 2.95 (SD: ± 0.11) partial set correct square tiles was reached by the fourteen participants. In sequence length seven the number of partial set correct was 6.66 (SD: ± 0.35) and 9.00 (SD: ± 0.65) square tiles were remembered partial set correctly in sequence length ten. This resulted in 6.06 (SD: ± 2.06) partial set correctly recalled square tiles averaged over all participants and sequence lengths.

Again a one-way repeated measures ANOVA was conducted. A Mauchly test indicated a violation of sphericity ($\chi^2(27) = 56.130$, $p < 0.01$) and a Greenhouse-Geisser correction ($\epsilon = 0.406$) was used furthermore. A highly significant increase of the length of partial set correct squares over the sequence lengths was observed ($F(2.845, 36.980) = 540.967$, $p < 0.001$, $\eta_P^2 = 0.977$). A post-hoc analysis revealed a significant difference between sequence length seven and eight ($p < 0.01$). All other sequence lengths differed highly significant ($p < 0.001$) from each other.

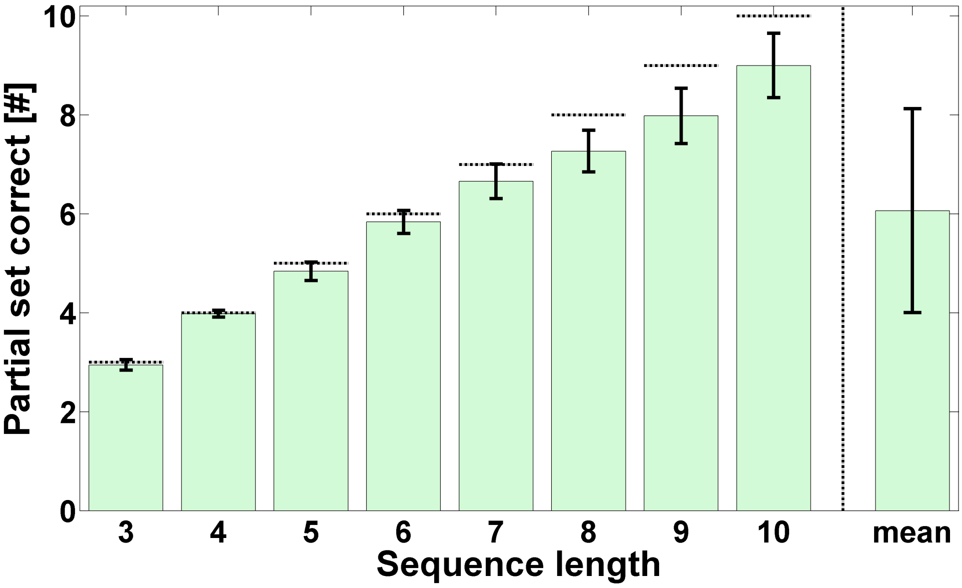

Figure 6.5.: Number of partial set correct. The number of partial set correctly reproduced square tiles averaged over the fourteen participants (y-axis) is shown for each sequence length (x-axis). The mean number of partial set correctly reproduced square tiles increased with increasing sequence length. All sequence lengths differed significantly among each other. Note: For reasons of presentation this differences are not depicted with stars. The right bar shows the mean over all sequence lengths and participants. The horizontal lines denote the maximum possible number of partial set correct squares. Error bars indicate the standard deviation.

6.2.4. Analysis of sequences

Again, the sequences were evaluated for differences in pattern orientation. Each of the two pattern orientations was used in 16 trials. For a pattern orientation similar to beginning at Start 1 participants solved 55.36 % (SD: ± 36.47) of the trials correctly. For a pattern orientation similar to Start 2 62.50 % (SD: ± 31.79) were solved properly. There was no difference between the two pattern orientations as a χ^2-test showed.

6.2.5. Comparison between males and females

The results of the percentage of correct trials, the length of the correct initial sequence and the partial set correctly recalled square tiles were compared between the two groups males, with eight participants, and females, with six participants. In none of the three factors a difference in performance between the two groups was observed.

6.2.6. Comparison with Corsi task 1

Like in the experiments before the results were compared with another experiment, in this case with Experiment 3: "Corsi task". For clarification the Corsi task solved in Experiment 3 will be called "Corsi task 1" for this comparison and the Corsi task solved in this experiment will be called "Corsi task 2". In Corsi task 1 thirteen participants attended and in Corsi task 2 fourteen participants took part.

Correct trials

The first comparison between the two experiments was the percentage of correctly solved trials by the participants (see Fig. 6.6). In both experiments the percentage of correct trials decreased with increasing sequence length, starting with 98.08 % (SD: ± 6.93) in Corsi task 1 and 94.64 % (SD: ± 10.65) in Corsi task 2 in sequence length three. In sequence length seven participants reached 51.92 % (SD: ± 25.94) in Corsi task 1 and 55.26 % (SD: ± 29.71) of correct trials in Corsi task 2 and in sequence length ten the percentage of correct trials amounted to 23.08 % (SD: ± 18.99) in Corsi task 1 and to 17.86 % (SD: ± 28.47) in Corsi task 2. The mean over all trials and participants amounted to 59.38 % (SD: ± 34.82) in Corsi task 1 and to 58.93 % (SD: ± 33.75) in Corsi task 2 (see Fig. 6.6 right bars).
A two-way ANOVA with repeated measures on one factor (sequence length) was conducted. For the factor sequence length a Mauchly test indicated a violation of sphericity ($\chi^2(27) = 50.258$, $p < 0.01$) and therefore a Greenhouse-Geisser correction ($\epsilon = 0.692$) was used for further analysis. A highly significant effect for the factor sequence length was observed (F(4.844, 121.108) = 85.974, $p < 0.001$, $\eta_P^2 = 0.775$), showing that the performance decreased with increasing sequence length. The comparison between the two experiments showed no difference (F(1, 25) = 0.011, $p = 0.918$, $\eta_P^2 = 0.00$) and there was no interaction between the two factors sequence length and experiment.

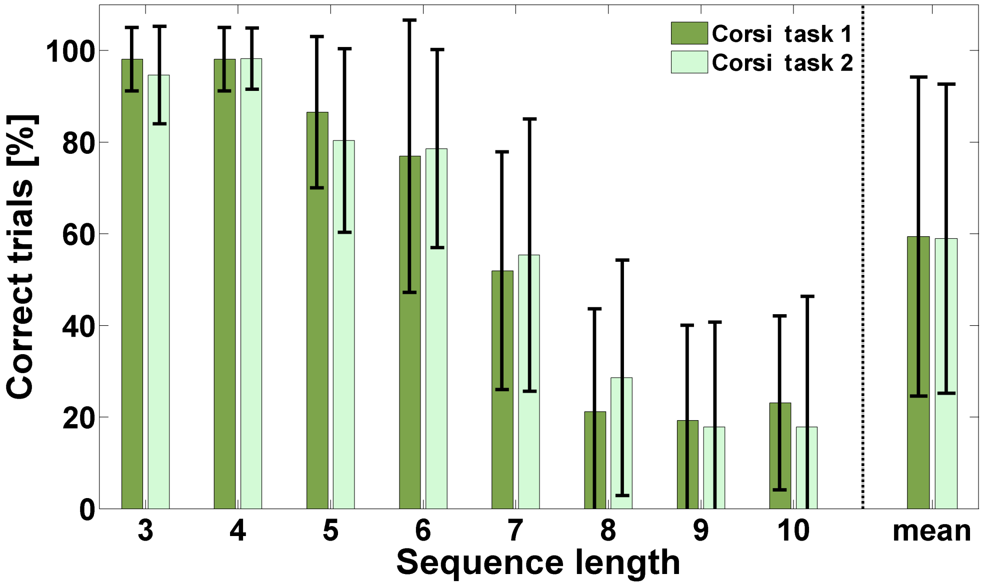

Figure 6.6.: Comparison between Corsi task 1 and Corsi task 2 in percentage of correct trials. For each sequence length (x-axis) the mean percentage of correct trials (y-axis) averaged over the thirteen participants in Corsi task 1 and fourteen participants in Corsi task 2 is depicted. In both experiments the percentage of correct trials decreased with increasing sequence length. There was no difference between the experiments. The mean percentage averaged over all participants and sequence lengths is shown on the right for both experiments. Green bars depict the percentage of correct trials of Corsi task 1 and mint green bars the percentage of correct trials of Corsi task 2. Error bars indicate the standard deviation.

Correct initial sequence length

After the percentage of correct trials the length of the correct initial sequence was compared (see Fig. 6.7). The number of correctly reproduced square tiles until the first error happened amounted to 2.9 square tiles in sequence length three in both experiments. In Corsi task 1 the length of the correct initial sequence increased to 5.30 (SD: ±1.11) squares in sequence length seven. The correct initial sequence length increased in Corsi task 2 until sequence length six to 5.48 (SD: ±0.55) square tiles. In sequence length ten the length of the correct initial sequence length amounted to 5.02 (SD: ±1.70) square tiles in Corsi task 1 and 3.96 (SD: ±2.41) square tiles in Corsi task 2. The total average over all trials and participants was 4.47 (SD: ±0.77) square tiles in Corsi task 1 and 4.30 (SD: ±0.76) square tiles in Corsi task 2 (see right bars in Fig. 6.7).
The two experiments were compared with a two-way ANOVA with repeated measures on one factor (sequence length). For the factor sequence length Mauchly's test indicated a violation of sphericity ($\chi^2(27) = 139.064$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\epsilon = 0.498$) was consulted for this factor. Again a highly significant effect for the factor sequence length was observed (F(3.486, 87.149) = 9.532, $p < 0.001$, $\eta_P^2 = 0.276$). No difference between the two experiments (F(1, 25) = 0.418, p = 0.524, $\eta_P^2 = 0.016$) and no interaction between the two factors sequence length and experiment was found.

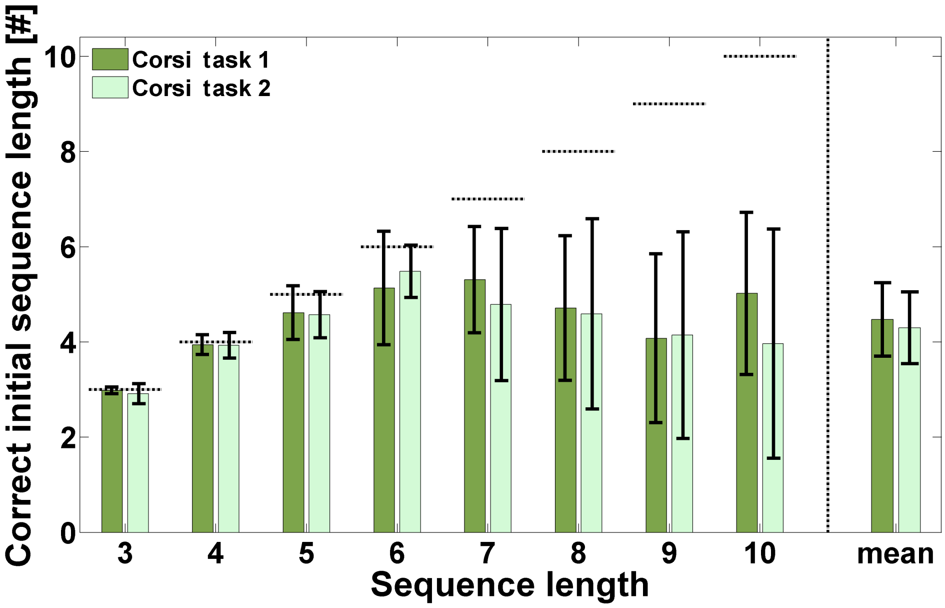

Figure 6.7.: Comparison between Corsi task 1 and Corsi task 2 in correct initial sequence length. The over thirteen and fourteen participants averaged length of the correct initial sequence (y-axis) is depicted for Corsi task 1 (green bars) and Corsi task 2 (mint green bars) for the sequence lengths three to ten (x-axis). The correctly reproduced initial sequence length increased slightly with increasing sequence length for both experiments and there was no difference between them. For both experiments the mean over all participants and sequence lengths is shown on the right. The horizontal lines indicate the maximum reachable number of correct initial sequence length. Error bars indicate the standard deviation.

Partial set correct

Last, a comparison between the two experiments for partial set correctly reproduced square tiles was carried out (see Fig. 6.8). In both experiments the number of correctly reproduced square tiles regardless of their order increased with increasing sequence length. In Corsi task 1 participants reached 2.98 (SD: ± 0.07) square tiles in sequence length three, this value increased over sequence length seven with 6.33 (SD: ± 0.59) square tiles to 8.42 (SD: ± 0.54) correctly remembered square tiles in sequence length ten. In Corsi task 2 the mean number of partial set correct square tiles amounted to 2.95 (SD: ± 0.11) in sequence length three, 6.66 (SD: ± 0.35) in sequence length seven and 9.00 (SD: ± 0.65) square tiles in sequence length ten. Hence, participants reached overall averages of 5.76 (SD: ± 1.77) square tiles in Corsi task 1 and 6.06 (SD: ± 2.06) squares in Corsi task 2 (see Fig. 6.8 right bars).
A two-way ANOVA with repeated measures on one factor (sequence length) was conducted and a violation of sphericity was revealed by Mauchly's test for the factor sequence length ($\chi^2(27) = 104.114$, $p < 0.001$). For further analyses a Greenhouse-Geisser correction ($\epsilon = 0.550$) was used. An ANOVA with corrected values revealed a highly significant increase for the factor sequence length ($F(3.849, 175) = 706.752$, $p < 0.001$, $\eta_P^2 = 0.966$). Also a significant difference between the two experiments was revealed by an ANOVA ($F(1, 25) = 10.836$, $p < 0.01$, $\eta_P^2 = 0.302$) and an interaction between the experiments was observed ($F(7, 175) = 5.024$, $p < 0.001$, $\eta_P^2 = 0.167$).

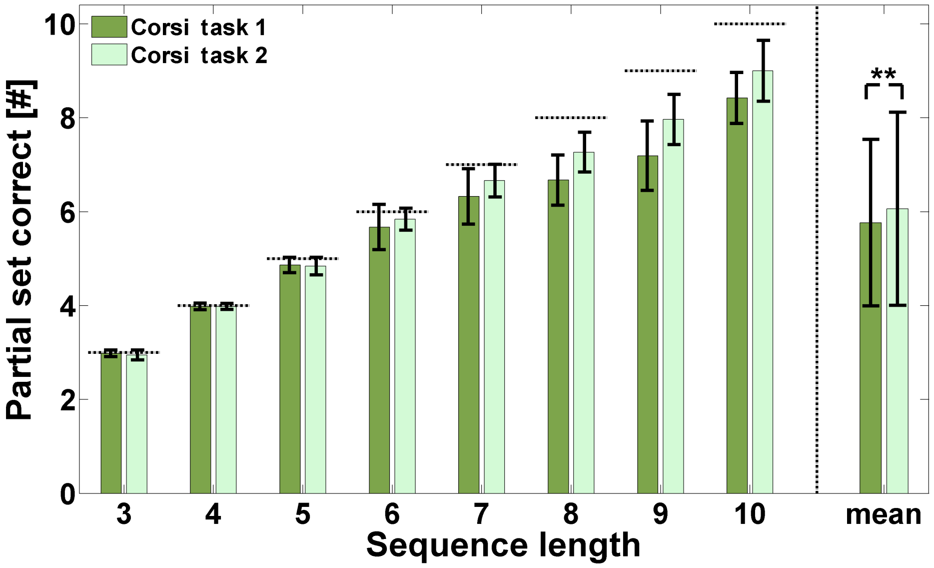

Figure 6.8.: Comparison between Corsi task 1 and Corsi task 2 in partial set correct. The number of partial set correctly reproduced square tiles (y-axis), averaged over thirteen and fourteen participants, is shown for the sequence lengths three to ten (x-axis). In both experiments the number of partial set correctly reproduced square tiles increased with increasing sequence length. The right bars depict the mean of correctly reproduced partial set correct square tiles for both experiments. There was a significant difference between Corsi task 1 and Corsi task 2 in number of partial set correct squares (depicted with stars above the means). The green bars show the results of Corsi task 1 and the mint green bars the results of Corsi task 2. The horizontal lines indicate the maximum reachable number of partial set correct squares. Error bars indicate the standard deviation.

Pattern Copying task

Similar to the Corsi task participants' mouse clicks were measured and evaluated for the Pattern Copying task. Exemplary click patterns are shown in Fig. 6.9.

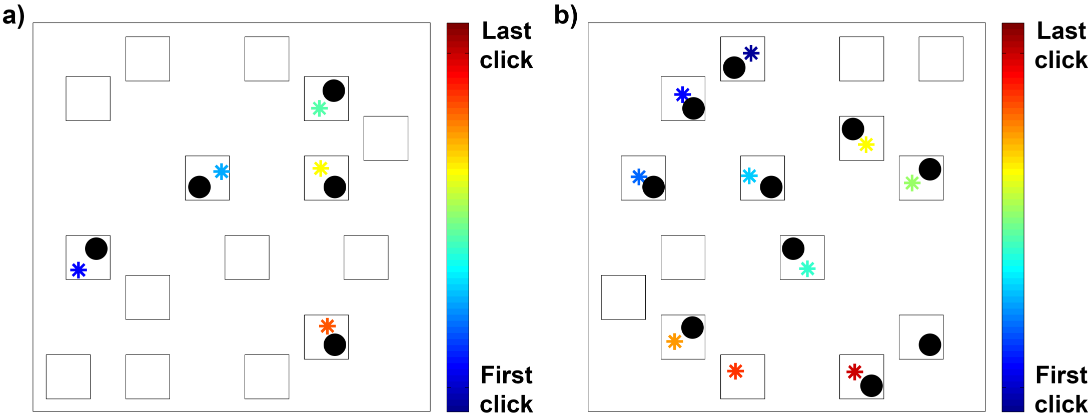

Figure 6.9.: Click patterns. a) A pattern with five squares to memorize is shown. All squares were remembered correctly. The orientation of the squares is identical to trials beginning at Start 2 in the experiments 1 and 2. b) A long pattern (ten squares) is depicted. In this case nine of the ten squares were recalled. The orientation of the squares is identical to Start 1. The black dots mark the squares included in the patterns. The color gradient indicates the order of the clicks, blue stars indicate early clicks and red stars late clicks.

6.2.7. Analysis of correct trials

Although, in this experiment there was no sequence to remember but only the positions of marked squares, a memory span of the remembered squares was calculated, too. It will be referred to as “Copy span” in the following. Participants’ Copy span was between 9.00 and 10.00 correctly reproduced squares (see Tab. 6.2), with an overall mean of 9.61 (SD: ± 0.31) squares.

Table 6.2.: Participants’ Copy span and the mean Copy span over all participants with standard deviation.

P 1	**P 2**	**P 3**	**P 4**	**P 5**	**P 6**	**P 7**	**P 8**	**P 9**	**P 10**	**P 11**	**P 12**	**P 13**	**P 14**	**mean**
9.25	9.50	9.75	9.75	10.00	9.50	10.00	9.50	9.25	9.00	9.75	9.50	9.75	10.00	9.61 (SD: ±0.31)

As next analysis the performance of the participants in the 32 trials was evaluated. The individual performance of the participants was between 87 % and 100 % (see Fig. 6.10 a)). The mean percentage of correct trials amounted to 98.21 % (SD: ± 6.68) in sequence length three (see Fig. 6.10 b)). In the sequence lengths four and five participants reached 100.00 % (SD: ± 0) of correct trials and still in sequence length eight a mean of 94.64 % (SD: ± 10.65) of correct trials was reached. The performance slightly decreased in the sequence lengths nine and ten with 85.71 % (SD: ± 18.90) and 87.50 % (SD: ± 18.99), respectively. Overall, a percentage of 95.09 % (SD: ± 5.55) of correct trials was reached by the participants (see Fig. 6.10 b) right bar).
A conducted one-way repeated measures ANOVA revealed a significant effect for the factor sequence length ($F(7, 91) = 3.401$, $p < 0.01$, $\eta_P^2 = 0.207$), indicating a loss of performance with increasing sequence length. A post-hoc analysis showed no difference between the sequence lengths.

6.2.8. Analysis of correct initial sequence length

The results of the correct initial sequence length is depicted in Fig. 6.11. Participants’ mean performance increased with increasing sequence length. In sequence length three the average length of the correct initial sequence was 2.96 (SD: ± 0.13) squares. In sequence length four and five participants reached the maximally possible number of squares. In sequence length seven 6.98 (SD: ± 0.07) square tiles were reproduced correctly and in sequence length ten an average of 9.64 (SD: ± 0.76) square tiles was reached. The correct initial sequence had an overall length of 6.38 (SD: ± 2.31) square tiles from first click to first error in all trials (see Fig. 6.11 right bar).
A conducted one-way repeated measures ANOVA revealed a highly significant increase of the length of the correct initial sequence with increasing sequence length ($F(7, 91) = 468.391$, $p < 0.001$, $\eta_P^2 = 0.973$). A post-hoc test revealed highly significant differences ($p < 0.001$) between all sequence lengths except for the sequence lengths eight and nine as well as the sequence lengths nine and ten, between these sequence lengths no difference was observed.

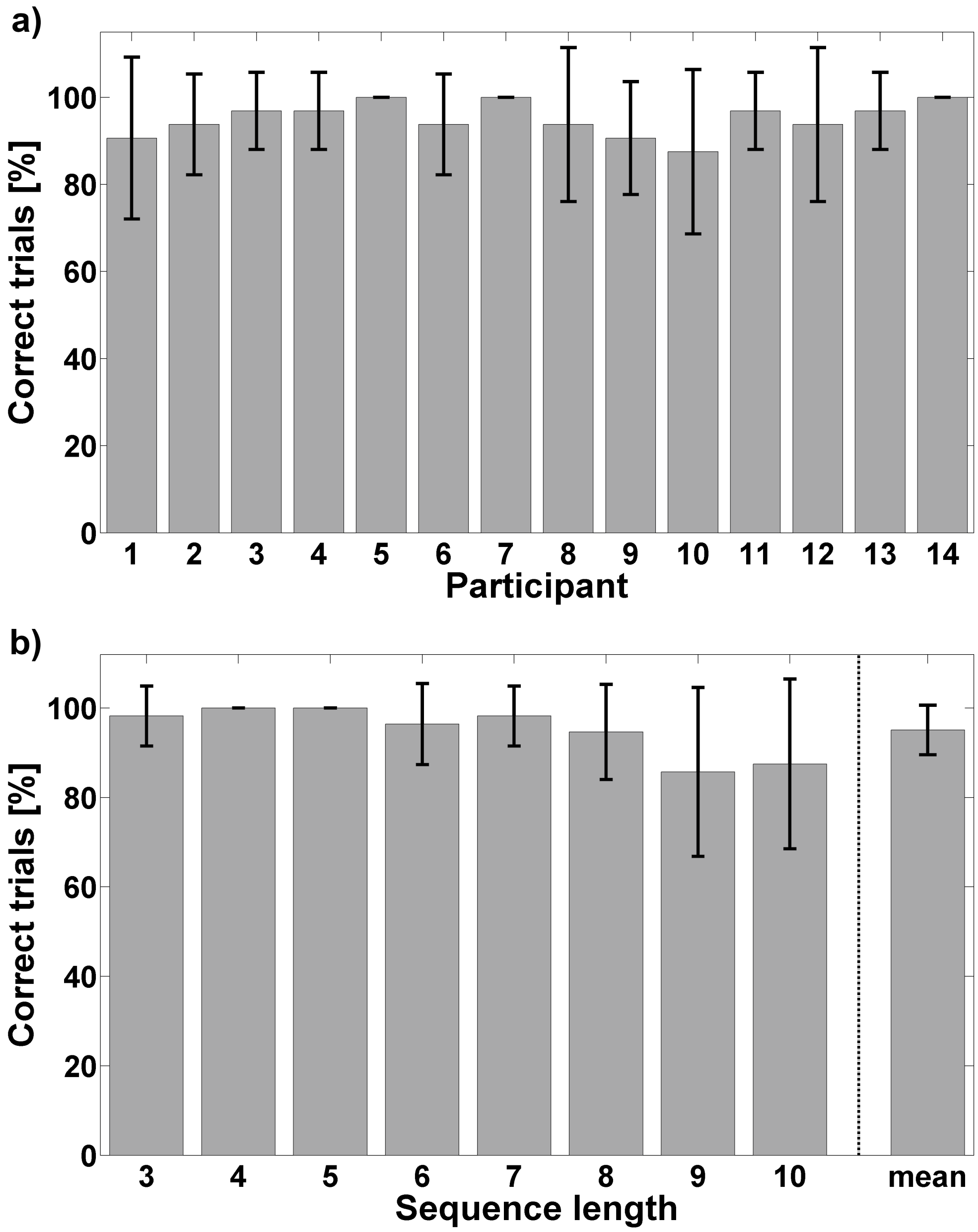

Figure 6.10.: Percentage of correct trials. a) For each participant (x-axis) the mean percentage of correct trials (y-axis) over all 32 trials is depicted. b) The mean percentage of correct trials over all fourteen participants (y-axis) per sequence length (x-axis) is shown. The performance decreased significantly in longer sequence lengths. The right bar shows the mean over all participants and sequence lengths. Error bars indicate the standard deviation.

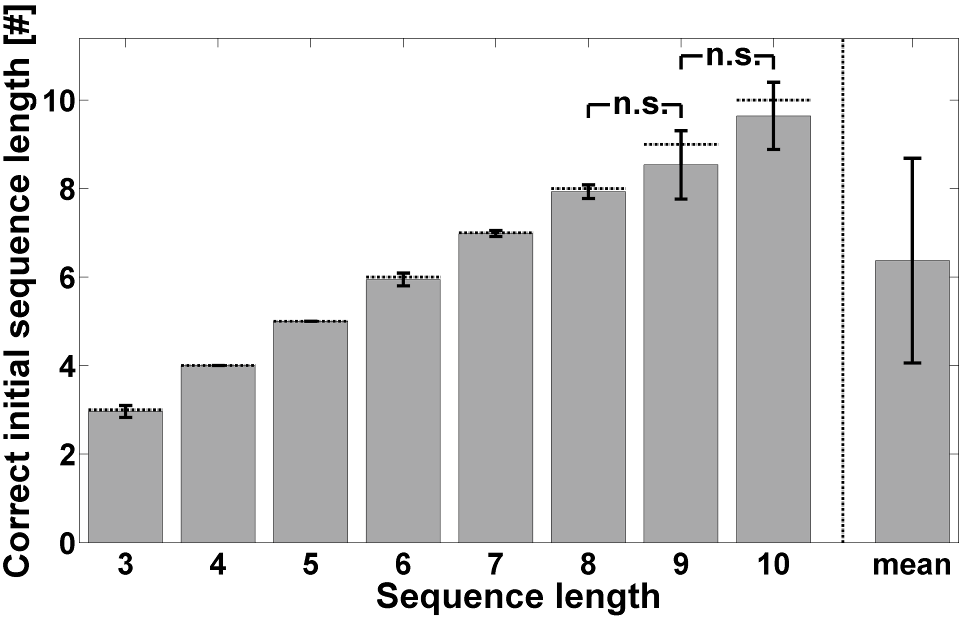

Figure 6.11.: Length of correct initial sequence. The length of the correct initial sequence averaged over all fourteen participants (y-axis) is depicted for the sequence lengths three to ten (x-axis). The initial sequence length increased significantly with increasing sequence length. There was no difference between sequence length eight and nine as well as between sequence length nine and ten. All other sequence lengths differed highly significantly between each other. On the right the mean over all trials and participants is shown. The horizontal lines indicate the maximum reachable length of the correct initial sequence. Error bars indicate the standard deviation.

6.2.9. Analysis of partial set correct

Further the mean number of partial set correctly reproduced square tiles in each trial was evaluated (see Fig. 6.12). The mean number of partial set correctly recalled square tiles increased with increasing sequence length. In sequence length three 2.96 (SD: ± 0.13) squares regardless of their order were reproduced correctly. In sequence length eight 7.95 (SD: ± 0.11) and in sequence length ten 9.89 (SD: ± 0.16) square tiles were recalled correctly. The total mean of the partial set correct squares amounted to a number of 6.44 (SD: ± 2.39) square tiles (see Fig. 6.12 right bar).
A one-way repeated measures ANOVA revealed a highly significant increase of correctly reproduced partial set correct square tiles with increasing sequence length ($F(7, 91) = 3136.469$, $p < 0.001$, $\eta_P^2 = 0.996$). A further post-hoc test showed highly significant differences ($p < 0.001$) between all sequence length.

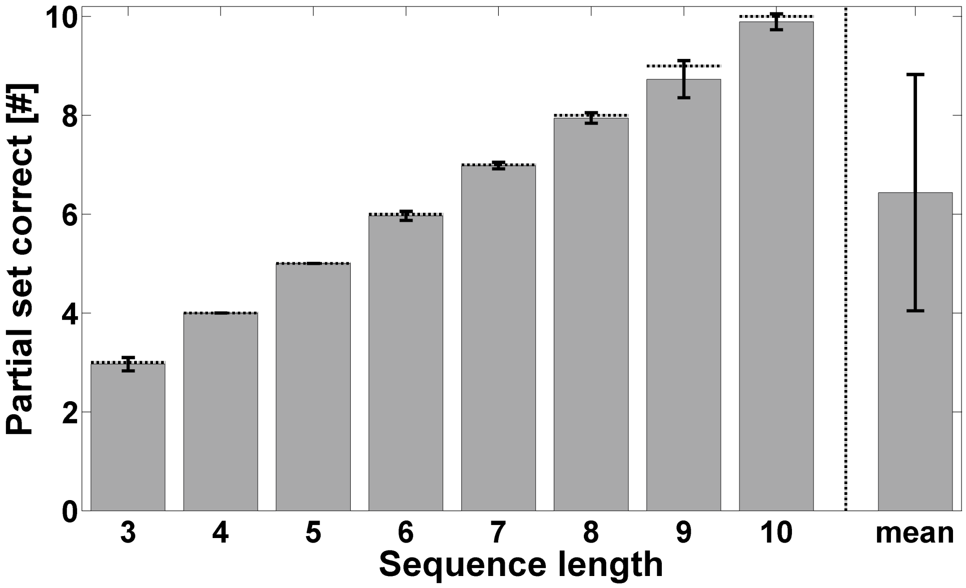

Figure 6.12.: Number of partial set correct. The number of partial set correctly reproduced square tiles averaged over the fourteen participants (y-axis) is depicted for each sequence length (x-axis). The number of partial set correct square tiles increased over the sequence lengths. This increase was significant for all sequence lengths. The right bar shows the average over all sequence lengths and participants. The horizontal lines denote the maximum possible number of partial set correct squares. Error bars indicate the standard deviation.

6.2.10. Analysis of sequences

Once more the patterns were evaluated for differences between the orientations. The two pattern orientations were used in 16 trials each. Pattern orientations similar to Start 1 were solved correctly in 94.20 % (SD: ± 10.18) of the cases. The pattern orientations similar to Start 2 were solved correctly in 95.98 % (SD: ± 6.37) of the trials. Again no difference between the two pattern orientations was found by a conducted χ^2-test.

Analysis of click patterns

The mouse clicks and hence the resulting click patterns of all participants were evaluated by the examiner for potentially favored clicking strategies, e.g. reading direction or circles etc. First the patterns were analyzed for a general direction, e.g. left to right, top to bottom, diagonal, etc. Then it was checked, whether the clicks followed a consecutive trail or had leaps. If they were following consecutive trails it was further analyzed whether these trails ran in circles or (wavy) lines (some examples are shown in Fig. 6.13). For this analysis the trials with three and four squares were excluded since in this short sets it is always possible to connect the squares in a circle or line.

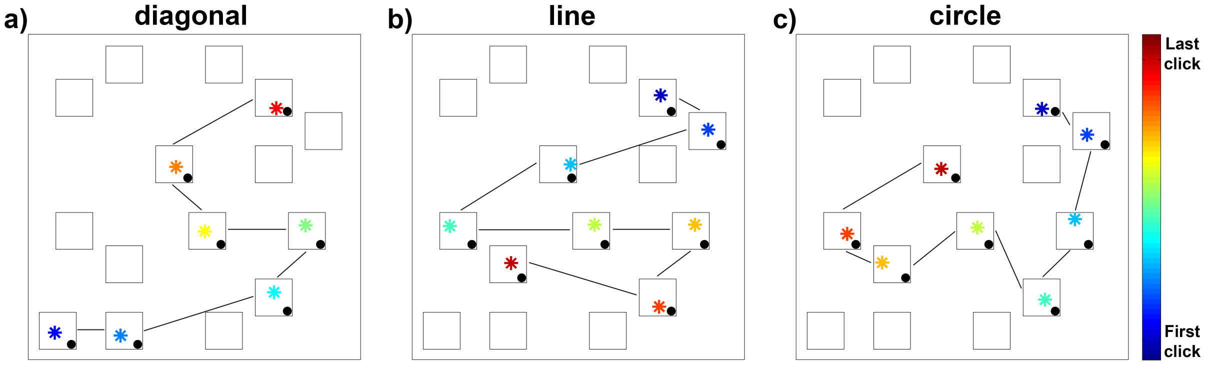

Figure 6.13.: Strategies for click patterns. a) A pattern of seven squares is shown which was solved in a consecutive trail and running diagonally from bottom-left to top-right. b) A consecutive trail in a line is depicted for a pattern with eight squares. c) The same trial as in b) is shown. In this example the pattern was also solved in a consecutive way, but in a circular execution. In all three figures the trials were solved correctly and the color gradient indicates the order of the clicks, blue stars mark early clicks and red stars late clicks. The black lines also visualize the order of the clicks and the black dots mark the squares included in the pattern.

None of the participants kept a constant direction in the click pattern. Because of that all possible directions were pooled and it was only checked whether a direction was recognizable or not. For patterns with five squares in about 65 % of the cases a clicking direction was observed. In patterns with six squares about 60 % showed a general direction. About 40 % of the trials in patterns with eight squares showed a clicking direction and in patterns with ten squares this was observed for about 53 % of the trials. Overall, a general direction in the click patterns was found for about 53 % of all trials.

In about 78 % of all trials participants followed a consecutive trail in clicking and in the remaining 22 % participants showed leaps in their click patterns. In patterns with five squares consecutive trails were found in about 90 % of all trials. Whereas in patterns with seven shown squares about 64 % of the trials were solved by clicks in consecutive trails and in patterns with ten squares in about 84 % of the cases. A reverse pattern was observed for trials which had leaps in their click patterns. In sequence length five about 10 % of the trials were solved with a leap in the click pattern. In patterns with seven squares about 36 % had a leap whereas a leap was present in click patterns with ten squares in about 16 % of the trials. The consecutive trails were composed by click patterns in circles for about 15 % and (wavy) lines in about 76 %. For the remaining 9 % of the cases a mix of both or no pattern at all was found.

6.2.11. Comparison between males and females

Again analyses for gender differences in performance were conducted. Like before the factors were the percentage of correct trials, the length of the correct initial sequence and the number of partial set correct square tiles. The conducted two-way ANOVAs did not reveal any differences between genders in one of these factors.

6.2.12. Comparison with Corsi task 2

Like in the experiments before the results of the Copying task were compared this time to the results participants reached in the Corsi task 2 (which will be referred to as “Corsi task” in the next subchapters again).

Correct trials

In the Corsi task as well as in the Copying task the percentage of correct trials decreased with increasing sequence length. Though, in the Copying task participants reached higher values in all sequence lengths (see Fig. 6.14). In the Corsi task participants reached a mean performance of 94.64 % (SD: ± 10.65) in sequence length three and in the Copying task a mean performance of 98.21 % (SD: ± 6.68). In the sequence lengths four and five participants reached 100 % in the Copying task, whereas the performance in the Corsi task in sequence length five already decreased and a value of 80.36 % (SD: ± 20.05) of correct trials was reached. In sequence length ten participants reached 87.50 % (SD: ± 18.99) in the Copying task and only 17.86 % (SD: ± 28.47) in the Corsi task. Overall, the average of correct trials amounted to 58.93 % (SD: ± 33.75) in the Corsi task and to 95.09 % (SD: ± 5.55) in the Copying task (see bars on the right in Fig. 6.14).
A two-way repeated measures ANOVA revealed highly significant differences between the Corsi task and the Copying task ($F(1, 13) = 188.285$, $p < 0.001$, $\eta_P^2 = 0.935$). There was also a highly significant effect for the factor sequence length, indicating that with increasing sequence length the performance decreased ($F(7, 91) = 35.932$, $p < 0.001$, $\eta_P^2 = 0.734$). Also an interaction between the factors sequence length and experiment was observed ($F(7, 91) = 27.364$, $p < 0.001$, $\eta_P^2 = 0.678$).

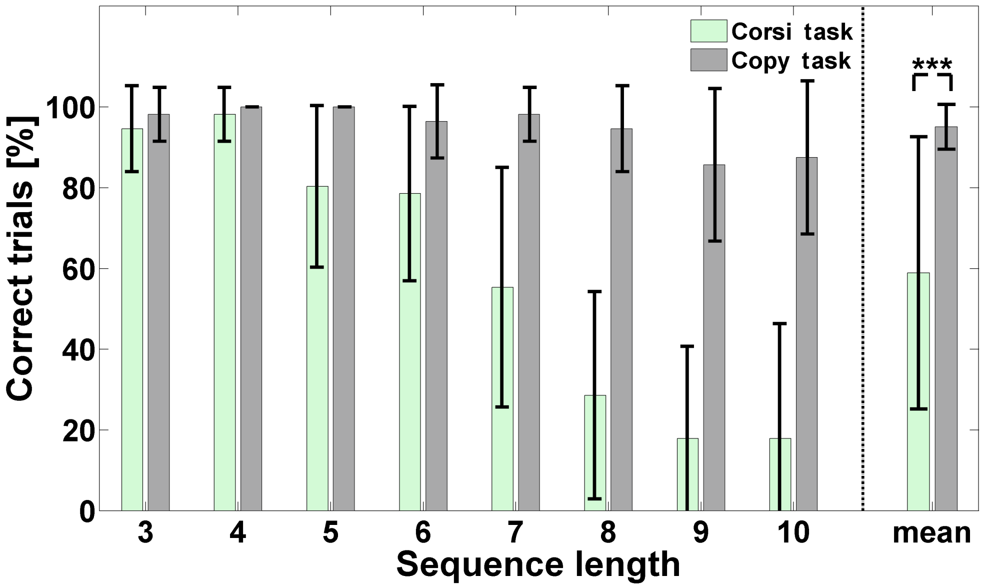

Figure 6.14.: Comparison between Corsi task 2 and Copying task in percentage of correct trials. The mean percentage of correct trials averaged over the fourteen participants (y-axis) is shown for each sequence length (x-axis). The percentage of correct trials decreased rapidly with increasing sequence length in the Corsi task (mint green bars). In the Copying task (gray bars) the performance slightly decreased in the higher sequence lengths. The percentage of correct trials was significantly different between the Corsi task and the Copying task (depicted with stars above the means) and there was an interaction between the experiments and the sequence lengths. The mean percentage averaged over all fourteen participants and over all eight sequence lengths is shown on the right for both experiments. Error bars indicate the standard deviation.

Correct initial sequence length

As second comparison the length of the correct initial sequence reached in both experiments was evaluated. In both experiments the correct initial sequence length increased up to sequence length six (see Fig. 6.15). In the Corsi task participants reached a mean average of 2.91 (SD: ± 0.21) squares in sequence length three. An almost identical value was reached in the Copying task with 2.96 (SD: ± 0.13) square tiles. In sequence length six the mean of the correct initial sequence length amounted to 5.48 (SD: ± 0.55) squares in the Corsi task and to 5.95 (SD: ± 0.14) squares in the Copying task. In the Corsi task the mean initial sequence length was about 4 in the sequence lengths seven to ten. Whereas the mean number in the Copying task still increased to 9.64 (SD: ± 0.76) squares in sequence length ten. The total mean over all participants and trials was 4.30 (SD: ± 0.76) in the Corsi task and 6.38 (SD: ± 2.31) in the Copying task.

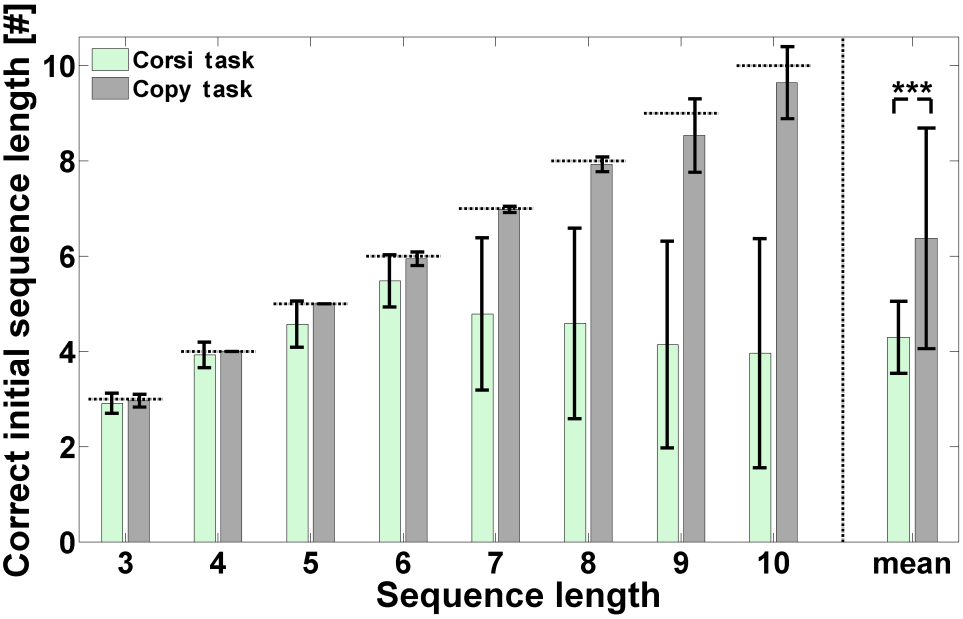

Figure 6.15.: Comparison between Corsi task 2 and Copying task in correct initial sequence length. For the sequence lengths three to ten (x-axis) the mean length of the correct initial sequence (y-axis), averaged over the fourteen participants, is shown. In the Corsi task (mint green) the correct initial sequence length increased with increasing sequence length for the shorter sequence lengths (three to six). In the Copying task (gray bars) the correct initial sequence length increased with increasing sequence length in all eight sequence lengths. The right bars show the mean over all participants and trials for both experiments. There was a highly significant difference between the experiments (depicted with stars above the means) and an interaction between the factors experiment and sequence length was found. The horizontal lines denote the maximum reachable number of correct initial sequence length. Error bars indicate the standard deviation.

A two-way repeated measures ANOVA was conducted and revealed a highly significant difference between the experiments (F(1, 13) = 122.476, $p < 0.001$, $\eta_P^2 = 0.904$). A Mauchly test indicated a violation of sphericity for the factor sequence length ($\chi^2(27) = 91.221$, $p < 0.001$). Greenhouse-Geisser ($\epsilon = 0.398$) corrected values revealed a highly significant effect for the factor sequence length (F(2.788, 36.247) = 43.905, $p < 0.001$, $\eta_P^2 = 0.772$). Also for the interaction between the factors sequence length and experiment a Mauchly test indicated a violation of sphericity ($\chi^2(27) = 77.834$, $p < 0.001$) and Greenhouse-Geisser ($\epsilon = 0.477$) corrected values were used further on. An interaction between the two factors sequence length and experiment was observed (F(3.338, 43.394) = 38.262, $p < 0.001$, $\eta_P^2 = 0.746$).

Partial set correct

Last, the number of partial set correctly remembered square tiles was analyzed (see Fig. 6.16). In both experiments the mean number of partial set correct square tiles increased with increasing sequence length. Again the values were a little higher in the Copying task than in the Corsi task. In sequence length three 2.95 (SD: ± 0.11) squares in the Corsi task and 2.96 (SD: ± 0.13) squares in Copying task were reached. In sequence length eight 7.27 (SD: ± 0.42) partial set correctly recalled square tiles were reached in the Corsi task and 7.95 (SD: ± 0.11) squares were reached in the Copying task. In the longest sequence length participants had a mean value of 9.00 (SD: ± 0.65) square tiles in the Corsi task and 9.89 (SD: ± 0.16) in the Copying task. The total mean amounted in the Corsi task to 6.06 (SD: ± 2.06) squares and in the Copying task to 6.44 (SD: ± 2.39) square tiles (see right bars in Fig. 6.16).

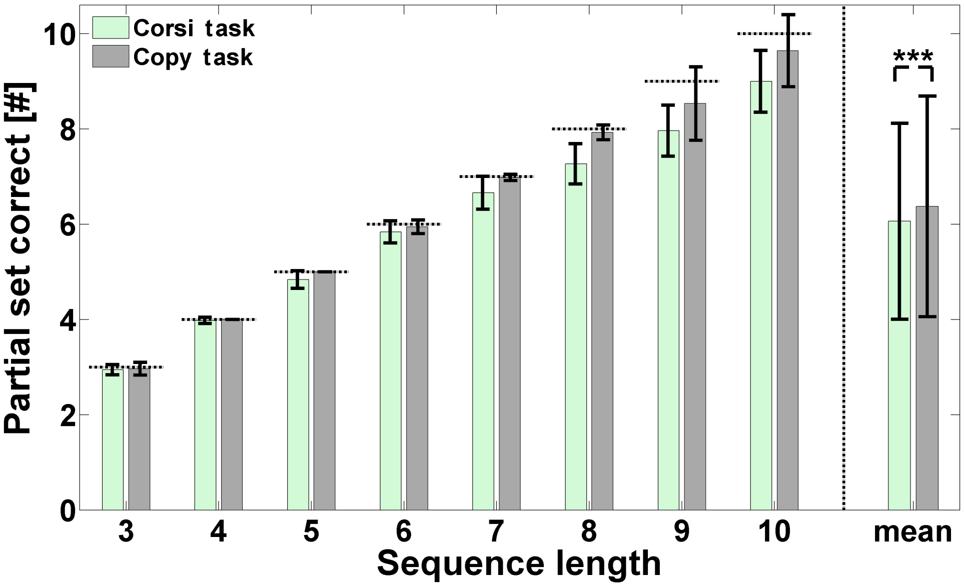

Figure 6.16.: Comparison between Corsi task 2 and Copying task in number of partial set correct. For both experiments the mean number of partial set correctly reproduced square tiles (y-axis) increased with increasing sequence length (x-axis). The overall mean over the fourteen participants and all sequence lengths is depicted on the right. There was a highly significant difference (depicted with stars above the means) between the mean number of partial set correctly reproduced square tiles in the Corsi task 2 (mint green bars) and in the Copying task (gray bars) and an interaction between the experiments and the sequence lengths was present. The horizontal lines denote the maximum possible number of partial set correct squares. Error bars indicate the standard deviation.

A conducted two-way repeated measures ANOVA showed a highly significant difference between the experiments, indicating a higher number of partial set correctly remembered square tiles in the Copying task (F(1, 13) = 55.903, $p < 0.001$, $\eta_P^2 = 0.811$). For the factor sequence length Mauchly's test indicated a violation of sphericity ($\chi^2(27) = 59.340$, $p < 0.001$), so a Greenhouse-Geisser correction ($\epsilon = 0.388$) was used for further analysis. There was a highly significant effect for the factor sequence length (F(7, 91) = 2063.264, $p < 0.001$, $\eta_P^2 = 0.994$), showing that the number of partial set correct squares increased with increasing sequence length. As for the factor sequence length, a Mauchly test also indicated a violation of sphericity for the interaction between sequence length and experiment ($\chi^2(27) = 58.771$, $p < 0.001$; Greenhouse-Geisser correction: $\epsilon = 0.469$). The Greenhouse-Geisser corrected values revealed an interaction between the factors experiment and sequence length ($F(7, 91) = 12.722$, $p < 0.001$, $\eta_P^2 = 0.495$).

6.3. Discussion

Participants' performance in copying a given pattern was investigated in this experiment. The load on working memory was caused by the number of shown squares and increased by increasing the number of squares. Remembering their correct position requires visuo-spatial working memory resources, though, in contrast to a Corsi task no order had to be memorized and therefore no additional working memory load caused by a temporal factor was present.

All of the participants were able to solve the task. For having a within-subject design, participants also solved a Corsi task, similar to the one in Experiment 3.

Corsi task

For the Corsi task it was again found that participants' performance in the percentage of correct trials decreased with increasing sequence length (cf. Fig. 6.3 b), p. 85). Up to sequence length six participants reached a percentage of about 80 % of correct trials. This value decreased further in the sequence lengths seven and eight and kept equal in the remaining two sequence lengths. The overall performance in this task was about 60 % of correctly solved trials. Like in Experiment 3 this expected performance decrease can once more be explained with the limited capacity of the working memory to three to five items (Cowan 2000).

Participants reached a Corsi span of 6.71, which was identical to the Corsi span of Experiment 3 in which participants had a Corsi span of 6.75. Corsi spans of about five (Corsi 1972, Orsini et al. 1987) and six (Kessels et al. 2000, Monaco et al. 2013) were found for classical versions of the Corsi tasks, as well as a Corsi span of about six in an electronic version (Perrochon et al. 2014).

In Experiment 2 it was already mentioned that presenting a walking version of the Corsi task by an experimenter could facilitate the memorizing of a sequence. Thus, the type of presentation might also have an influence on participants' Corsi span, not only the configuration of the sequences (e.g. lengths of the sequences and crossings) or the calculation of the Corsi span. Therefore, different presentation and recall types are investigated in Experiment 5.

The length of the correct initial sequence increased up to a sequence length of six and remained equal for the longer sequence lengths (cf. Fig. 6.4, p. 86). Once more, this value is in line with Cowan's (2000) reported capacity limit of the working memory.

For the number of partial set correctly reproduced square tiles an increase was found over the sequence lengths (cf. Fig. 6.5, p. 87). The higher number of correctly recalled square tiles compared to the length of the correct initial sequence could be explained by the missing temporal factor, because of the orderless recall of the squares and also by the in the previous experiments already mentioned chance of 66.7 % to click on a correct square tile in sequence length ten without remembering it at all.

Again, the orientations of the pattern configuration were evaluated for differences in performance, though, it was not expected to find differences between the two orientations. There was no difference between the performance for trials with a pattern orientation similar to Start 1 and the performance for trials with a pattern orientation similar to Start 2.

All results were analyzed for gender differences. There were no differences between males and females in the percentage of correct trials, the length of the correct initial sequence and in the number of partial set correct squares. Since no gender differences were found in Experiment 3 it was not expected to find any differences in this Corsi task. Again, the results are in line with the findings of e.g. Kessels et al. (2000) and Monaco et al. (2013).

Comparison with Corsi task 1

Comparing the results of Corsi task 2 with the results of Corsi task 1 revealed no difference in performance for the percentage of correct trials (cf. Fig. 6.6, p. 89) and for the length of the correct initial sequence (cf. Fig. 6.7, p. 90).
Though, for the comparison of the number of partial set correctly reproduced square tiles not only an increase of performance over the sequence lengths was found for both tasks, but also a highly significant difference between the two experiments, showing a higher number of partial set correct squares in Corsi task 2. Also an interaction between the factors experiment and sequence length (cf. Fig. 6.8, p. 91) was found. The reason for this difference could be that participants received feedback in Corsi task 1. When they clicked into a wrong square a red circle in the square which would have been the next in the sequence was shown. In contrast, participants got no feedback in Corsi task 2. Each time participants clicked into a square a green circle was shown whether it was the correct square or not. This feedback could reduce the number of partial set correct square tiles in Corsi task 1. If participants forgot or mixed up a square of the sequence the feedback could lead to a second click into the same square right after the last click, at least if participants supposed that this square should have come next. When participants got no feedback they did not know that the order they clicked was wrong and there was no need to click a second time into a square right after the last click. This resulted in a higher number of partial set correct square tiles in Corsi task 2.

For a more detailed analysis, similar to the previous experiments, the performances in the two shortest sequence lengths (three and four) were compared to the performances in the two longest sequence lengths (nine and ten). This was done for the percentage of correct trials, the percental length of the correct initial sequence and the percental number of partial set correct squares (see Fig. 6.17).
For the percentage of correct trials and the percental length of the correct initial sequence both experiments had the same decrease over the sequence lengths, shown by parallel lines in Fig. 6.17 a) and b). For the percental number of partial set correct square tiles the decrease in Corsi task 1 was higher than the decrease in Corsi task 2 (see Fig. 6.17 c)). This difference was probably caused by the feedback which was given in Corsi task 1 and led to a better performance for partial set correct squares in Corsi task 2.

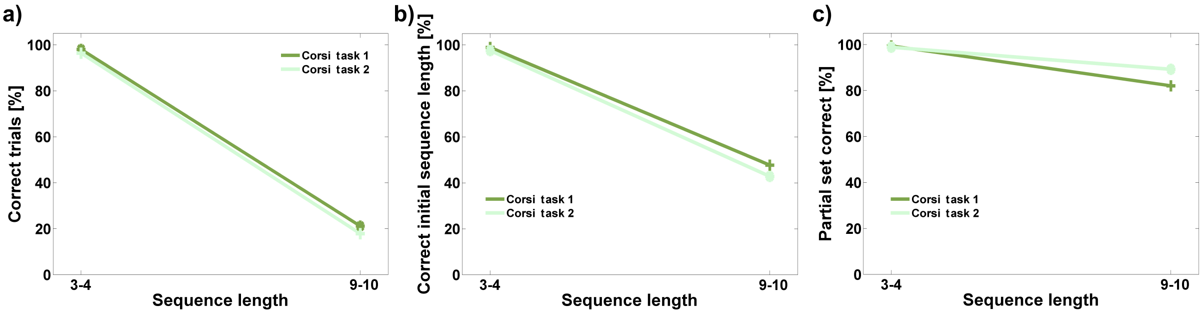

Figure 6.17.: Interaction plots for the percentage of correct trials (a), the correct initial sequence length (b) and partial set correct squares (c). For all fourteen participants the mean performance in percent (y-axis) in the sequence lengths three and four and in the sequence lengths nine and ten (y-axis) is shown for Corsi task 1 (green lines) and Corsi task 2 (mint green lines). a) Both Corsi tasks showed a similar decrease in percentage of correct trials (parallelism of the lines). b) Again, the decrease of performance was almost equal in the both tasks for the percental correct initial sequence length. c) For the percentage of partial set correct reproduced squares, Corsi task 1 had a slightly larger decrease in performance than Corsi task 2. None of the shown factors had an interaction between the experiments in this comparisons.

Pattern Copying task

For the Copying task it was hypothesized that participants had a better performance than in the Corsi task because there was no sequence but only orderless locations of squares to remember. This means almost all working memory resources could be used by visuo-spatial demands since the temporal load on working memory was eliminated. It was also supposed that participants' performance would decrease with increasing sequence length but increase again in the longer sequence lengths. An example with theoretical values is depicted in Fig. 6.18. This effect should be caused by a strategy chance in solving the task. In the shorter sequence lengths it should be easier to memorize the marked squares and recall them in the reproduction phase. Because of the limited capacity of the working memory the performance should decrease with increasing sequence length. Though, in the longer sequences it should be easier to memorize the less squares which are not included in the pattern and this should result in an increase of performance in the longer sequence lengths.

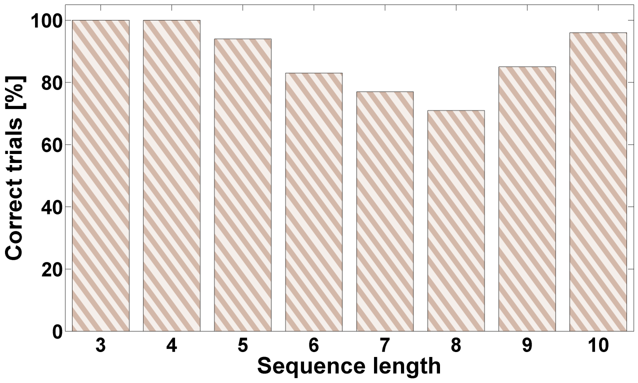

Figure 6.18.: Theoretical performance values. For each sequence length (x-axis) fictional values of percentage of correct trials (y-axis) are depicted. Hypothetical participants' performance should decrease with increasing sequence length, but due to a strategy change it should increase in the higher sequence lengths again.

The performance in the Copying task decreased with increasing sequence length, although no differences between the single sequence lengths were found. In contrast to the hypothesis the performance did not increase again in the longer sequence lengths but it only slightly decreased in the sequence lengths nine and ten (cf. Fig. 6.10 b), p. 93). A reason for the good results could be the time the sequences were shown. For having no time difference in the encoding phase the squares were shown the same time it would have needed to show them as a sequence in which each square was marked for 2 s. This means the pattern was displayed for the number of squares multiplied with two. In contrast to a sequence, seeing the squares all at once makes it easier to chunk them into groups or lines, which facilitates to memorize and correctly reproduce them later in the recall phase. This could result in a consistently good performance and possibly makes a strategy change redundant.

Similar to the Corsi spans in the former experiments this time a Copy span was calculated. All participants reached a Copy span between 9.00 and 10.00 with an overall mean of 9.61, which were thus invariably higher than the Corsi spans participants reached in the other task. Since the Copy spans were considerably higher than the limited capacity of the working memory with about five items, it is supposed that participants grouped some of the squares together and recalled them as chunks.
In a study by Della Sala et al. (1999) they investigated visual short-term memory without the spatial factor with a "Visual Patterns Test". Therefore, participants were presented with matrices of different sizes on cards. In these matrices, ranging from 2 x 2 to 5 x 6, half of the squares were filled and participants had to reproduce the filled squares on an empty card. Della Sala et al. measured a mean score of 9.08 and thus a similar value to the Copy span found here.

As expected, the length of the correct initial sequence increased with increasing sequence length (cf. Fig. 6.11, p. 94) and was equal or close to the maximum possible number. Similarly, an increase of the number of partial set correctly reproduced squares over all sequence lengths was found (cf. Fig. 6.12, p. 95), which was also equal or close to the maximum possible number in all sequence lengths.

Like in the former Corsi task experiments no difference between the two possible pattern orientations was found for the performance in the Copying task.

As participants did not have to follow an order by recalling the shown squares it could have been possible that they recalled all trials the same way, e.g. in reading direction, in top-down direction or vice versa or in circles. The click patterns were evaluated for such strategies but none of the participants kept a straight strategy in the click pattern over the whole experiment. Though, it was found that the squares were mostly clicked in consecutive ways. Thus, it could be concluded that the click patterns depending on the layout of the shown patterns and not on potential preferences of the participants.

Similar to the Corsi task there was no difference in performance between male and female participants.

Comparison with Corsi task 2

Comparing a Corsi task with a given sequence to a Copying task with orderless squares, it was hypothesized that the performance would be better in the Copying task. In both tasks the same number of squares had to be memorized in each trial, but the temporal factor of the sequence was non-existent in the Copying task.

As hypothesized, participants' performance was better in the Copying task. The percentage of correct trials decreased in the Corsi task with increasing sequence length, whereas the performance in the Copying task remained mostly constant over the sequence lengths (cf. Fig. 6.14, p. 97). This resulted in a highly significant difference between the two experiments and also an interaction between the factors experiment and sequence length was observed. Since participants only had to remember the squares but not their (correct) order and therefore the demands on working memory were less in the Copying task this result is not surprising. The better performance resulted in a higher span in the Copying task compared to the Corsi task.
In a study by Rossi-Arnaud et al. (2012) participants had to reproduce a sequence shown on a computer screen in a classical version of a Corsi task, which means during recall they had to tap the sequence on wooden blocks. The sequences were shown sequentially, like in the Corsi task, or simultaneously, like in the Copying task. They also found that participants' performance was better at simultaneous presentation than with sequential presentation. Della Sala et al. (1999) compared the results of a classical version of the Corsi task with the already mentioned Visual Patterns test. Healthy participants reached a Corsi span of about 5 in the Corsi task and a score of about 8 in the Visual Patterns test. Again, it was shown that the performance in the Corsi task is lower than in a Pattern Copying task. Logie & Pearson (1997) investigated the performance of children in a classical Corsi task and in a Visual Pattern test. Children's performance was better in the Visual Pattern test than in the Corsi task. Della Sala et al. (1999) also reported that the differences between the two tasks were results of different components which were required for each task. The Visual Pattern test requires visual working memory but almost no spatio-sequential working memory component. The Corsi task requires not as much visual working memory load as the Visual Pattern test but the spatio-sequential component instead (Della Sala et al. 1999). This is also true for the comparison of the Corsi task and the Pattern Copying task of this experiment; the temporal factor was excluded in the Copying task.

The correct initial sequence length increased in the Corsi task up to a sequence length of six and remained similar then. In the Copying task the initial sequence length increased in all sequence lengths (cf. Fig. 6.15, p. 98). Again, this resulted in a highly significant difference between the two tasks and an interaction between the experiments and the sequence lengths was found, too. Remembering the correct sequence requires more working memory resources than just remembering the position of the squares. Further, seeing the squares all at once allows to chunk them in e.g. geometric forms, lines or other helpful forms which makes it easier to memorize and correctly recall the squares and therefore will result in a better performance.

The number of partial set correct squares increased in both experiments with increasing sequence lengths (cf. Fig. 6.16, p. 99), but again a highly significant difference between the experiments was found. In the Copying task a higher number of partial set correct squares was reached compared to the Corsi task. There was also an interaction between the two experiments indicating that in the Copying task a higher number of partial set correctly reproduced square tiles was reached especially in the longer sequence lengths. Again, this result could be explained with the higher working memory load for recalling a correct sequence and also the possible facilitation for memorizing the squares by showing them all simultaneously. Rossi-Arnaud et al. (2012) reported in their study that the simultaneous presentation of their patterns facilitated the recognition of vertical, horizontal and diagonal symmetries, which resulted in higher memory spans than asymmetric patterns.

Again, for a further analysis the two shortest (three and four) and the two longest (nine and ten) sequence lengths were averaged and the resulting means were compared. Again, this was done for the percentage of correct trials, the percental length of the correct initial sequence and the percental number of partial set correct squares (see Fig. 6.19). For the Copying task the performance was about the same in the sequence lengths in all of the three mentioned factors (see Fig. 6.19 a) - c), gray lines), whereas a clearly decrease for the percentage of correct trials and the percental correct initial sequence length in the Corsi task (see Fig. 6.19 a) and b), mint green lines) was present. Only for the number of partial set correct square tiles the percental number in the Corsi task stayed about the same as in the Copying task (see Fig. 6.19 c)).
In the Corsi task the working memory resources had to be split up between the visuo-spatial demands on working memory and between the temporal demands on working memory; this led to a performance decrease in the longer sequence lengths. In the Copying task almost all resources except resources which were needed in both tasks for e.g. finger tapping, holding posture and so on were available for the visuo-spatial demands on working memory. This led to a better performance in the longer sequence lengths compared to the Corsi task.

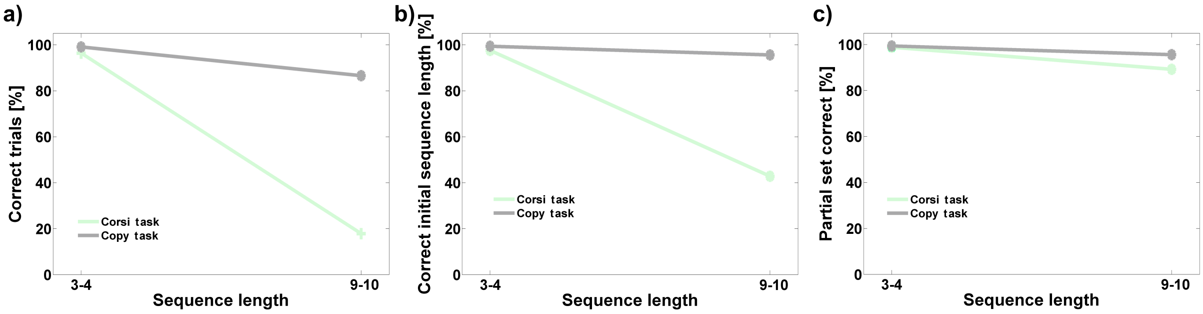

Figure 6.19.: Interaction plots for the percentage of correct trials (a), the percental correct initial sequence length (b) and the percental partial set correct reproduced squares (c) are depicted. The mean performance in percent (y-axis) of all participants in the sequence lengths three and four and the sequence lengths nine and ten (y-axis) is shown for Corsi task 2 (mint green lines) and the Copying task (gray lines). a) There was only a little decrease of performance in the Copying task. In the Corsi task a strong decrease of performance was found for the longer sequence lengths. b) The Corsi task had a decrease in performance of the correct initial sequence length, whereas there was no difference in performance between the sequence lengths three and four as well as nine and ten in the Copying task. c) For the performance of partial set correct there was almost no difference between the two tasks, both only had a slight decrease in performance. For none of the shown factors an interaction between the experiments was found for this comparison.

The constant performance over the sequence lengths in the Copying task was not in line with the hypothesis that the performance would decrease with increasing sequence length and increase in the longer sequence lengths again. Though, caused by the experimental setup, this result was nevertheless not unusual and could be explained by the time the pattern was shown in the encoding phase. Watching the squares all at the same time probably made it easier to group some of the squares and memorize them as chunks. This could have facilitated the recall of the squares in the reproduction phase and probably led to the similar performance in all sequence lengths.

The comparisons between a Copying and a Corsi task are in line with the expected results. Participants had a better performance in all of the evaluated factors in the Copying task. By comparing the two Corsi tasks it could be shown that receiving feedback during an experiment could worsen participants' performance, here, at least in the number of partial set correct square tiles.

Conclusion

With the comparison of these two tasks it could be shown that remembering the correct order of a sequence requires more working memory resources, caused by the temporal factor that is included in the task, in contrast to simply remembering the correct positions of the shown squares. The Corsi task and the Copying task might therefore serve as different tasks to investigate the visual and the spatio-sequential component of the working memory.

In Experiment 3 the comparisons between the Walking Corsi task and the Corsi task revealed that e.g. reference frame transformation and spatial updating caused a lower performance in the walking version compared to the computerized version. Though, it was not possible to distinguish the working memory costs between these factors. Therefore in the next experiment the influence of reference frame transformations, spatial updating and walking itself shall be investigated further by using different types of sequence presentation and recall. Thus, participants have to solve different versions of the Corsi task in Experiment 5.

7. Experiment 5: Corsi task in different modality conditions[1]

In the experiments 2, 3 and 4 it was shown that an increasing sequence length led to a decrease of performance in a Corsi task. It was also shown that participants had a better performance when they recalled the sequences seated in front of the computer screen instead of walking to the square tiles on the floor.

Comparisons of walking, tapping and computerized versions of the Corsi task are generally complicated by the different working memory requirements, or more specifically by the different types and amounts of spatial processing associated with each of the Corsi versions.

Additionally, mere finger tapping lacks a number of task components such as maintenance of posture, body turns, orienting behavior, etc. which are required for walking. As a consequence, the time for solving a walking version is longer than for tapping and participants need extended rehearsal to keep the Corsi sequence in mind while walking.

In this experiment, different versions of the Corsi task and their demands on spatial processing will be addressed. A full-factorial, within-subject design is presented to investigate whether the performance of the participants depends on the modality of task presentation (encoding) or reproduction (recall). For that purpose, two different presentation types (Screen and Floor) were combined with two different types of reproduction (Screen and Floor). With such combination (encoding-recall) four different modality conditions (i.e., Screen-Screen, Screen-Floor, Floor-Screen and Floor-Floor) had to be accomplished by all participants. With these modality conditions, three working memory processes (factors) can be distinguished: visuo-spatial and temporal sequence learning (performance), screen to floor or floor to screen reference frame transformation and spatial updating (including mental rotation and all other possible costs associated with walking-based recall, i.e., motor control, keeping posture, etc.). The modality condition demanding all three of these factors is Screen-Floor. In the modality condition Screen-Screen only one factor (performance) is required. The modality conditions Floor-Screen and Floor-Floor have intermediate demands and require two factors each (Floor-Screen: performance and reference frame transformation; Floor-Floor: performance and spatial updating). The demands of each modality condition are summarized also in Tab. 7.2 (p. 139).

It is hypothesized that participants' performance decreases again with increasing sequence length. Further it is assumed that participants reach a better performance in the Corsi task (i.e., modality condition Screen-Screen) than in the Walking Corsi task (i.e., modality condition Screen-Floor). Since the modality conditions Floor-Screen and Floor-Floor have intermediate demands on working memory it is supposed that participants' performance in these two

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[1] Most parts of this chapter have been used and were published in the paper Röser et al. (2016) and were adopted here almost one to one. The final publication is available at link.springer.com/article/10.1007%2Fs00221-016-4582-z. Further results have been added, too. The raw data were collected by Dörte Kuhrt who used the data also for her bachelor thesis. The programs for data collection were written by myself and also all analyses were done by myself. No parts of the bachelor thesis have been used for this doctoral thesis only the same raw data is underlying both theses.

modality conditions is between the performances of the modality conditions Screen-Screen and Screen-Floor.

7.1. Material and methods

7.1.1. Participants

This experiment was again a purely behavioral experiment and informed consent was obtained from all individual participants included in the study prior to the experiment. Fourteen volunteers, six males (mean age: 21.83 years, SD: ±2.23) and eight females (mean age: 21.12 years, SD: ±0.99), with normal or corrected to normal vision performed in all four different modality conditions (see subsection 7.1.4 "Modality conditions", p. 111 f) of a Corsi task in a within-subject design. All participants were university or high school students. Participants were paid 8 € per hour.

7.1.2. Experimental setup and design

For presenting stimuli and recording data the computer, tracking-computer and laptop already described in subsection 2.3 "Computers" (p. 15) were used.
Stimulus presentation on the floor was achieved by highlighting the square tiles with fifteen flashlights mounted at the ceiling above each square tile (see Fig. 7.1). These flashlights were controlled by the flashlight-computer.

The experiment was carried out in the same experimental room as the experiments 1 to 3 (see subsection 2.1 "Experimental room" (p. 13 f) and Fig. 7.1) with controlled lighting. In contrast to the former experiments this time a 5 x 5 m gray carpet was laid out on the floor. On the carpet a 4 x 4 m square frame was marked by light tape. Within this frame the same pattern configuration of the fifteen square tiles, already used in the previous experiments, was located. This time two more additional square tiles as starting positions were placed outside, centered along the sides of the frame (see Fig. 7.1 and Fig. 7.2). Fifteen computer controlled flashlights were installed on the ceiling of the experimental room, one above each square tile, and controlled by a MATLAB script running on the flashlight-computer. The light disks produced by the flashlights had a diameter of about 0.2 m and were clearly visible from everywhere in the room.

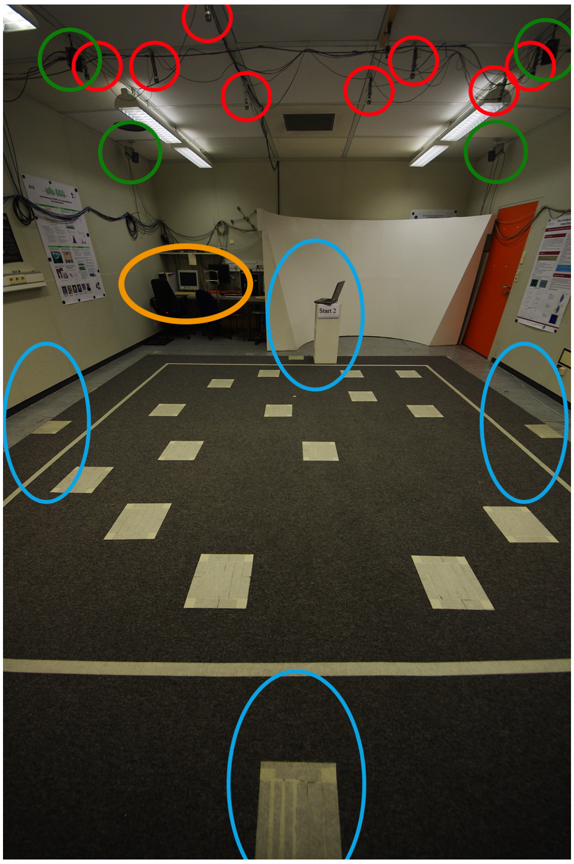

Figure 7.1.: Experimental room. The picture shows the experimental room with the frame of square patterns (4 x 4 m) on the gray carpet (comprising fifteen illuminated squares) and the flashlights at the ceiling (red circles). The green circles mark four of the six infrared light cameras of the motion tracking system. At the far end of the room a starting station (here Start 2) with the laptop can be seen (upper blue ellipse); the three other possible starting positions are also marked with blue ellipses. The orange ellipse marks the tracking-computer and the computer. Note: In this figure only at Start 2 a rack for the laptop is shown, during the experiment at all four starting positions a rack was placed.

Depending on the modality condition (see subsection 7.1.4 “Modality conditions”, p. 111 f) the presentation and recall of Corsi sequences could be accomplished either on a computer or laptop screen or on the floor (see Fig. 7.2). The configuration of the fifteen square tiles on the floor was identical to those presented on the computer and laptop screen. Similar to the former experiments the squares covered about 2.5° of visual angle (80 x 80 pixels) on the computer screen and about 2° of visual angle (100 x 100 pixels) on the laptop screen.

7.1.3. General procedure

The four modality conditions (see subsection 7.1.4 “Modality conditions”, p. 111 f) of the Corsi task were tested in a within-subject design in randomized order and balanced across participants in two sessions on two consecutive days.

Prior to the experiment the whole experimental procedure and data usage was explained to the participants in oral and written form and all of their questions were answered. Then, the participants gave informed written consent and the experiment started.

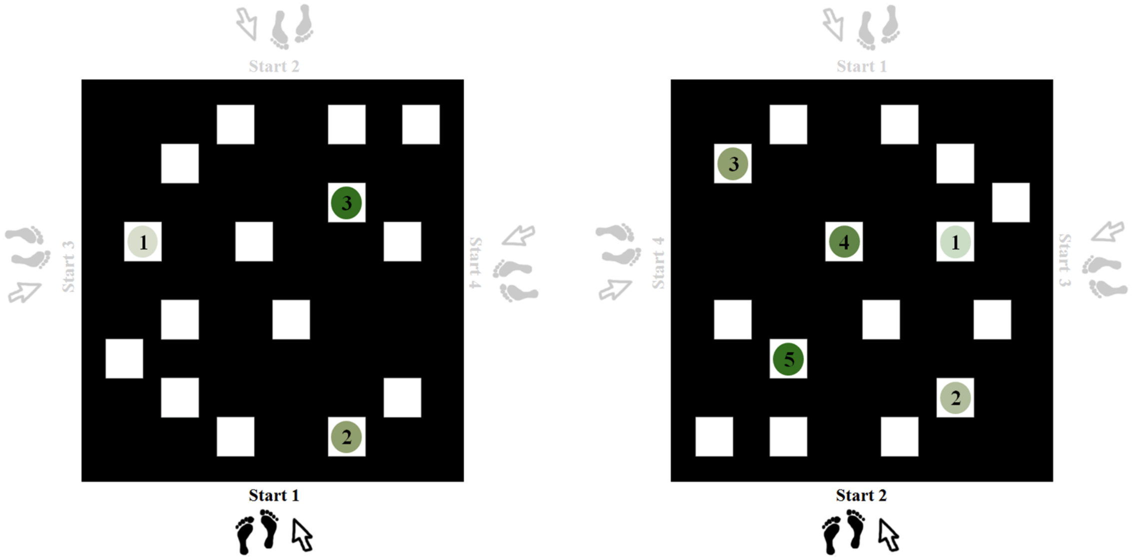

Figure 7.2.: Experimental setup. Configuration of the fifteen square tiles as potential locations to remember, this time with four different starting positions (Start 1, Start 2, Start 3 and Start 4), indicated by the feet and the mouse cursors which were not visible for the participants. Also the numbers at the starting positions were not visible on the screens. Both configurations are identical but rotated by 180°. The squares covered about 2.5° of visual angle (80 x 80 pixels) on the computer screen and about 2° of visual angle (100 x 100 pixels) on the laptop because of a different screen resolution. The walking area (frame) had a size of 4 x 4 m. The black feet and mouse cursors indicate the starting position of the current trial (left: Start 1, right: Start 2) and the gray ones the remaining possible starting positions. The orientation of the configuration of squares on the screen was adapted to the viewing direction of the participant in each trial. A sequence length of three squares is shown in the left and a sequence length of five squares is shown in the configuration on the right (green circles). The numbers in the green circles and the color gradient from lightest (first) to darkest (last) green specify the position of the squares in the sequence.

In Experiment 3: "Corsi task" (p. 65 ff) participants' individual mean walking speed in each sequence length, measured during Experiment 2: "Walking Corsi task" (p. 39 ff), was used to calculate the time delay between two mouse clicks. This was done to have the appropriate time delay in each sequence length. But therefore, the Corsi task always had to be carried out after the Walking Corsi task. In both tasks the same sequences have been used and so there might have been a possible advantage in sequence recall in the Corsi task as participants might have remembered one or the other sequence.

To rule out such an advantage, this time, all modality conditions were carried out in randomized order between participants. For calculating the time delays in the screen-recall modality conditions (Screen-Screen and Floor-Screen) participants' individual walking speed was measured in a practice trial with a mean sequence length of five squares. This practice trial took place before the main experiment and was also meant for the participants to familiarize with the procedure of the task.

In each trial, participants were presented with a specific sequence which they then had to reproduce. Like in the other experiments, for a given sequence length, four different trials had to be performed. Each of these four trials started at a different starting position randomly selected, but equal for all participants. Thus, each starting position was used once per sequence length. The sequence length increased after each fourth trial from three, but this time only up to eight squares regardless of task performance. Thus, in this experiment 24 different sequences (6 sequence lengths x 4 repetitions) had to be reproduced in each of the four modality conditions. To avoid learning effects of sequences over the four modality conditions, two different sets of sequences were generated for each sequence length (see appendix Fig. C.1 to Fig. C.6, p. 193 ff) and randomly assigned to the participants in a balanced way. For having a greater variety of sequences, the order of the sequences within both sets was changed in two of the four modality conditions (e.g. in the first modality condition Set 1 was used, in the second modality condition Set 1 with different sequence order was used, in modality condition three Set 2 was used and in the last modality condition Set 2 with changed sequence order was used). All sequences in both sets were chosen to comprise about the same metric distances (mean sequence length: 11.71 m, SD: ±0.42) to avoid any effect of different distances.

After completing one of the four modality conditions the participants continued with the next modality condition of the Corsi task. The remaining two modality conditions of the experiment were carried out on the following day. Selection and assignment of the modality conditions per day to the participants was randomized and balanced across participants.

7.1.4. Modality conditions

Screen-Screen modality condition. The procedure of this modality condition is equal to the procedures of the Corsi tasks in the experiments 3 (p. 65 ff) and 4 (p. 81 ff).

All 24 sequences were presented on the computer (see subsection 2.3 “Computers”, p. 15) by highlighting the squares in the sequence with a green circle centered in the square (screen-encoding). The green circle was again shown for 2 s with a delay of 0.5 s between the highlighting of two consecutive sequence positions. Participants were informed about the length of the upcoming trial and should reproduce the sequence using the computer mouse by clicking on the squares in the right order (screen-recall). Like in the Corsi task of the former experiments the mouse cursor disappeared for the time the respective participant would have needed to walk the respective distance in the floor-recall modalities (i.e., Screen-Floor and Floor-Floor). After this delay, the mouse cursor reappeared and the participant was able to click on the next square. For more information see subsection 5.1.2 “Experimental setup and design” (p. 65 f) and subsection 5.1.3 “General procedure” (p. 67).

Like in the Corsi task of Experiment 4 participants did not get feedback about their performance. After each mouse click a green circle appeared in the square participants had clicked before. When they did not click into a square but besides one, the whole pattern configuration was lit up red for 1.5 s.

Screen-Floor modality condition. The procedure of this modality condition is equal to the Walking Corsi task in Experiment 2 (see subsections 4.1.2 “Experimental setup and design” (p. 39 ff) and 4.1.3 “General procedure” (p. 41)).

The sequences were presented in the same way as in the Screen-Screen modality condition, but now on the laptop screen (screen-encoding). The laptop was placed on a rack at one of the four starting positions (see Fig. 7.1 and Fig. 7.2) on the carpet. Before each trial a notice on the monitor informed the participants at which starting position the upcoming trial was going to begin. The laptop was then carried over by the participants. At the new starting position the participant pressed the space bar and the sequence length of the upcoming trial was shown on the monitor. The orientation of the configuration of squares on the monitor was aligned with the configuration of squares on the floor when viewed from the current starting position.

For recall, participants then were asked to reproduce the observed sequence by walking from square to square in the correct order, thereby stepping on the respective square with both feet (floor-recall). Participants should not stand longer than 2 s on the square tiles and they also should not stop walking on the way to the next square tile.

Floor-Screen modality condition. In this modality condition all 24 sequences were shown on the floor by highlighting the corresponding squares with the fifteen computer controlled flashlights. Again, each square was illuminated for 2 s with a delay of 0.5 s between two consecutive squares (floor-encoding). The examiner told the length of each sequence before the presentation started. Participants' recall of memorized squares was assessed with a computer mouse on the laptop (screen-recall) which was placed at the respective starting position. The recall procedure was identical to that in the Screen-Screen modality condition. After recalling the remembered sequence, the starting position of the next sequence appeared on the laptop monitor and participants walked to this starting position on the carpet to begin the next trial.

Floor-Floor modality condition. In this modality condition, the examiner informed the participants verbally about the position of the start and the sequence length for each particular trial. The actual sequence was then presented using the computer controlled flashlights on the floor (floor-encoding) as described for the Floor-Screen modality condition. For recall, participants stepped on the remembered squares (floor-recall) just as described in the Screen-Floor modality condition.

7.1.5. Analysis

For all four modality conditions participants' correct performance of the sequence recall in all 24 trials were analyzed. In the modality conditions Screen-Screen and Floor-Screen the data of the participants' mouse click responses were used for the analyses. In the Screen-Floor and Floor-Floor modality conditions the data of the tracking system was used to evaluate their performance.

As dependent variables a) the number of correctly reproduced trials, b) the length of the correctly reproduced initial sequence and c) the number of squares correctly reproduced by the participants regardless of the squares' order of appearance during presentation (i.e., partial set correct) were analyzed. For the modality conditions Floor-Floor and Screen-Floor d) the walking speed in the six sequence lengths and e) the standing time on the single square tiles as well as f) comparisons between performance and minimal number of crossings as well as minimal rotation angle of each sequence were made.

Similar to the experiments 2 - 4 the individual Corsi span of each participant was calculated for each modality condition (for method see subsection 4.1.4 “Analysis”, p. 41 f).

7.2. Results

For each of the four modality conditions one example of participants' results is shown. For the modality conditions Screen-Screen and Floor-Screen click patterns were evaluated (see Fig. 7.3 a) and b)) and for the modality conditions Floor-Floor and Screen-Floor walking trajectories were analyzed (see Fig. 7.3 c) and d)).

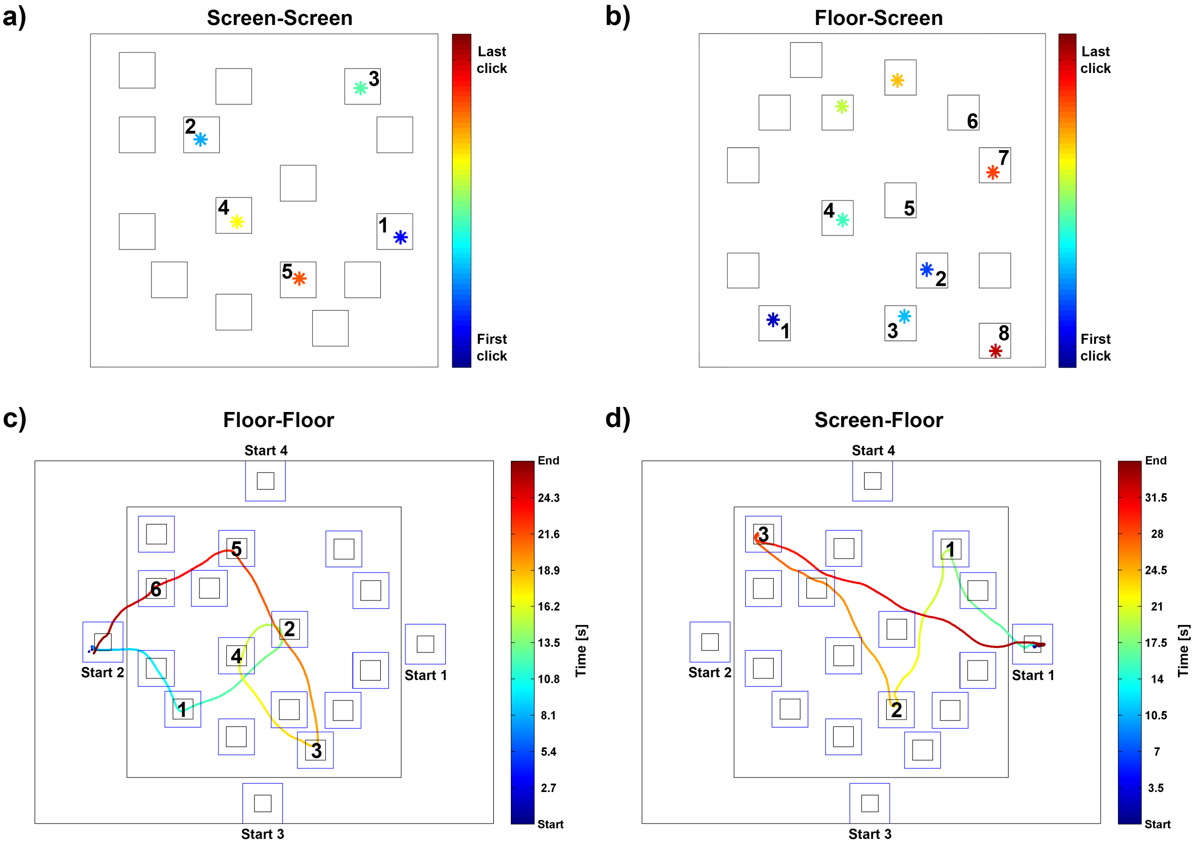

Figure 7.3.: Click patterns and walking trajectories. a) For Screen-Screen a sequence with five squares to memorize is shown, which was reproduced correctly. The orientation of the squares is identical to trials beginning at Start 3 in the walking modality conditions. b) A click pattern of Floor-Screen with a long sequence (eight squares) is depicted. This sequence was not recalled correctly. The orientation of the squares is identical to Start 4. c) A walking trajectory of modality condition Floor-Floor is shown. The sequence had a length of six squares and was not reproduced correctly. The sequence began at Start 2. d) A short sequence length (three squares) is depicted for Screen-Floor. The sequence started at Start 1 and was remembered correctly. In all figures the numbers indicate the position of the square in the sequence. The color gradient indicates the order of the clicks in a) and b), blue stars mark early clicks and red stars late clicks, and the time [s] participants needed to solve the trial in c) and d), also from blue (early) to red (late).

7.2.1. Analysis of correct trials

For the first analysis, participants' performance of correct trials and their Corsi span were evaluated. Overall, a decrease in performance with increasing sequence length was observed for all modality conditions. The number of correct trials (see Fig. 7.4) and also the Corsi span (see Tab. 7.1) in the four modality conditions decreased from Screen-Screen via Floor-Screen and Floor-Floor to the modality condition Screen-Floor.

Participants' Corsi span lay between 5.25 and 8.00 with an overall average of 6.54 (SD: ±0.64) in the modality condition Screen-Screen. In the modality condition Floor-Screen participants' Corsi span was between 3.75 and 6.50 with a total mean of 5.11 (SD: ±0.84) and in the modality condition Floor-Floor the overall average was 5.05 (SD: ±1.20) with individual Corsi spans between 3.00 and 6.75. In the modality condition Screen-Floor the

Corsi spans lay between 3.00 and 5.25 and an average of 4.09 (SD: ±0.65) was reached (see Tab. 7.1).

Table 7.1.: Participants' Corsi span and the mean Corsi span with standard deviation of all participants for each of the four modality condition.

Participant	**Screen-Screen**	**Floor-Screen**	**Floor-Floor**	**Screen-Floor**
1	6.75	6.50	3.00	4.75
2	7.00	6.00	5.25	4.50
3	7.00	5.25	6.75	5.00
4	6.00	3.75	3.75	4.00
5	6.75	4.75	4.50	4.25
6	8.00	6.00	5.75	3.00
7	6.00	5.00	5.75	3.25
8	6.25	3.75	3.50	3.50
9	6.50	4.25	5.50	4.25
10	5.25	4.50	3.50	3.50
11	6.75	5.00	5.25	5.25
12	6.75	5.75	6.00	4.00
13	6.00	5.50	5.75	4.00
14	6.50	5.50	6.50	4.00
mean	6.54 (SD ±0.64)	5.11 (SD ±0.84)	5.05 (SD ±1.20)	4.09 (SD ±0.65)

In the Screen-Screen modality condition participants recalled in the sequence lengths three and four almost 100 % of the trials correctly (see Fig. 7.4 a)). For a sequence length of six they still performed 71.43 % (SD: ±19.26) of the trials correctly. The performance decreased to 50.00 % (SD: ±27.74) of correct trials in a sequence length of eight squares. Overall, participants recalled 75.60 % (SD: ±10.70) of the trials correctly (see Fig. 7.4 b)).
In the modality condition Floor-Screen 51.79 % (SD: ±14.03) of all trials were reproduced correctly. For a sequence length of three participants recalled 78.57 % (SD: ±19.56) correctly. In the sequence lengths four and five participants reached a performance of about 55 %. In sequence length eight the performance decreased to 32.14 % (SD: ±26.73).
In the modality condition Floor-Floor 50.99 % (SD: ±19.98) of the trials were reproduced properly. For a sequence length of three 80.95 % (SD: ±26.84) of the trials were solved correctly. Still, for sequence length six participants reached a result of 50.00 % (SD: ±32.52) of correct trials. Then, the performance decreased more than in the modality condition Floor-Screen and in the sequence length eight participants reproduced only 21.43 % (SD: ±23.73) of the sequences properly.
In the modality condition Screen-Floor participants had an overall average of only 34.82 % (SD: ±10.79) of correct trials. At sequence length three participants' performance was 76.79 % (SD: ±24.93). In the following sequence lengths participants' performance decreased fast. In sequence length four the performance dropped to 51.79 % (SD: ±22.92) already. For the sequence lengths five to eight the performance was between 25.00 % (SD: ±25.94; sequence length five) and 12.50 % (SD: ±21.37; sequence length eight).

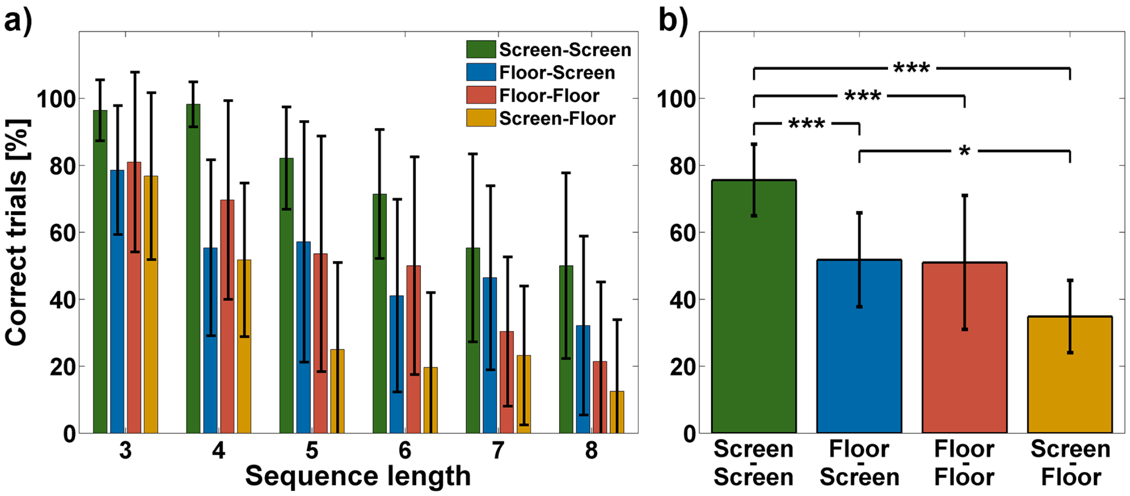

Figure 7.4.: Percentage of correct trials. a) For each modality condition the percentage of correct trials (y-axis) is plotted against the sequence length (x-axis). Overall, the task performance decreased with increasing sequence length for all modality conditions. The performance also decreased from Screen-Screen (green bars) via Floor-Screen (blue bars) and Floor-Floor (red bars) to the modality condition Screen-Floor (orange bars). b) The mean percentage over all sequence lengths and all fourteen participants (y-axis) is depicted for each modality condition (x-axis). The percentage of correct trials decreased from Screen-Screen via Floor-Screen and Floor-Floor to the modality condition Screen-Floor. This decrease was significant between all modality conditions except for the comparison of Floor-Screen and Floor-Floor, as well as Floor-Floor and Screen-Floor. Significant differences are depicted with stars. Error bars indicate the standard deviation.

To analyze main effect differences of the two factors modality condition and sequence length a two-way repeated measures ANOVA was conducted. The factor modality condition revealed a highly significant effect on the overall task performance (F(3, 39) = 25.855, $p < 0.001$, $\eta_P^2 = 0.665$; see Fig. 7.4).
A post hoc analysis showed significant differences between the modality conditions Screen-Screen and Floor-Screen ($p < 0.001$), Screen-Screen and Floor-Floor ($p < 0.001$), Screen-Screen and Screen-Floor ($p < 0.001$) and Floor-Screen and Screen-Floor ($p < 0.05$; depicted with stars in Fig. 7.4 b)). No differences between the modality conditions Floor-Floor and Screen-Floor as well as Floor-Screen and Floor-Floor have been found. An ANOVA also revealed a highly significant effect of the factor sequence length (F(5, 65) = 42.601, $p < 0.001$, $\eta_P^2 = 0.766$) and an interaction between the two factors modality condition and sequence length (F(15, 195) = 1.772, $p < 0.05$, $\eta_P^2 = 0.120$).

To further analyze whether performance differed between good and not as good participants they were split into two groups (above and below average; see Fig. 7.5). Therefore, the percentage of correct trials was evaluated in each modality condition and the seven participants with the best performance were grouped. This was done separately for each modality condition, so the seven participants in the above average group in modality condition Screen-Screen are not necessarily the same as e.g. the best seven participants in the Floor-Screen modality condition. Similarly, seven participants each were assigned to the below average group in each modality condition.
For each modality condition a t-test was conducted between the above and below groups. All four comparisons revealed significant differences ($p < 0.01$ or better).
In the above average group performance decreased from Screen-Screen (83.33 %, SD: ±7.61) via Floor-Screen (63.10 %, SD: ±6.98) and Floor-Floor (66.67 %, SD: ±7.61) to Screen-Floor

(42.86 %, SD: ± 7.50; see Fig. 7.5, dark bars). A similar course was found for the below average group (see Fig. 7.5, light bars). They reached 67.86 % (SD: ± 7.10) of correct trials in modality condition Screen-Screen, 40.48 % (SD: ± 8.91) in Floor-Screen and 35.32 % (SD: ± 15.30) in the modality condition Floor-Floor. In the modality condition Screen-Floor the below average group had a performance of 26.79 % (SD: ± 6.74) of correct trials. A conducted two-way ANOVA revealed no interaction between the factors modality condition and group.

To further analyze the main factor modality condition a one-way ANOVA for the above average group was conducted. A highly significant difference of the factor modality condition was found ($F(3, 24) = 35.041$, $p < 0.001$, $\eta_P^2 = 0.814$). A post-hoc analysis revealed highly significant differences between the modality conditions Screen-Screen and Floor-Screen, Screen-Screen and Screen-Floor, Floor-Screen and Screen-Floor, as well as for Floor-Floor and Screen-Floor (all with $p < 0.001$). Also for the modality conditions Screen-Screen and Floor-Floor a significant difference was observed ($p < 0.01$). No difference was found between Floor-Screen and Floor-Floor (see Fig. 7.5). A one-way ANOVA for the below average group revealed also highly significant differences between the modality conditions ($F(3, 24) = 21.566$, $p < 0.001$, $\eta_P^2 = 0.729$). A post-hoc test showed significant differences between Screen-Screen and all of the other three modality conditions (all $p < 0.001$). No differences were found between the modality conditions Floor-Screen and Floor-Floor, Floor-Screen and Screen-Floor and between Floor-Floor and Screen-Floor (see Fig. 7.5).

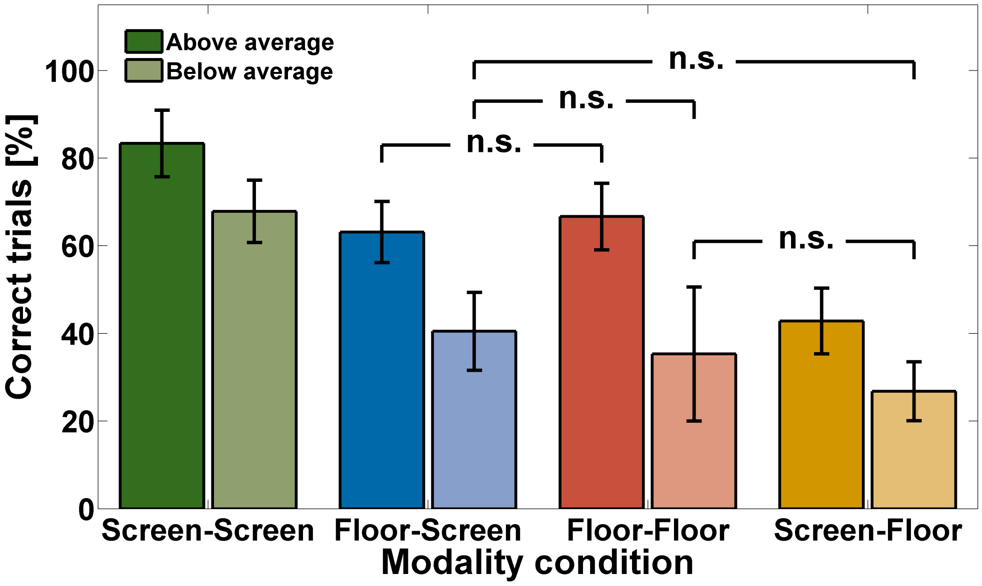

Figure 7.5.: Percentage of correct trials for participants above and below average for each modality condition. The percentage of correct trials (y-axis) is plotted for each modality condition (x-axis). The above average groups (dark bars) showed a performance decrease from Screen-Screen (green bars) via Floor-Screen (blue bars) and Floor-Floor (red bars) to Screen-Floor (orange bars). The below average groups (light bars) had similar courses, though with lower performances. Error bars indicate the standard deviation.

7.2.2. Analysis of correct initial sequence length

In addition to the percentages of correct trials the recall performance was also analyzed for the length of correct initial segments of each sequence (see Fig. 7.6).
At a sequence length of three almost all participants had the initial sequence correct in all modality conditions. For longer sequence lengths a separation was apparent. The length of the correct initial sequence increased significantly with increasing sequence length for the modality conditions Screen-Screen ($F(5, 65) = 8.70$, $p < 0.001$, $\eta_P^2 = 0.401$), Floor-Screen ($F(5, 65) = 6.276$, $p < 0.001$, $\eta_P^2 = 0.326$) and Floor- Floor ($F(5, 65) = 5.110$, $p < 0.01$, $\eta_P^2 = 0.282$) but not for the modality condition Screen-Floor ($F(5, 65) = 1.742$, $p = 0.137$, $\eta_P^2 = 0.118$) where the initial sequence length remained at 2.98 (SD: ±0.35) on average. Compared to the other three modality conditions the increase was largest and performance was best (mean: 5.19, SD: ±1.90) at a sequence length of eight in the Screen-Screen modality condition. Initially, the performance in the Floor-Floor modality condition was better than in the Floor-Screen one, but this effect changed between a sequence length of six and seven where the performance in the Floor-Screen modality condition got better than in the Floor-Floor modality condition. This matches the results of Fig. 7.4 when there was an inversion of the percentage of correct trials for these modalities.

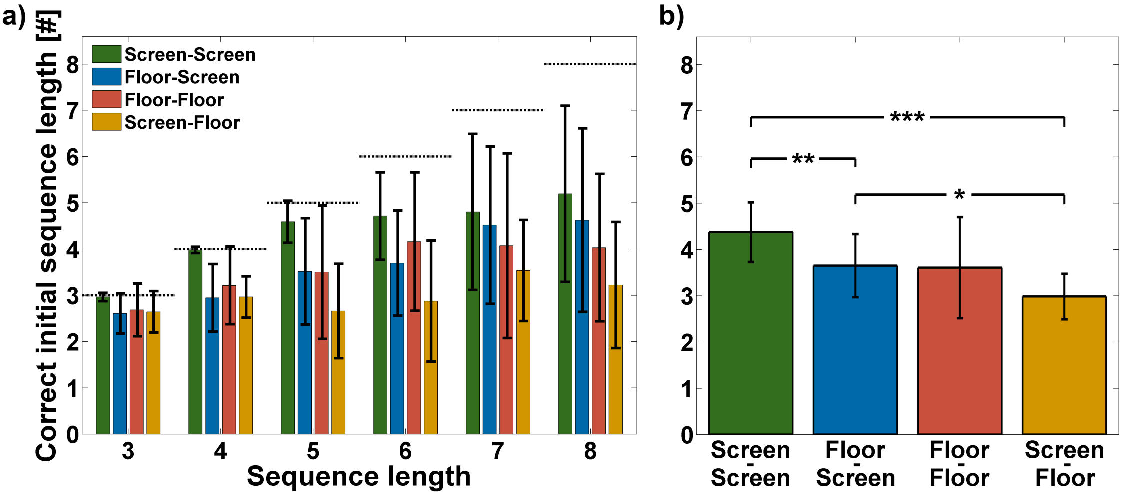

Figure 7.6.: Length of correct initial sequence. a) The over the fourteen participants averaged number of correctly reproduced initial squares (y-axis) in each modality condition is shown for all sequence lengths (x-axis). The length of correct initial sequence increased in the Screen-Screen modality condition (green bars) with increasing sequence length as well as for the Floor-Screen (blue bars) and Floor-Floor (red bars) modality conditions. In the Screen-Floor modality condition (orange bars) there was no change across sequence lengths. The horizontal lines denote the maximum possible number of correct initial sequence length. b) The mean length (over all sequence lengths) of correct initial sequences (y-axis) is shown for the four modality conditions (x-axis). The number decreased from Screen-Screen via Floor-Screen and Floor-Floor to Screen-Floor. This decrease was significant between the modality conditions Screen-Screen and Floor-Screen, Screen-Screen and Screen-Floor, as well as between Floor-Screen and Screen-Floor (depicted with stars). Error bars indicate the standard deviation.

On average, participants correctly recalled 4.38 (SD: ±0.65) initial squares in the modality condition Screen-Screen (see Fig. 7.6). The overall performance in the Floor-Screen (mean: 3.65, SD: ±0.68) and Floor-Floor (mean: 3.61, SD: ±1.09) modality conditions was identical. In the Screen-Floor modality condition the correct initial sequence length was 2.98

(SD: ±0.49) squares.
A two-way repeated measures ANOVA revealed highly significant differences between the modality conditions ($F(3, 39) = 11.375$, $p < 0.001$, $\eta_P^2 = 0.467$; see Fig. 7.6). A post hoc analysis revealed significant differences in the modality conditions Screen-Screen and Floor-Screen ($p < 0.01$), Screen-Screen and Screen-Floor ($p < 0.001$) and Floor-Screen and Screen-Floor ($p < 0.05$; all differences are depicted with stars in Fig. 7.6 b)). There was no difference between the modality conditions Screen-Screen and Floor-Floor as well as Floor-Screen and Floor-Floor and Floor-Floor and Screen-Floor.
A two-way repeated measures ANOVA showed also significant effects for the factor sequence length on the correct initial sequence length ($F(5, 65) = 14.445$, $p < 0.001$, $\eta_P^2 = 0.526$). No interaction between the factors modality condition and sequence length was found ($F(15, 195) = 1.587$, $p = 0.08$, $\eta_P^2 = 0.109$).

7.2.3. Analysis of partial set correct

Further, the number of correctly recalled squares from the shown sequence (see Fig. 7.7) but regardless of their order of reproduction (i.e., partial set correct) was analyzed.

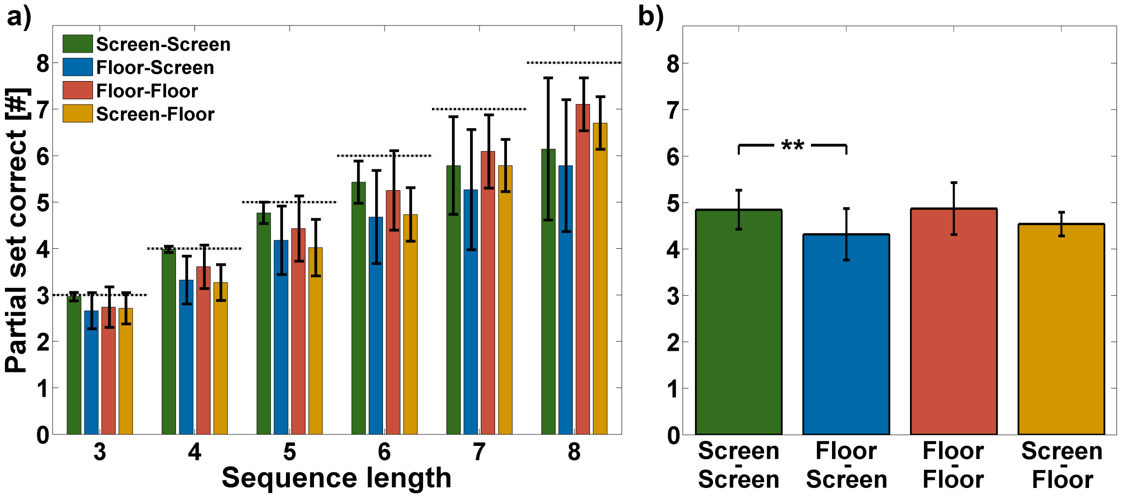

Figure 7.7.: Number of partial set correct. a) The mean number of partial set correct (y-axis) for all modality conditions (green, blue, red and orange bars) and sequence lengths (x-axis) are plotted. The number of squares correctly reproduced increased for all sequence lengths. The horizontal lines denote the maximum possible number of partial set correct square tiles. b) The mean number (average over the fourteen participants and six sequence lengths) of partial set correct (y-axis) is shown for the modality conditions (x-axis). The number was about the same for the modality conditions Screen-Screen and Floor-Floor as well as for the modality conditions Floor-Screen and Screen-Floor. The modality condition Screen-Screen was significantly different to the modality condition Floor-Screen. Error bars indicate the standard deviation.

In the modality condition Screen-Screen the participants recalled about 4.85 (SD: ±0.42) squares of the memorized sequence regardless of their order in the shown sequence (see Fig. 7.7). About the same number of partial set correct square tiles was reproduced in the Floor-Floor modality condition (mean: 4.87, SD: ±0.56). In the modality condition Floor-Screen 4.32 (SD: ±0.55) squares and in the Screen-Floor modality condition 4.54 (SD: ±0.25) squares regardless of their order were reproduced correctly.

A two-way repeated measures ANOVA revealed a significant effect for the modality conditions (F(3, 39) $= 5.653$, $p < 0.01$, $\eta_P^2 = 0.303$). Significant differences between the modality conditions were found between Screen-Screen and Floor-Screen ($p < 0.01$; see Fig. 7.7 b)). No differences were found between the other modality conditions. A highly significant effect (F(5, 65) $= 213.187$, $p < 0.001$, $\eta_P^2 = 0.943$) was found for the factor sequence lengths as well as an interaction between modality conditions and sequence lengths (F(15, 195) $= 2.905$, $p < 0.001$, $\eta_P^2 = 0.183$) was observed.

7.2.4. Analysis of walking speed

The mean walking speed of the fourteen participants was measured in the modality conditions Floor-Floor and Screen-Floor. The walking speeds decreased with increasing sequence length in both modality conditions from about 3.3 km/h in sequence length three, over 2.82 km/h in sequence length six to about 2.7 km/h in sequence length eight (see Fig. 7.8). In the modality condition Floor-Floor participants had a mean walking speed of 3.00 km/h (SD: ±0.24) over the six sequence lengths and in Screen-Floor the average amounted to 2.94 km/h (SD: ±0.27). There was no difference in walking speed between the two modality conditions.

For the analysis of the sequence length a Mauchly test indicated a violation of sphericity ($\chi^2(14) = 36.358$, $p < 0.01$), so degrees of freedom were adapted with Greenhouse-Geisser correction ($\epsilon = 0.414$). A two-way repeated measures ANOVA revealed a significant decrease of walking speed with increasing sequence length (F(1, 5) $= 89.885$, $p < 0.001$, $\eta_P^2 = 0.874$).

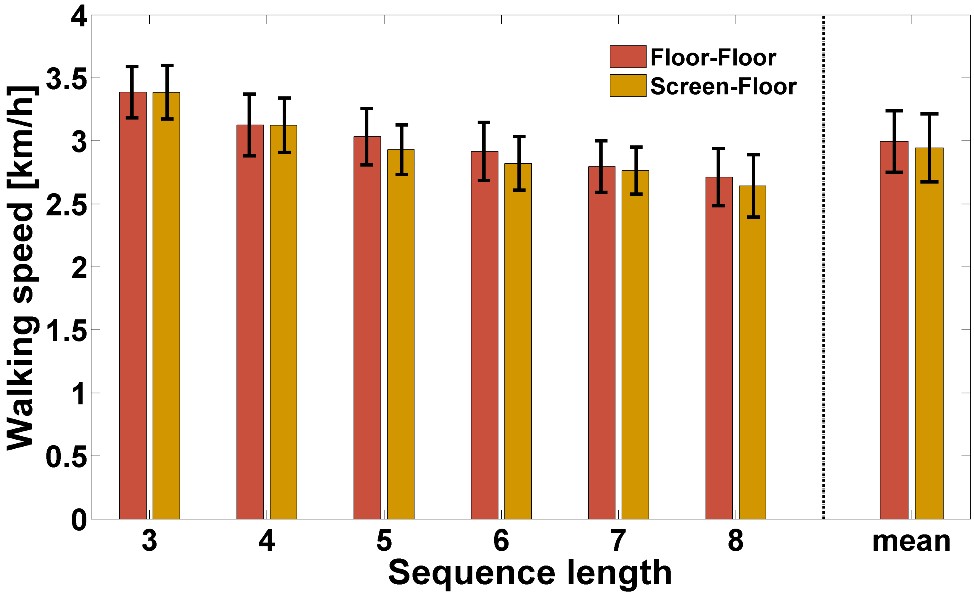

Figure 7.8.: Mean walking speed per sequence length. The mean walking speed (y-axis) averaged over the fourteen participants is depicted for all six sequence lengths (x-axis) and the modality conditions Floor-Floor and Screen-Floor. The walking speed decreased significantly with increasing sequence length in both modality conditions. There was no difference between the modality conditions. The red bars show the mean walking speeds in the modality condition Floor-Floor and the orange bars the ones in the modality condition Screen-Floor. Error bars indicate the standard deviation.

Comparison of walking speed in correct and false trials

Furthermore, for both modality conditions the walking speeds were split up in correctly solved trials and in false trials (see Fig. 7.9 a) and b)). A two-way ANOVA was conducted for both modality conditions to analyze main effect differences between the factors performance, means correct and false trials, respectively, and sequence length. As shown before for all trials, for the modality condition Floor-Floor again a highly significant decrease of walking speed with increasing sequence length was found (F(5, 125) = 17.334, $p < 0.001$, $\eta_P^2 = 0.409$). Also for the factor performance a significant difference was found (see Fig. 7.9 a)), showing that participants had a higher walking speed in the correctly solved trials than in the false trials (F(1, 125) = 3.968, $p < 0.05$, $\eta_P^2 = 0.031$). There was no interaction between the factors sequence length and performance.

In the modality condition Screen-Floor the walking speed in the false and correct trials also decreased with increasing sequence length (F(5, 121) = 24.088, $p < 0.001$, $\eta_P^2 = 0.499$; see Fig. 7.9 b)). In contrast to the modality condition Floor-Floor there was no difference in walking speed between the correct and false trials. No interaction between the factors sequence length and performance was observed.

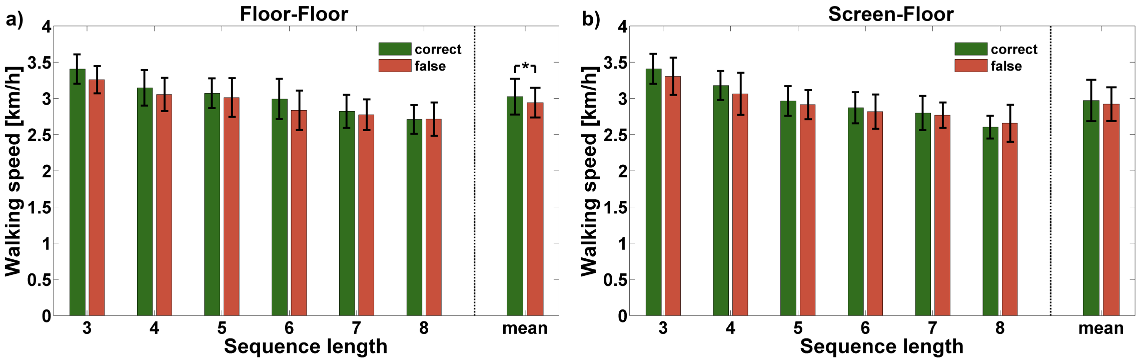

Figure 7.9.: Comparison of walking speed in correct and false trials. a) The mean walking speed (y-axis) is depicted for all six sequence lengths (x-axis) in modality condition Floor-Floor. The walking speed decreased with increasing sequence length in correct (green bars) as well as false (red bars) trials. The walking speed in the correct trials was significantly higher than in the false trials (depicted with a star above the overall mean over the fourteen participants and six sequence lengths on the right). b) The mean walking speed for each sequence length is shown for the modality condition Screen-Floor. Again the walking speed decreased with increasing sequence length in both groups. There was no difference between correct and false trials in this modality condition. The mean over all fourteen participants and six sequence lengths is shown on the right. Error bars indicate the standard deviation.

Analysis of walking speeds of different route segments

Similar to Experiment 1 and Experiment 2 the walking speeds were analyzed for each of the 28 segments (for classification of the different segments see Experiment 1: "Traveling Salesman task" chapter 3.2.3 "Analysis of walking speeds of different route segments" (p. 27) and appendix Fig. A.7 (p. 183) and Tab. A.1 (p. 184)).

For modality condition Floor-Floor 19 out of 28 segments were evaluated. No analyses were made for Segment 6, Segment 16, the segments 18 and 19, as well as the segments 21, 23, 24, 27 and 28, because of missing or not enough values. For two (Segment 3 and Segment 15) of the remaining 19 segments a significant decrease of walking speed with increasing sequence length was found (see Fig. 7.10 red lines at the top) and for Segment 14 a trend for a decrease

of walking speed was observed ($p = 0.055$). For Segment 3 a conducted one-way ANOVA revealed highly significant differences of the walking speeds ($F(4, 223) = 3.571$, $p < 0.01$, $\eta_P^2 = 0.060$). A post hoc analysis showed a significant decrease of walking speed between the sequence lengths four and eight ($p < 0.05$). Also a trend for differences in walking speeds was observed for the sequence lengths four and five ($p = 0.057$) and the sequence lengths four and seven ($p = 0.052$). For Segment 15 a one-way ANOVA showed a highly significant decrease of walking speed over the sequence lengths ($F(4, 101) = 4.290$, $p < 0.01$, $\eta_P^2 = 0.145$). A further post hoc test revealed significant differences between sequence length four and seven, five and seven, as well as six and seven (all with $p < 0.05$). Also between sequence length three and seven a highly significant decrease of walking speed was found ($p < 0.001$).
For modality condition Screen-Floor 21 out of 28 segments were analyzed. For the segments 6, 16, 18, 21 23 and 28 no evaluations were made because of missing values. For Segment 4 a trend for a decrease of walking speed was observed ($p = 0.061$). For five (Segment 7, Segment 10, Segment 13, Segment 15 and Segment 17) of the 21 segments a significant decrease of walking speed was found (see Fig. 7.10 orange lines at the bottom). For Segment 7 a conducted one-way ANOVA showed a highly significant decrease of walking speed with increasing sequence length ($F(4, 66) = 3.927$, $p < 0.01$, $\eta_P^2 = 0.192$). A post hoc analysis revealed significant differences between the sequence lengths six and eight ($p < 0.05$) and seven and eight ($p < 0.01$). Also for Segment 10 a highly significant decrease of walking speed was found ($F(5, 134) = 5.628$, $p < 0.001$, $\eta_P^2 = 0.174$). Sequence length three differed highly significant from the sequence lengths six ($p < 0.01$), seven ($p < 0.01$) and eight ($p < 0.001$). And sequence length four differed significantly from sequence length eight ($p < 0.05$). A conducted one-way ANOVA revealed a highly significant decrease of walking speed over the sequence lengths for Segment 13 ($F(4, 78) = 4.672$, $p < 0.01$, $\eta_P^2 = 0.204$). Significant differences were found between the sequence lengths three and five ($p < 0.05$) and the sequence lengths three and seven ($p < 0.01$). For Segment 15 a one-way ANOVA showed a highly significant decrease of walking speed ($F(5, 121) = 3.203$, $p < 0.01$, $\eta_P^2 = 0.117$). A further post hoc analysis revealed significant differences between sequence length three and six, as well as sequence length three and seven (both $p < 0.05$). Again for Segment 17 a decrease of walking speed with increasing sequence length was observed ($F(4, 72) = 3.585$, $p < 0.05$, $\eta_P^2 = 0.166$). A post hoc test showed significant differences between sequence length four and six ($p < 0.05$). All significant differences are depicted with stars in Fig. 7.10.

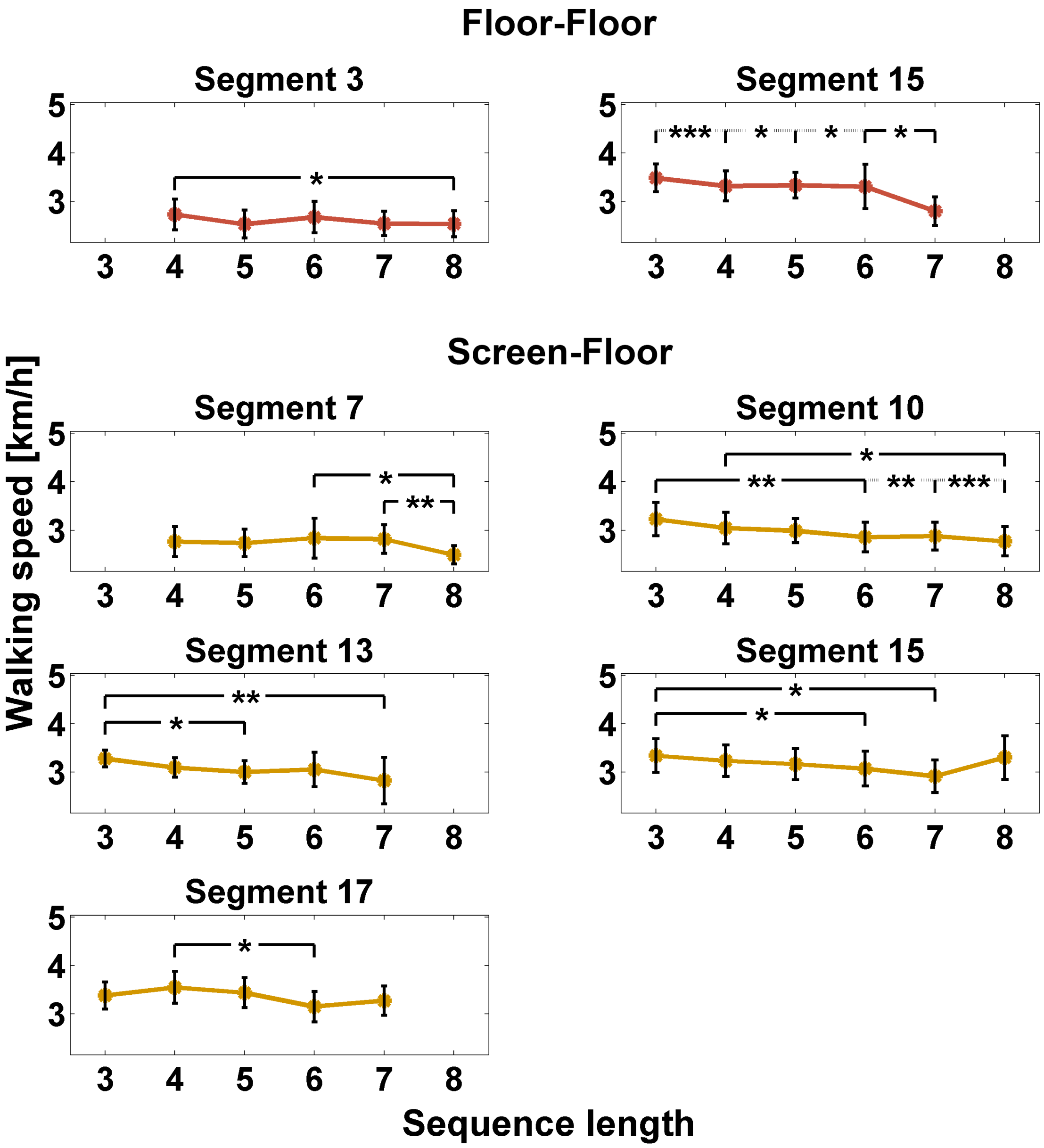

Figure 7.10.: Mean walking speeds of different segments of a sequence. The mean walking speeds (y-axes) are depicted with a dot for each of the eight sequence lengths (x-axes) for Floor-Floor (top; red lines) and Screen-Floor (bottom; orange lines). For the modality condition Floor-Floor a decrease of walking speed with increasing sequence lengths was found for Segment 3 and Segment 15. For modality condition Screen-Floor decreases of walking speed were found for five segments (Segment 7 to Segment 17). For sequence lengths without a dot no walking speeds for analyzing existed (e.g. Floor-Floor Segment 3: Participants were only walking the distances of Segment 3 in the sequence lengths four to eight, but not in sequence length three). All of the shown seven segments had significant differences in walking speeds over the sequence lengths. The significant differences among the sequence lengths are depicted with stars. Note: For reasons of presentation the depiction of significant differences between the sequence lengths are condensed in Segment 15 of Floor-Floor and Segment 10 of Screen-Floor and the dotted lines indicate the extension of the solid lines. In Segment 15 of Floor-Floor the sequence lengths three, four, five and six all differed significantly from sequence length seven, but not among each other. In Segment 10 of Screen-Floor sequence length three differed highly significant from the sequence lengths six, seven and eight. Error bars indicate the standard deviation.

To analyze whether there was a correlation between walking speed and distance, participants' walking speeds between two square tiles have been plotted against the distances of the squares, similarly as it was done for the experiments 1 and 2. This analysis was done for the modality conditions Floor-Floor and Screen-Floor (see Fig. 7.11).

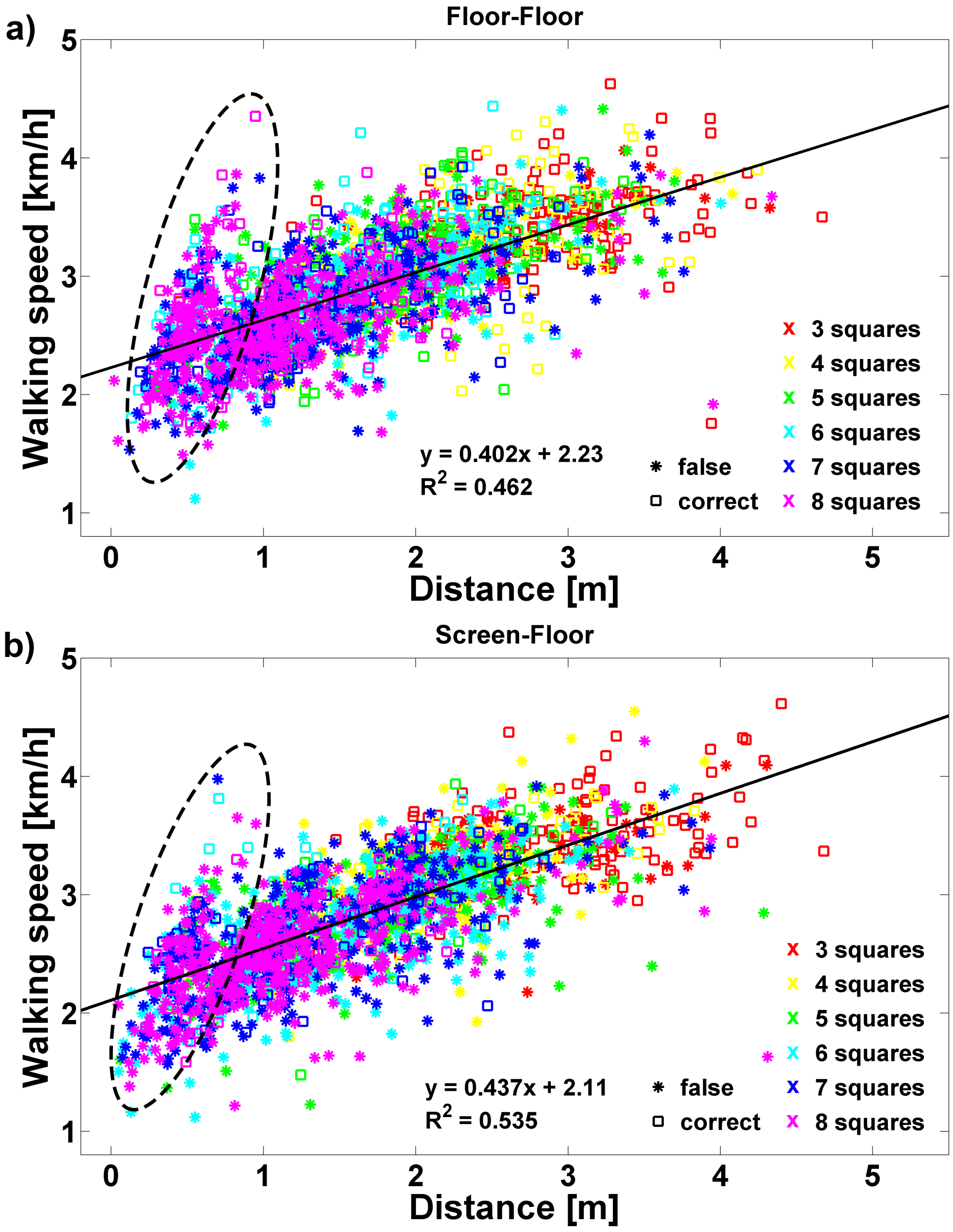

Figure 7.11.: Correlations between the mean walking speed and the distance between two square tiles. a) The correlation for the modality condition Floor-Floor is depicted. b) The correlation for the modality condition Screen-Floor is shown. In both modality conditions for each trial and participant the mean walking speed (y-axis) between two square tiles is plotted against the walked distance (x-axis) between these squares. In both cases a correlation was found which showed that with increasing distance the walking speed increased, too (Floor-Floor: $R^2 = 0.462$ and Screen-Floor: $R^2 = 0.535$). The dotted ellipses mark the second arms. Correct trials are depicted with squares, false trials with stars and the six sequence lengths with different colors.

In both cases a correlation between walking speed and distance was found. Like for the Trav-

eling Salesman task and the Walking Corsi task the walking speed increased with increasing distance between two squares (Floor-Floor: Pearson: $r = 0.680$, $p < 0.001$ and Screen-Floor: Pearson: $r = 0.731$, $p < 0.001$).
Similar to the experiments 1 and 2 before, a second arm was found in both modality conditions, too, which showed a stronger increase of walking speed for short distances. This second arm was still visible in the correct as well as the false trials of the modality conditions Floor-Floor and Screen-Floor (see appendix Fig. C.15 (p. 203) and Fig. C.16 (p. 204)).

7.2.5. Analysis of standing time

Besides walking speed also the mean standing time on a single square tile was evaluated for each sequence length in the modality conditions Floor-Floor and Screen-Floor (see Fig. 7.12). In the modality condition Floor-Floor the mean standing time of the fourteen participants was 1.02 s (SD: ±0.30) in sequence length three, 1.11 s (SD: ±0.36) in sequence length five and 1.19 s (SD: ±0.23) in sequence length eight. Participants had a mean standing time of 1.13 s (SD: ±0.08) in the modality condition Floor-Floor. In the modality condition Screen-Floor the mean standing time in sequence length three was 1.17 s (SD: ±0.31), in sequence length five it was 1.28 s (SD: ±0.31) and in sequence length eight 1.30 s (SD: ±0.26). This resulted in an averaged standing time on a single square tile of 1.26 s (SD: ±0.07).

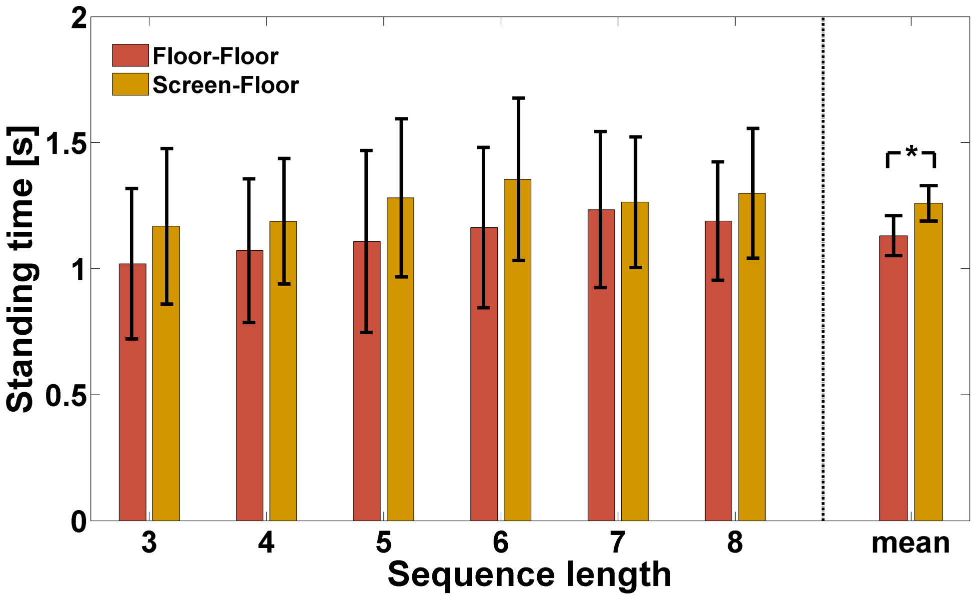

Figure 7.12.: Comparison between Floor-Floor and Screen-Floor in standing time. The over the fourteen participants averaged standing times on a single square tile (y-axis) are depicted for all sequence lengths (x-axis). The red bars show the standing times in the Floor-Floor modality condition and the orange bars the ones in the Screen-Floor modality condition. There was a trend that the standing time increased with increasing sequence length. The standing time differed significantly between the two modality conditions (depicted with stars above the overall means on the right). Error bars indicate the standard deviation.

A conducted two-way repeated measures ANOVA revealed a significant difference between the two modality conditions ($F(1, 13) = 4.950$, $p < 0.05$, $\eta_P^2 = 0.276$), showing that the standing time in the modality condition Screen-Floor was longer than in the modality condition Floor-Floor. For the factor sequence length the assumption of sphericity had been violated as Mauchly's test indicated ($\chi^2(14) = 40.420$, $p < 0.001$), for the following analysis Greenhouse-Geisser corrected ($\epsilon = 0.425$) values were used. Afterwards, a two-way repeated measures ANOVA did not reveal a difference in standing time over sequence lengths, but there was a trend that with increasing sequence length the standing time increased ($p = 0.062$).

Next, the standing time course within the shown sequences was investigated further for the modality conditions Floor-Floor and Screen-Floor. For each of the six sequence lengths the mean standing times on the single square tiles were plotted (see Fig. 7.13 a) and c)). For the modality condition Floor-Floor the mean standing time on the squares was between 1.0 and 1.3 s, whereas the sequence lengths three and four had the shortest standing times with 1.0 to 1.1 s. Sequence length seven had only a little increase of standing time for the first squares in the sequence, for the later squares in the sequence the standing time decreased (see Fig. 7.13 a) and b)). All of the other sequence lengths of modality condition Floor-Floor showed apparently a stronger increase for the first squares and also a decrease of standing time for the last squares of a sequence.

For modality condition Screen-Floor the mean standing times on the squares within a sequence length were between 1.0 and 1.6 s. Again there was a visible increase of the standing time at the beginning of the sequences and a decrease at the end of the sequences (see Fig. 7.13 c) and d)).

For each sequence length in both modality conditions a one-way ANOVA with repeated measures was conducted to investigate the factor standing time within a sequence.

For the modality condition Floor-Floor no differences in the standing times within a sequence were found for the sequence lengths three, four and six. For sequence length five a conducted one-way ANOVA with repeated measures revealed significant differences between the standing times on the squares during the sequence ($F(4, 52) = 5.335$, $p < 0.01$, $\eta_P^2 = 0.291$). A post hoc analysis revealed significant differences between the squares one and two ($p < 0.01$), one and three ($p < 0.01$), as well as two and five ($p < 0.05$). Also for the sequence lengths seven ($F(6, 78) = 3.124$, $p < 0.01$, $\eta_P^2 = 0.194$) and eight ($F(7, 91) = 2.651$, $p < 0.05$, $\eta_P^2 = 0.169$) significant differences for the standing times on the squares during the sequences were observed. A post hoc test showed no differences between the squares in both sequence lengths.

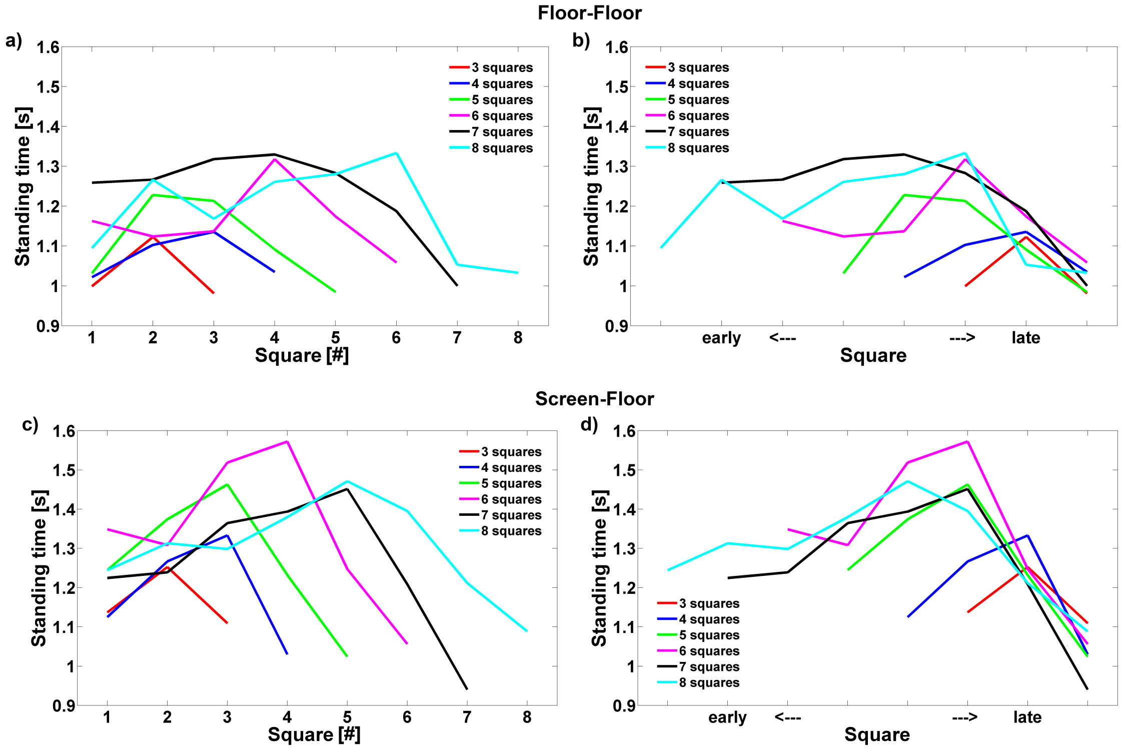

Figure 7.13.: Standing time courses. a) The mean standing time (y-axis) of the fourteen participants on a square tile (x-axis) is shown for each sequence length for Floor-Floor. All sequence lengths showed apparently an increase in standing time during the first squares of a sequence and a decrease at the end of a sequence. Only sequence length seven (black line) had no clearly visible increase of standing time at the beginning. Though, no differences in the standing times were found for the sequence lengths three, four and six. b) Again, the mean standing times (y-axis) of Floor-Floor are plotted, but this time aligned with the last square (x-axis) of a sequence. All sequence lengths tended to have a decrease of standing time from the last two to three squares before the end. c) The mean standing time (y-axis) of the fourteen participants on a square (x-axis) within a sequence is depicted for all sequence lengths, this time for Screen-Floor. Apparently all sequence lengths tended to have an increase of standing time in the first squares of a sequence and a decrease of standing time at the end of a sequence. No differences in standing times on a square were found for the sequence lengths three and eight. d) Again, the mean standing times (y-axis) were aligned with the last square (x-axis) of a sequence. Like before the decrease of the standing times was present for all sequence lengths for the last two to three squares of a sequence. The six sequence lengths are depicted with different colored lines.

In the modality condition Screen-Floor no difference in standing time course was found for the sequence lengths three and eight. For sequence length four a difference between standing times on the squares was shown by a one-way repeated measures ANOVA (F(3, 39) = 6.227, $p < 0.01$, $\eta_P^2 = 0.324$). A following post hoc analysis revealed significant differences between the squares two and four ($p < 0.05$) and three and four ($p < 0.05$). For sequence length five a Mauchly test indicated a violation of sphericity ($\chi^2(9) = 41.989$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\epsilon = 0.377$) was used for further analysis. Again a difference between the standing times was found (F(1.507, 19.597) = 6.173, $p < 0.05$, $\eta_P^2 = 0.322$). The squares one and five ($p < 0.05$), two and five ($p < 0.05$) and four and five ($p < 0.05$) differed significantly from each other. Also for sequence length six a Mauchly test indicated a violation of sphericity ($\chi^2(14) = 32.261$, $p < 0.01$) and Greenhouse-Geisser corrected values ($\epsilon = 0.545$) were used further on. The standing times within the sequence differed significantly (F(2.723, 35.399) = 6.340, $p < 0.01$, $\eta_P^2 = 0.328$). Significant differences between square one and six ($p < 0.05$), two and six ($p < 0.05$), as well as four and six ($p < 0.05$) were found with a post hoc analysis. Once more for sequence length seven a Mauchly test indicated a violation of sphericity ($\chi^2(20) = 36.555$, $p < 0.05$) and Greenhouse-Geisser corrected values were used ($\epsilon = 0.427$). Significant differences in standing time were also observed for sequence length seven (F(2.564, 33.337) = 4.851, $p < 0.01$, $\eta_P^2 = 0.272$). The squares two and seven ($p < 0.05$), three and seven ($p < 0.01$) and four and seven ($p < 0.05$) differed significantly in the standing times.

For both modality conditions the standing times were plotted again, but this time aligned with the last square of a sequence (see Fig. 7.13 b) and d)). This was done for comparison reasons. In Floor-Floor as well as Screen-Floor the standing times tended to increase in the first squares of the sequences and to decrease at the end. This apparent decrease was present for all sequence lengths in both modality conditions and it began in all sequence lengths about three squares before the end.

7.2.6. Analysis of sequences

As for the experiments “Traveling Salesman task” and “Walking Corsi task” the starting positions for the modality conditions Floor-Floor and Screen-Floor were evaluated in more detail. In contrast to the two already mentioned experiments, this time participants began the trials from four different starting positions (see e.g. Fig. 7.3). In each sequence length participants started one of the four trials from one of the four starting position, so in total each starting position was the beginning of a sequence for six times.

In the modality condition Floor-Floor participants remembered 59.76 % (SD: ±49.34) of the sequences which began at Start 1 correctly. Beginning at Start 2 44.05 % (SD: ±49.94) of the sequences were solved properly and at Start 3 47.62 % (SD: ±50.24) of the memorized sequences were remembered in the correct order. 53.01 % (SD: ±50.21) of the sequences which began at Start 4 were reproduced correctly. A conducted χ^2-test revealed no difference in performance between the four starting positions.

Beginning at Start 1 in modality condition Screen-Floor participants solved 35.71 % (SD: ±48.20) of the sequences correctly. Starting at Start 2 32.14 % (SD: ±46.98) of the trials were remembered correctly. Beginning at Start 3 participants solved 30.95 % (SD: ±46.51) of the sequences properly and beginning at Start 4 43.04 % (SD: ±49.83) of the trials were reproduced in the right order. Again a χ^2-test was conducted. Like for modality condition Floor-Floor no difference in performance between the starting positions was found.

Not only the starting positions in the modality conditions Floor-Floor and Screen-Floor, but also the pattern orientations in the modality conditions Screen-Screen and Floor-Screen were analyzed for differences. Again each pattern orientation was used six times for each of the fourteen participants. In the modality condition Screen-Screen participants solved 75.00 % (SD: ± 43.57) of the trials correctly, with a pattern orientation similar to Start 1. For pattern orientations equal to Start 2 72.62 % (SD: ± 44.86) of the trials were solved properly. In both of the pattern orientations similar to Start 3 and Start 4 a performance of 77.38 % (SD: ± 42.09) correct trials was reached by the participants. A χ^2-test showed no difference between the four pattern orientations.

Similar evaluations were made for the modality condition Floor-Screen. In the pattern orientation equal to Start 1 participants remembered 47.62 % (SD: ± 50.24) of the trials properly and in the pattern orientation similar to Start 2 a performance of 45.24 % (SD: ± 50.07) was reached. In the pattern configuration similar to Start 3 participants recalled 52.38 %

(SD: ± 50.24) of the trials correctly and in pattern orientations equal to Start 4 61.91 % (SD: ± 48.85) of the trials were solved correctly. Once more a χ^2-test was conducted, but again no difference between the pattern orientations was found.

Participants' performance in the modality conditions Floor-Floor and Screen-Floor was compared with the minimal number of crossings (Fig. 7.14 a)) and the minimal rotation angles of each sequence (Fig. 7.14 b)). The correctness of the sequences in these modality conditions was correlated with the minimal number of crossings (Spearman: r_s = -0.408, $p < 0.01$). There was also a significant correlation between the correctness of the sequences and the minimal rotation angle (Pearson: r = -0.787, $p < 0.001$). Overall, an increase in number of crossings and in size of rotation angles resulted in a poorer performance in the percentage of correct trials.

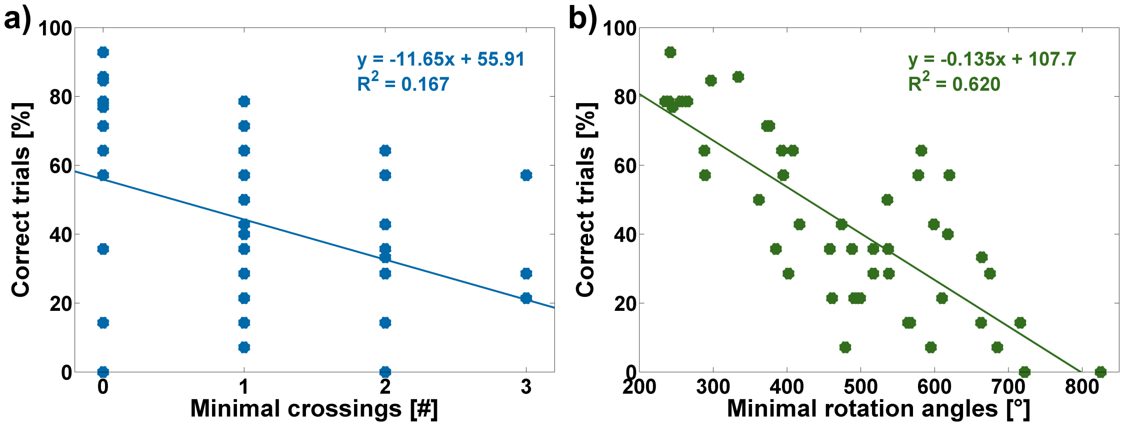

Figure 7.14.: Correlations between the mean percentage of correctly reproduced sequences and minimal crossings or rotations. a) Correlation between the mean percentage of correctly reproduced sequences (y-axis) in the modality conditions Floor-Floor and Screen-Floor and the number of minimal crossings (x-axis) for each sequence. There was a correlation showing that with more crossings the percentage of correctly reproduced sequences decreased (R^2 = 0.167). b) Correlation between the mean percentages of correctly reproduced sequences (y-axis) and the minimal rotation angle (x-axis) of the sequences. With increasing rotation angle the percentage of correctly reproduced sequences decreased (R^2 = 0.620). Note: Less than 48 dots were caused by overlapping dots.

7.2.7. Comparison between males and females

For the six male and eight female participants performance comparisons were made for each of the four modality conditions.

Screen-Screen: In the modality condition Screen-Screen the factors percentage of correct trials, correct initial sequence length and partial set correct square tiles were compared for gender differences. For the factor percentage of correct trials a conducted two-way ANOVA revealed a significant difference between male and female participants, with males performing better ($F(1, 72) = 7.666$, $p < 0.01$, $\eta_P^2 = 0.096$; see appendix Fig. C.7, p. 199). There was no interaction between the factors gender and sequence length.
Also for the factor correct initial sequence length a difference between males and females was found ($F(1, 72) = 5.017$, $p < 0.05$, $\eta_P^2 = 0.065$). Males had a slightly longer initial sequence length (see appendix Fig. C.8, p. 199), but there was no interaction between gender and

sequence length.
A two-way ANOVA for the third factor partial set correct showed again a difference between the genders (see appendix Fig. C.9, p. 200), indicating that males had a better performance than females (F(1, 72) $= 6.082$, $p < 0.05$, $\eta^2_P = 0.078$). Though, once more no interaction between gender and sequence length was observed.

Floor-Screen: In the modality condition Floor-Screen the same three factors like before in the modality condition Screen-Screen were analyzed for gender differences. In this modality condition no differences between the genders were found in any of these factors.

Floor-Floor: Five factors (percentage of correct trials, correct initial sequence length, number of partial set correct squares, walking speed and standing time on a single square tile) were evaluated for gender differences in the modality condition Floor-Floor. A two-way ANOVA resulted in a significant difference between the genders for the factor correct initial sequence length (F(1, 72) $= 6.775$, $p < 0.05$, $\eta^2_P = 0.086$), showing that males had a longer correct initial sequence length than females (see appendix Fig. C.10, p. 200). No interaction between the factors gender and sequence length was found.
The factor number of partial set correct squares also differed among males and females (F(1, 72) $= 4.745$, $p < 0.05$, $\eta^2_P = 0.062$). The number of partial set correct squares was higher in male participants than in female participants (see appendix Fig. C.11, p. 201), but there was no interaction between the factors gender and sequence length.
A two-way ANOVA revealed a significant difference for the factor walking speed (F(1, 72) $= 6.012$, $p < 0.05$, $\eta^2_P = 0.077$). Males had a higher walking speed than females (see appendix Fig. C.12, p. 201). Again the factors gender and sequence length had no interaction.
For the factors percentage of correct trials and standing time no differences between males and females were observed.

Screen-Floor: In this modality condition the factors percentage of correct trials, the length of the correct initial sequence, the number of partial set correctly reproduced squares as well as the walking speed and the standing time were analyzed for differences among genders. A two-way ANOVA revealed a difference between males and females for the factor correct initial sequence length (F(1, 72) $= 3.991$, $p < 0.05$, $\eta^2_P = 0.053$). Males' correct initial sequence length was longer than females' correct initial sequence length (see appendix Fig. C.13, p. 202). The factors gender and sequence length did not show an interaction.
For the factor walking speed a highly significant difference between the genders was found (F(1, 72) $= 23.537$, $p < 0.001$, $\eta^2_P = 0.246$). Males' walking speed was faster than females' walking speed (see appendix Fig. C.14, p. 202). There was no interaction between the factors gender and sequence length.
In this modality condition no differences between the genders were observed for the factors percentage of correct trials, number of partial set correctly reproduced square tiles and standing time.

7.2.8. Comparison with Corsi task 1 and Corsi task 2

Like in the experiments before the results were compared with other experiments. For the modality conditions Screen-Screen and Floor-Screen the results were compared to the results of the Corsi tasks in Experiment 3 (Corsi task 1) and Experiment 4 (Corsi task 2). Corsi task 1 and Corsi task 2 did not differ in the percentage of correct trials and in the length of the correct initial sequence, but the number of partial set correctly reproduced square tiles was different between the two tasks. Therefore the two tasks were not merged but kept separately for all comparisons. The comparisons here were made for the percentage of correctly reproduced trials, the length of the correctly reproduced initial squares and the number of partial set correctly remembered squares. In the modality conditions Screen-Screen and Floor-Screen participants had to solve trials up to a sequence length of eight squares, so all comparisons between the experiments were only made for the sequence lengths three to eight.

Correct trials

The results of the percentage of correct trials in the four experiments (Corsi task 1, Corsi task 2, Screen-Screen and Floor-Screen) are depicted in Fig. 7.15. In all experiments a decrease in percentage of correct trials with increasing sequence length was observed. In Corsi task 1, Corsi task 2 and Screen-Screen the performance of the participants was over 90 % in the sequence lengths three and four. In sequence length six still over 70 % of correctly reproduced trials were reached. In sequence length eight the results split up a bit, in the both Corsi tasks over 20 % were recalled correctly, but in the Screen-Screen modality condition still 50.00 % (SD: ±27.74) were solved correctly. In the Floor-Screen modality condition participants reached a performance of 78.57 % (SD: ±19.26) in sequence length three and 55.34 % (SD: ±26.27) in sequence length four. In sequence length six 41.07 % (SD: ±28.77) of the trials were solved properly and in sequence length eight 32.14 % (SD: ±26.73; see Fig. 7.15 a)). The mean percentage of correct trials over all sequence lengths was between 72 % and 75 % in Corsi task 1, Corsi task 2 and Screen-Screen. In the modality condition Floor-Screen 51.79 % (SD: ±14.03) of correctly reproduced trials were reached over all sequence lengths (see Fig. 7.15 b)).

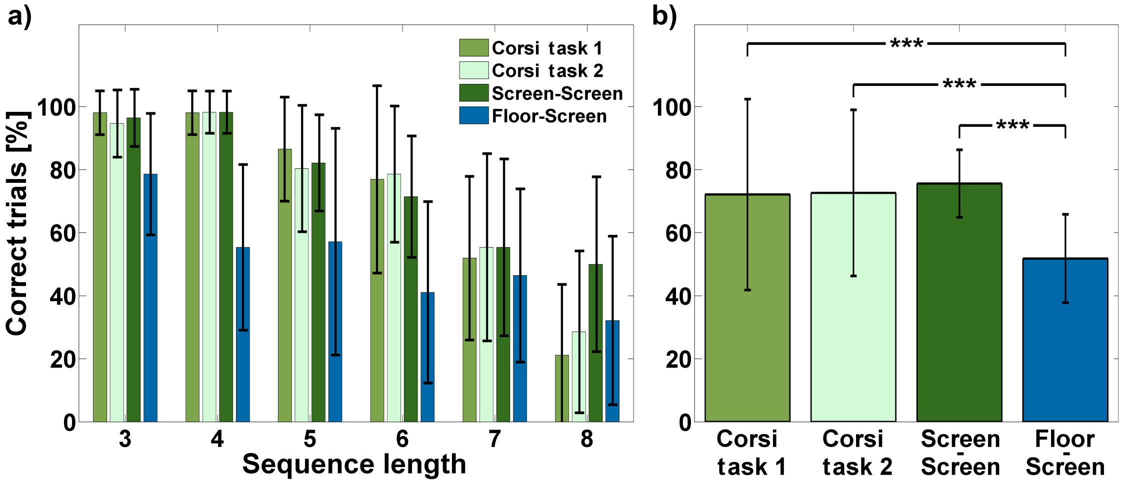

Figure 7.15.: Comparison between Corsi task 1, Corsi task 2, Screen-Screen and Floor-Screen in percentage of correct trials. a) The mean percentage of correct trials (y-axis) is depicted for the four experiments (blue and green bars) in the six different sequence lengths (x-axis). In all experiments the performance decreased with increasing sequence length. b) The overall mean over the sequence lengths (y-axis) is shown for the four experiments (x-axis). The performance in Corsi task 1 (green bar), Corsi task 2 (mint green bar) and Screen-Screen (dark green bar) was equal and all three experiments differed significantly from the performance in Floor-Screen (blue bar). Error bars indicate the standard deviation.

To compare main effects of the two factors experiment and sequence length, a two-way

ANOVA with repeated measures on one factor (sequence length) was conducted. A Mauchly test revealed a violation of sphericity for the factor sequence length ($\chi^2(14) = 39.537$, $p < 0.001$), so a Greenhouse-Geisser correction ($\epsilon = 0.815$) was used for further analyses. An ANOVA revealed a highly significant decrease of performance with increasing sequence length ($F(4.074, 207.757) = 62.128$, $p < 0.001$, $\eta_P^2 = 0.549$). Also significant differences between the experiments were found ($F(3, 51) = 12.790$, $p < 0.001$, $\eta_P^2 = 0.429$). The modality condition Floor-Screen had a highly significant difference ($p < 0.001$) to all of the three other experiments (depicted with stars in Fig. 7.15 b)). The two Corsi tasks and Screen-Screen showed no difference among each other. An interaction between the factors experiment and sequence length was observed ($F(5, 207.757) = 2.926$, $p < 0.001$, $\eta_P^2 = 0.147$).

Correct initial sequence length

Afterwards, the length of the correct initial sequence was compared between Corsi task 1, Corsi task 2, Screen-Screen and Floor-Screen (see Fig. 7.16).

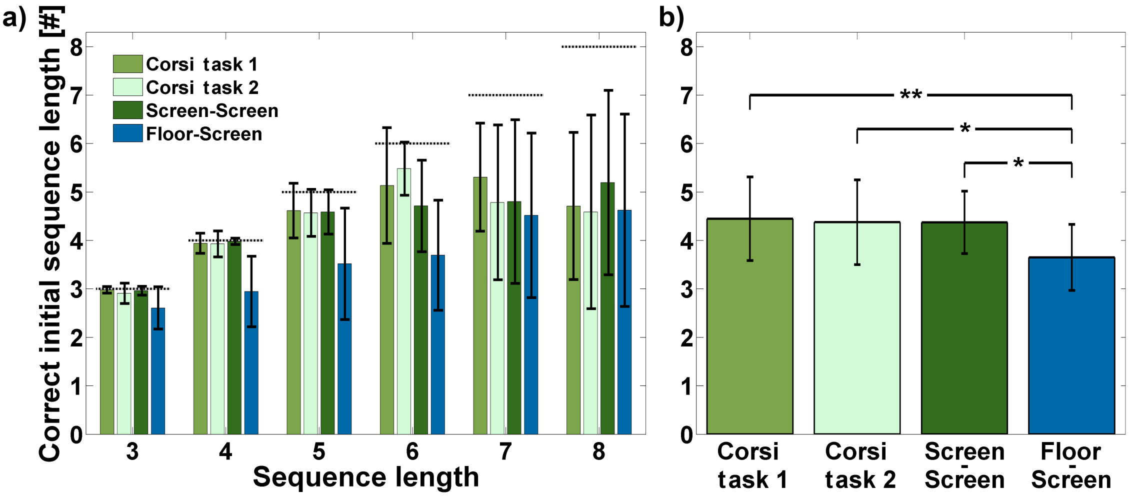

Figure 7.16.: Comparison between Corsi task 1, Corsi task 2, Screen-Screen and Floor-Screen in correct initial sequence length. a) The mean number of correctly reproduced initial squares (y-axis) in each experiment (green and blue bars) is depicted for all sequence lengths (x-axis). The length of the correct initial sequence increased with increasing sequence lengths in all four experiments. The horizontal lines denote the maximum possible length of correct initial sequence. b) The mean average of correct initial sequence length over all sequence lengths (y-axis) is depicted for each experiment (x-axis). The means were equal for the experiments Corsi task 1 (green bar), Corsi task 2 (mint green bar) and Screen-Screen (dark green bar), but differed significantly from Floor-Screen (blue bar). Error bars indicate the standard deviation.

In all four experiments the correct initial sequence length increased with increasing sequence length. In the sequence lengths three and four participants almost reached the maximum possible initial sequence length of three and four, respectively, in the experiments Corsi task 1, Corsi task 2 and Screen-Screen. In Floor-Screen participants had a mean initial sequence length of 2.61 (SD: ±0.44) squares in the sequence length three and 2.95 (SD: ±0.73) squares in sequence length four. In sequence length eight participants reached a correct initial sequence length between 4.59 and 5.19 square tiles in the experiments Corsi task 1, Corsi task 2 and Screen-Screen. The correct initial sequence length in Floor-Screen was 4.63 (SD: ±1.98; see Fig. 7.16 a)). The average initial sequence length over all sequence lengths and participants

amounted to about 4.30 in the experiments Corsi task 1, Corsi task 2 and Screen-Screen. All three experiments differed significantly from Floor-Screen, in which a mean of 3.65 (SD: ±0.68) was reached (see Fig. 7.16 b); differences are depicted with stars).
For analyzing main effect differences of the factors experiment and sequence length a two-way ANOVA with repeated measures on one factor (sequence length) was carried out. For further analysis of the factor sequence length a Greenhouse-Geisser correction ($\epsilon = 0.558$) was used, because a Mauchly test revealed a violation of sphericity ($\chi^2(14) = 148.586$, $p < 0.001$) before. A highly significant effect for the factor sequence length was observed, indicating that the length of the correct initial sequence increased over the sequence lengths ($F(2.788, 142.205) = 30.844$, $p < 0.001$, $\eta_P^2 = 0.377$). The comparison between the experiments revealed also significant differences ($F(3, 51) = 5.703$, $p < 0.01$, $\eta_P^2 = 0.251$). A post hoc test showed a difference between Corsi task 1 and Floor-Screen ($p < 0.01$). Corsi task 2 and Screen-Screen also differed from Floor-Screen ($p < 0.05$; see also stars in Fig. 7.16 b)).

Partial set correct

As last comparison between these four experiments, the number of partial set correctly reproduced square tiles was compared (see Fig. 7.17).

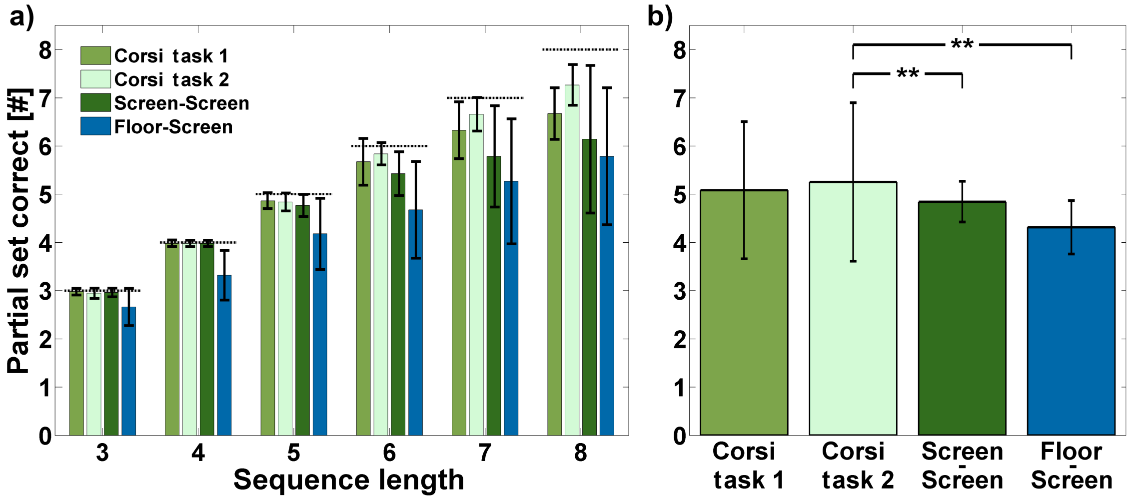

Figure 7.17.: Comparison between Corsi task 1, Corsi task 2, Screen-Screen and Floor-Screen in number of partial set correct. a) The mean number of partial set correctly reproduced square tiles (y-axis) is plotted for each experiment (green and blue bars) and sequence length (x-axis). In all experiments the number of partial set correctly reproduced square tiles increased with increasing sequence length. The horizontal lines denote the maximum possible number of partial set correct squares. b) The average of partial set correct squares over the participants and sequence lengths (y-axis) is depicted for the four experiments (x-axis). The experiments Corsi task 1 (green bar), Corsi task 2 (mint green bar) and Screen-Screen (dark green bar) reached about the same average. Corsi task 2 and Screen-Screen differed significantly from Floor-Screen (blue bar). Error bars indicate the standard deviation.

In all four experiments the number of correctly reproduced square tiles regardless of their order increased with increasing sequence length (see Fig. 7.17 a)). In Corsi task 1 the number of partial set correct increased from 2.98 (SD: ±0.07) square tiles in sequence length three to 6.67 (SD: ±0.53) squares in sequence length eight. In Corsi task 2 2.95 (SD: ±0.11) squares in sequence length three and 7.27 (SD: ±0.42) of partial set correct square tiles in sequence length

eight were reached. The number of partial set correct squares in Screen-Screen amounted to 2.96 (SD: ±0.09) square tiles in sequence length three and 6.14 (SD: ±1.53) square tiles in sequence length eight. In the modality condition Floor-Screen participants had a mean number of partial set correct of 2.66 (SD: ±0.39) squares in sequence length three and 5.79 (SD: ±1.42) squares in sequence length eight (see Fig. 7.17 a)). The total mean was between 4.84 and 5.26 in Corsi task 1, Corsi task 2 and Screen-Screen. In Floor-Screen an average of 4.31 (SD: ±0.55) was reached (see Fig. 7.17 b)).
Like in the both comparisons for the percentage of correct trials and the length of the correct initial sequence again a two-way ANOVA with repeated measures on one factor (sequence length) was conducted. For the analysis of sequence length a Greenhouse-Geisser correction was used ($\epsilon = 0.422$; Mauchly test: $\chi^2(14) = 284.656$, $p < 0.001$). A highly significant increase of partial set correct squares with increasing sequence length was observed ($F(2.112, 107.719) = 322.377$, $p < 0.001$, $\eta_P^2 = 0.863$). Also the experiments differed significantly from each other ($F(3, 51) = 5.340$, $p < 0.01$, $\eta_P^2 = 0.239$). A post hoc test showed significant differences of Corsi task 2 from Screen-Screen and Floor-Screen (both with $p < 0.01$; depicted with stars in Fig. 7.17 b)). An interaction between the factors sequence length and experiment was found, too ($F(6.336, 107.719) = 2.433$, $p < 0.05$, $\eta_P^2 = 0.125$).

7.2.9. Comparison with Traveling Salesman task and Walking Corsi task

As for the modality conditions Screen-Screen and Floor-Screen, the modality conditions Floor-Floor and Screen-Floor were compared with the results of the previous experiments. This time the comparisons were made with Experiment 1: “Traveling Salesman task” and Experiment 2: “Walking Corsi task”. The results of these four experiments were compared for the percentage of correct trials, the length of the correct initial sequence, the number of partial set correctly reproduced squares, the walking speed as well as the standing time. Again, the comparisons were only made between the route and sequence lengths three to eight, since participants did not solve trials in the sequence lengths nine and ten in the modality conditions Floor-Floor and Screen-Floor. Because for the Traveling Salesman task there were no results for the length of the correct initial sequence and for partial set correct squares, in these cases only comparisons between the Walking Corsi task and the modality conditions Floor-Floor and Screen-Floor were made.

Correct trials

As first comparison between the four experiments the percentages of correct trials were analyzed (see Fig. 7.18). In all experiments a decrease of performance with increasing route and sequence length was found. In the Traveling Salesman task participants' performance decreased from 96.43 % (SD: ±13.36) in route length three to 75.00 % (SD: ±24.02) in route length eight, though in route length seven only 42.86 % (SD: ±15.28) were reached. For Walking Corsi task the performance in sequence length three amounted to 60.71 % (SD: ±21.29) and to 7.14 % (SD: ±11.72) in sequence length eight. The mean percentage of correct trials in Floor-Floor was 80.95 % (SD: ±26.84) in sequence length three and 21.43 % (SD: ±23.73) in sequence length eight. 76.79 % (SD: ±24.93) of correct trials were reached in sequence length three in modality condition Screen-Floor and 12.50 % (SD: ±21.37) in sequence length eight (see Fig. 7.18 a)). Overall, participants reached 75.09 % (SD: ±18.91) of correct trials in the Traveling Salesman task and 50.99 % (SD: ±19.98) in the modality condition Floor-Floor.

The averages in the Walking Corsi task and in the modality condition Screen-Floor were similar with about 24 % (see Fig. 7.18 b)).
A two-way ANOVA with repeated measures on one factor (route and sequence length) revealed a highly significant decrease for the factor route and sequence length (F(5, 260) = 57.010, $p < 0.001$, $\eta_P^2 = 0.523$) and highly significant differences between the experiments (F(3, 52) = 32.440, $p < 0.001$, $\eta_P^2 = 0.652$). Also an interaction between the experiments and route and sequence lengths was observed (F(15, 260) = 4.274, $p < 0.001$, $\eta_P^2 = 0.198$). A post hoc analysis showed highly significant differences between the Traveling Salesman task and each of the three other experiments ($p < 0.001$). Floor-Floor differed from the Walking Corsi task with $p < 0.01$ and from Screen-Floor with $p < 0.05$. There was no difference between the Walking Corsi task and Screen-Floor (see Fig. 7.18 b); significant differences are depicted with stars).

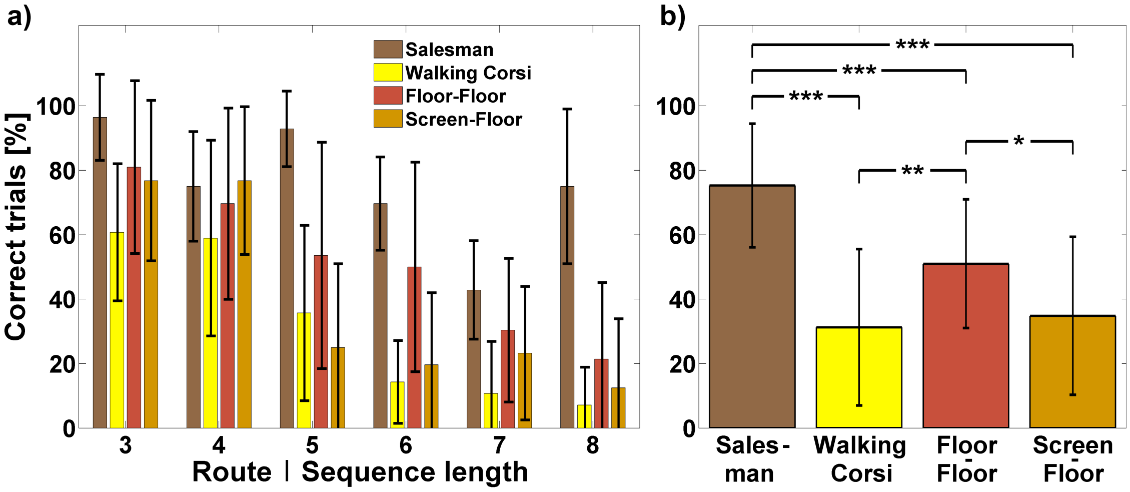

Figure 7.18.: Comparison between Traveling Salesman task, Walking Corsi task, Floor-Floor and Screen-Floor in percentage of correct trials. a) The mean percentage of correct trials (y-axis) of the four experiments (brown, yellow, red and orange bars) is shown for all route and sequence lengths (x-axis). With increasing route and sequence length the performance in the four experiments decreased. b) The performance over all route and sequence lengths (y-axis) is depicted for each experiment (x-axis). The percentage of correct trials decreased from Traveling Salesman task (brown bar) over Floor-Floor (red bar) to Walking Corsi task (yellow bar) and Screen-Floor (orange bar). The performance was significantly different in all experiments except for Walking Corsi task and Screen-Floor. Error bars indicate the standard deviation.

Correct initial sequence length

Next, the length of the correct initial sequence was compared for Walking Corsi task, Floor-Floor and Screen-Floor (see Fig. 7.19). In the modality condition Floor-Floor the length of the correct initial sequence increased over the sequence lengths from 2.68 (SD: ±0.57) squares in sequence length three to 4.03 (SD: ±1.59) squares in sequence length eight. For the Walking Corsi task and Screen-Floor no difference over the sequence lengths was observed (see Fig. 7.19 a)). The average over all sequence length was about 2.90 squares for the experiments Walking Corsi task and Screen-Floor. In the modality condition Floor-Floor participants reached an overall mean of 3.61 (SD: ±1.01) correct reproduced initial squares (see Fig. 7.19 b)).
A two-way ANOVA with repeated measures on one factor (sequence length) was conducted. Because the assumption of sphericity had been violated as Mauchly's test indicated

($\chi^2(14) = 45.451$, $p < 0.001$), a Greenhouse-Geisser correction ($\epsilon = 0.752$) was used in the following for the factor sequence length. There was a highly significant effect for the factor sequence length ($F(3.759, 146.615) = 4.605$, $p < 0.001$, $\eta_P^2 = 0.106$). The three experiments did not show a difference in the correct initial sequence length, but there was a trend that Floor-Floor differed from the experiments Walking Corsi task and Screen-Floor ($p = 0.053$).

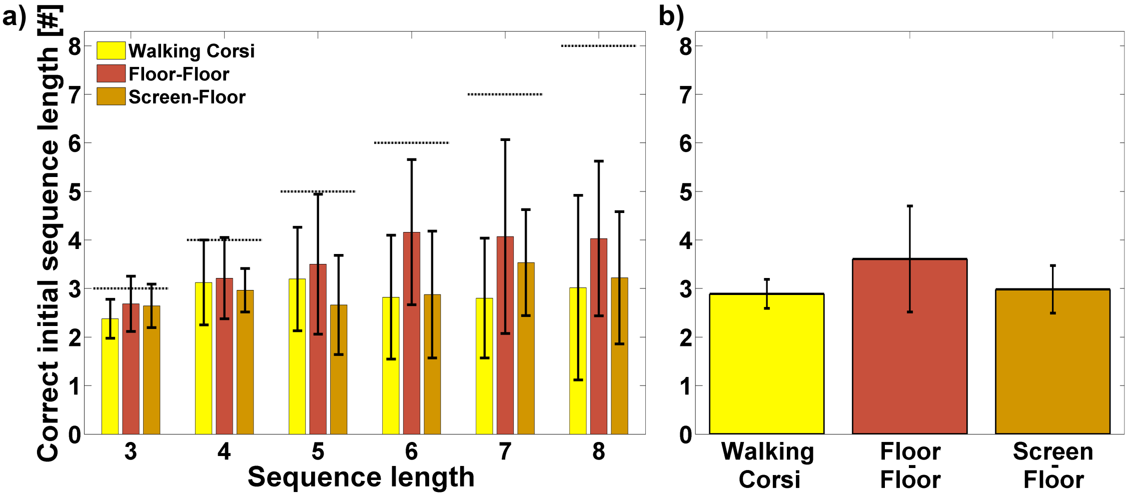

Figure 7.19.: Comparison between Walking Corsi task, Floor-Floor and Screen-Floor in correct initial sequence length. a) The mean number of the correct initial sequence length (y-axis) is plotted for each sequence length (x-axis). In the experiment Floor-Floor (red bars) the correct initial sequence length increased with increasing sequence length. For the experiments Walking Corsi task (yellow bars) and Screen-Floor (orange bars) no differences in length of correct initial sequence were observed over the sequence lengths. The horizontal lines denote the maximum possible initial sequence length. b) The average over the sequence lengths of the correct initial sequence length (y-axis) is depicted for the three experiments (x-axis). Participants reached about the same average in the Walking Corsi task (yellow bar) and in Screen-Floor (orange bar). There was no difference in the correct initial sequence length to Floor-Floor (red bar), but a trend for a difference was observed. Error bars indicate the standard deviation.

Partial set correct

The mean number of partial set correct square tiles increased over the sequence lengths for the experiments Walking Corsi task, Floor-Floor and Screen-Floor (see Fig. 7.20). In the Walking Corsi task the number of partial set correct squares increased from 2.55 (SD: ±0.31) in sequence length three over 4.64 (SD: ±0.41) in sequence length six to 6.36 (SD: ±0.63) squares in sequence length eight. In the modality condition Floor-Floor the number of partial set correct squares increased from 2.74 (SD: ±0.43) square tiles in sequence length three over 5.25 (SD: ±0.85) squares in sequence length six to 7.11 (SD: ±0.57) square tiles in sequence length eight. In sequence length three of the modality condition Screen-Floor 2.71 (SD: ±0.34) squares were reproduced partial set correctly, in sequence length six 4.73 (SD: ±0.58) squares and in sequence length eight 6.70 (SD: ±0.57; see also Fig. 7.20a)) squares. In the experiments Walking Corsi task and Screen-Floor participants had an average over all sequence lengths of about 4.4 square tiles. In Floor-Floor participants reached a value of 4.87 squares (SD: ±0.56; see also Fig. 7.20 b)).
A two-way ANOVA with repeated measures on one factor (sequence length) revealed a highly significant increase over the sequence lengths ($F(5, 195) = 460.946$, $p < 0.001$, $\eta_P^2 = 0.922$) and

a significant difference between the experiments ($F(2, 39) = 4.166$, $p < 0.05$, $\eta_P^2 = 0.176$). With a post hoc analysis significant differences between the Walking Corsi task and Floor-Floor ($p < 0.05$) could be shown (depicted with a star in Fig. 7.20 b)). No difference between the Walking Corsi task and the modality condition Screen-Floor was found for partial set correctly reproduced square tiles. There was also no difference between the modality conditions Floor-Floor and Screen-Floor.

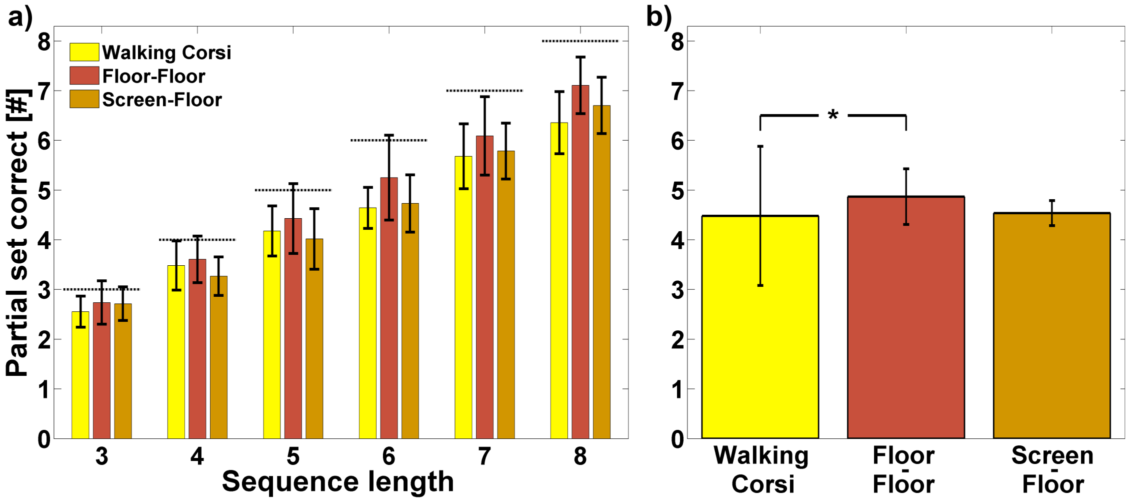

Figure 7.20.: Comparison between Walking Corsi task, Floor-Floor and Screen-Floor in partial set correctly reproduced squares. a) For all experiments (yellow, red and orange bars) and sequence lengths (x-axis) the mean number of partial set correct squares (y-axis) is shown. With increasing sequence length the number of partial set correct square tiles increased for all experiments. The horizontal lines denote the maximum possible number of partial set correct squares. b) The average of partial set correct over the six sequence lengths and all participants (y-axis) is plotted for the experiments (x-axis). Walking Corsi task (yellow bar) and Screen-Screen (orange bar) reached about the same average. Floor-Floor (red bar) differed significantly from the Walking Corsi task. Error bars indicate the standard deviation.

Walking speed

The comparison of walking speed was again made for all four experiments, including the Traveling Salesman task.

For all experiments the walking speed decreased with increasing route and sequence length (see Fig. 7.21). For the Traveling Salesman task and the Walking Corsi task the walking speed decreased from 3.50 km/h in route and sequence length three over 2.99 km/h in route and sequence length six to 2.86 km/h in route and sequence length eight. For Floor-Floor and Screen-Floor the walking speed decreased from 3.38 km/h in sequence length three over 2.91 km/h (SD: ±0.23) in Floor-Floor and 2.82 km/h (SD: ±0.21) in Screen-Floor in sequence length six to 2.71 km/h (SD: ±0.23) in Floor-Floor and 2.64 km/h (SD: ±0.25) in Screen-Floor in sequence length eight (see Fig. 7.21 a)). The total average over all route and sequence lengths and participants amounted to 3.12 km/h for the Traveling Salesman task and the Walking Corsi task and about 2.9 km/h for the modality conditions Floor-Floor and Screen-Floor (see Fig. 7.21 b)).

For analyzing main effect differences for the factors route and sequence length and experiment a two-way ANOVA with repeated measures on one factor (route and sequence length) was used. For further analyses a Greenhouse-Geisser correction ($\epsilon = 0.485$; Mauchly test: $\chi^2(14) = 115.960$, $p < 0.001$) was used for the factor route and sequence length. A highly significant decrease of walking speed over the route and sequence lengths was found ($F(2.427, 126.190) = 311.564$, $p < 0.001$, $\eta_P^2 = 0.857$). A significant difference between the experiments was observed ($F(3, 52) = 2.849$, $p < 0.05$, $\eta_P^2 = 0.141$), though a further post hoc test revealed no difference between the single experiments.

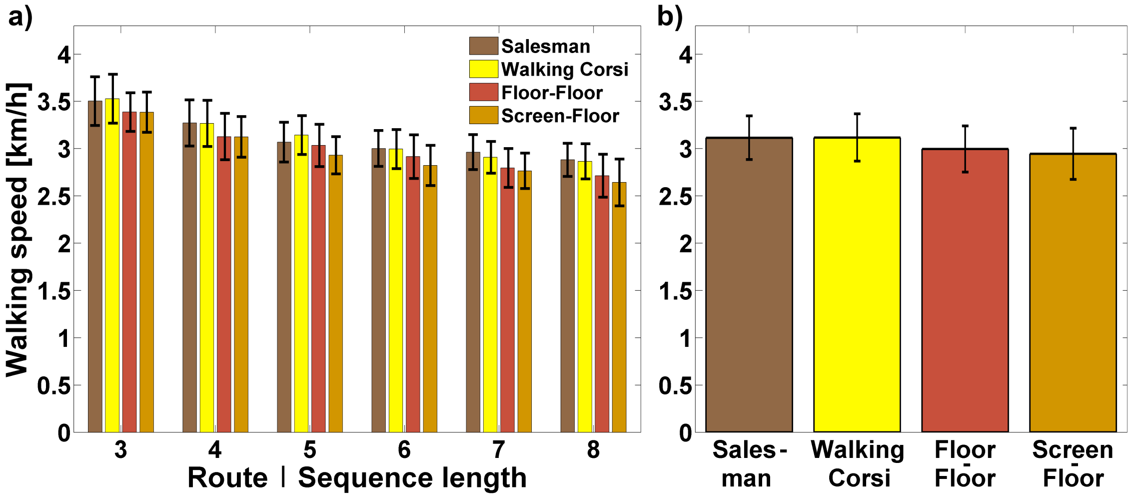

Figure 7.21.: Comparison between Traveling Salesman task, Walking Corsi task, Floor-Floor and Screen-Floor in walking speed. a) The mean walking speed (y-axis) is plotted for all route and sequence lengths (x-axis; brown, yellow, red and orange bars). With increasing route and sequence length the mean walking speed decreased in all four experiments. b) The over the route and sequence lengths averaged walking speed (y-axis) is depicted for Traveling Salesman task (brown bar), Walking Corsi task (yellow bar), Floor-Floor (red bar) and Screen-Floor (orange bar). The mean average is about the same in all experiments. Error bars indicate the standard deviation.

Standing time

The last comparison between the four experiments was made for the factor standing time (see Fig. 7.22).

The standing time in the Traveling Salesman experiment decreased with increasing route length, from route length three with 1.15 s (SD: ±0.55) to route length five with a standing time of 0.78 s (SD: ±0.35) and remained constant for the remaining route lengths. In the Walking Corsi task the standing time increased with increasing sequence length, starting with 1.38 s (SD: ±0.48) in sequence length three to 1.78 s (SD: ±0.56) in sequence length eight. The standing time in Floor-Floor stayed approximately the same for all sequence length with about 1.1 s, though, there was a trend for an increase of standing time with increasing sequence length ($p = 0.051$). In Screen-Floor the standing times lay between 1.1 and 1.3 s over the sequence lengths, though, no difference between them was observed (see Fig. 7.22 a)). The overall mean in standing time was 0.91 s (SD: ±0.12) for the Traveling Salesman task and 1.53 s (SD: ±0.18) for the Walking Corsi task. In the modality condition Floor-Floor participants remained standing on a single square tile for 1.13 s (SD: ±0.08) and for 1.26 s (SD: ±0.07) they stood on a square in Screen-Floor (see Fig. 7.22 b)).

Again a two-way ANOVA with repeated measures on one factor (route and sequence length) was conducted, a Mauchly test revealed significant results ($\chi^2(14) = 48.186$, $p < 0.001$), so for further analyses of the factor route and sequence length a Greenhouse-Geisser correction ($\epsilon = 0.71$) was used. A highly significant effect for the factor route and sequence length was observed ($F(3.550, 184.612) = 6.399$, $p < 0.001$, $\eta_P^2 = 0.11$). The four experiments differed highly significant in the standing times ($F(3, 52) = 7.896$, $p < 0.001$, $\eta_P^2 = 0.313$) and there was also an interaction between the factors experiment and route and sequence length ($F(10.651, 184.612) = 4.960$, $p < 0.001$, $\eta_P^2 = 0.222$). A post hoc analysis revealed a highly significant difference between the experiments Traveling Salesman task and Walking Corsi task ($p < 0.001$). A trend for a difference between the experiments Traveling Salesman task and Screen-Floor was observed ($p = 0.062$). The experiment Walking Corsi task did not only differ in standing time from the Traveling Salesman task but also from the modality condition Floor-Floor ($p < 0.05$; differences are depicted with stars in Fig. 7.22 b)). There was no difference in standing time between the experiments Walking Corsi task and Screen-Floor.

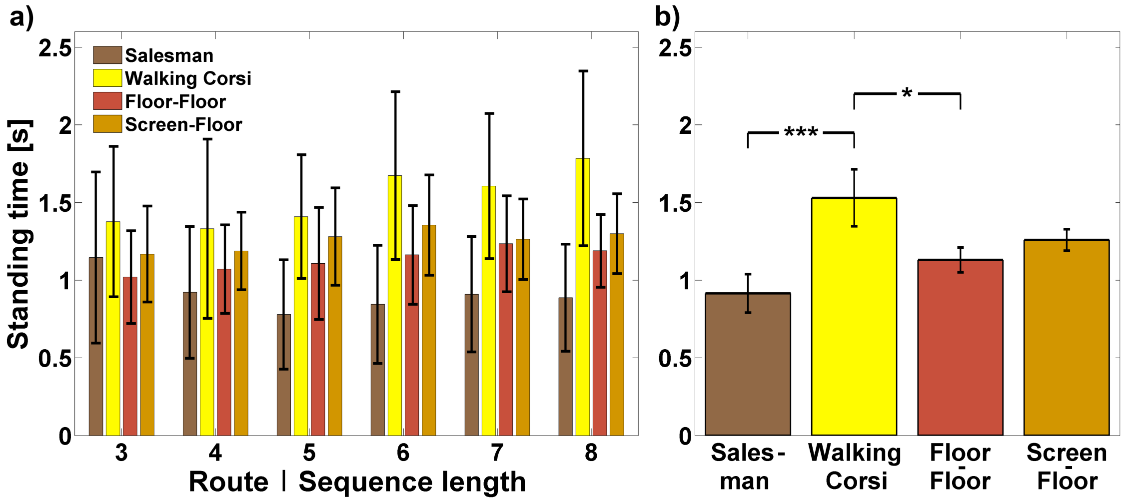

Figure 7.22.: Comparison between Traveling Salesman task, Walking Corsi task, Floor-Floor and Screen-Floor in standing time. a) The mean standing time (y-axis) of the participants is shown for the six route and sequence lengths (x-axis). For the Traveling Salesman task (brown bars) the mean standing time decreased for the route lengths three to five and remained constant for the remaining route lengths. In the Walking Corsi task (yellow bars) the mean standing time increased with increasing sequence length. For Floor-Floor (red bars) and Screen-Floor (orange bars) the standing time did not differ between sequence lengths, but there was a trend for an increase with increasing sequence length. b) The averaged standing time over the route and sequence lengths (y-axis) is plotted for the experiments (x-axis). The mean standing time of the Walking Corsi task differed significantly from the mean standing time of the Traveling Salesman task and the modality condition Floor-Floor. Error bars indicate the standard deviation.

7.3. Discussion

In this experiment participants were asked to solve Corsi tasks in four different modality conditions to investigate the influence of different encoding and recall demands on spatial working memory. It was designed to probe varying spatial abilities in a controlled and balanced way. More specifically, for all of the four modality conditions, three distinct working memory processes can be identified: visuo-spatial and temporal sequence learning (performance), screen to floor or floor to screen reference frame (RF) transformation and spatial updating (including mental rotation). In the latter factor - spatial updating - all other possible costs associated with walking-based recall, including motor control, keeping posture, etc. were aggregated, since these costs could not be distinguished between with this design. The different types and amounts of requirements needed in each modality condition are summarized in Tab. 7.2.

Table 7.2.: Factors of spatial processing and their requirement in each modality condition. The required factors for the given modality condition are marked with a black square.

modality conditions	factor		
	performance (p)	spatial updating (u)	RF transformation (t)
Screen-Screen	■		
Floor-Screen	■		■
Floor-Floor	■	■	
Screen-Floor	■	■	■

Overall, participants were able to complete all modality conditions, though with substantial differences in performance. As predicted, in all modality conditions a decrease in performance with increasing sequence length was observed (cf. Fig 7.4 a), p. 115). This general decrease in performance can be explained with the limited capacity of the working memory and is generally found when performing Corsi tasks (e.g. Busch et al. 2005, Piccardi et al. 2008, Perrochon et al. 2014, etc.).
The highest Corsi span and thus the best performance was reached in the modality condition Screen-Screen, followed by Floor-Screen, Floor-Floor and finally the modality condition Screen-Floor (cf. Tab. 7.1 (p. 114) and Fig. 7.4 b) (p. 115)). Corsi (1972) and Orsini et al. (1987) mentioned a Corsi span of about five for healthy adults. This value was also reached by the participants in the modality conditions Floor-Screen and Floor-Floor. The Corsi spans in the modality conditions Screen-Screen and Screen-Floor deviated about ±1 from this value. Thus, performance clearly depends on the modality of encoding and recall.
As a possible explanation of the differences between modality conditions it is suggested that in modality conditions in which the floor was involved in encoding, recall or both (i.e., Screen-Floor, Floor-Screen and Floor-Floor), additional (spatial) working memory resources are recruited which were not required in the Screen-Screen modality condition. Depending on which combination of modalities was used in encoding and recall, such additional resources might be required for spatial updating, mental rotation of the memorized pattern during walking, reference frame transformation from the computer screen to the floor of the experimental room and vice versa, or the control of walking itself. Since these tasks are thought to be executed in parallel to the primary tasks of encoding and recall of a given Corsi sequence, impairments in performance are plausible.

The Screen-Screen modality condition required no further spatial resources besides sequence learning. The modality conditions Floor-Screen and Screen-Floor demanded just one additional spatial factor each and in the Screen-Floor modality condition all three factors were involved. Assuming that the costs spatial updating and Floor/Screen reference frame transformations demand about the same spatial processing capacities, working memory mechanisms may predict the relative performance levels of the four modality conditions.
This hypothesis can also be clarified with the following simple linear model (see Eq. 7.1) for the number of correctly reproduced trials in the four modality conditions (left side) and a design matrix reproducing the relationships listed in Tab. 7.2. The general Corsi performance (p) supports the number of correctly reproduced trials and is therefore represented with a positive sign, while spatial updating (u) and reference frame transformation (t) are treated as costs, i.e., with negative signs in the design matrix:

$$\begin{pmatrix} Screen - Screen \\ Floor - Screen \\ Floor - Floor \\ Screen - Floor \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 1 & 0 & -1 \\ 1 & -1 & 0 \\ 1 & -1 & -1 \end{pmatrix} * \begin{pmatrix} p \\ u \\ t \end{pmatrix} + \varepsilon \tag{7.1}$$

Here, epsilon is a four-dimensional vector of the residual errors in the four conditions. A regression analysis based on this model, carried out for each participant individually, yields the three factors: overall performance, spatial updating costs and reference frame transformation costs. One sample t-tests for each factor estimate revealed a significant difference from zero (see Fig. 7.23). The residual error (ε) averaged over all modality conditions was significantly different from zero but small, allowing a satisfactory fit of the performance of the participants in the four modality conditions.

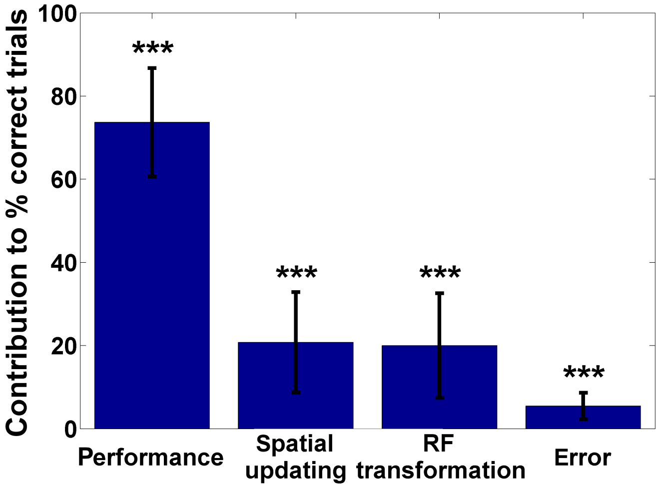

Figure 7.23.: Model estimates. The three factors (performance, spatial updating and RF transformation) and the residual error (x-axis) are depicted regarding their weighting to the contribution to % correct trials (y-axis). All factors were highly significant different from zero as calculated by t-tests (Performance: t(13) = 21.147, p < 0.001; Spatial updating: t(13) = -6.445, p < 0.001); and Reference frame transformation: t(13) = -5.947, p < 0.001). Also, the small residual error differed highly significant from zero (t(13) = 6.432, p < 0.001). Error bars show the standard deviation over all participants.

Similar to the former experiments, not only the percentage of correct trials, but also the length of the correct initial sequence was evaluated. For three of the four modality conditions (Screen-Screen, Floor-Screen and Floor-Floor) an increase of the correct initial sequence length was found with increasing sequence length. For the modality condition Screen-Floor no difference of the correct initial sequence between the sequence lengths was observed. The longest correct initial sequence was reached in the modality condition Screen-Screen; it differed significantly from the modality conditions Floor-Screen and Screen-Floor. In the modality conditions Floor-Screen and Floor-Floor a correct initial sequence length lower than in Screen-Screen, but higher than in Screen-Floor was reached by the participants. For modality condition Floor-Screen a significant difference from modality condition Screen-Floor was found (cf. Fig. 7.6 b), p. 117). These findings can be explained, since in the modality condition Screen-Floor the largest additionally working memory load, caused by sequence recalling, spatial updating and reference frame transformation, existed. The three other modality conditions all required less additionally working memory loads, because in this modality conditions there were only one to two demanding factor costs.

For the evaluation of the partial set correctly reproduced square tiles an increase of the number of partial set correct square tiles with increasing sequence lengths was found (cf. Fig. 7.7 a), p. 118).
Interestingly, the results concerning partial set correct differed markedly from the correct trials and the correct initial sequence data. Again, the analysis of partial set correct is presented to differentiate between memories representing sequence information and memories representing only the set of squares included in the sequence. Taking a look at this data, it becomes noticeable that in modality conditions in which presentation and reproduction modalities were the same (i.e., Screen-Screen and Floor-Floor), participants' performance was comparable, that is, participants recalled obviously the same number of squares. Also, performances did not differ between the Floor-Screen and Screen-Floor modality conditions. Overall, there was a tendency that participants performed slightly better in the modality conditions in which the presentation and reproduction modalities were the same. This might indicate that reference frame transformation of information between modalities leads to a decreased number of correctly remembered or recalled squares irrespective of their order of appearance.
Furthermore, the almost similar partial set correct performance in the four modality conditions indicates that the decreased correct trials performance found in the Floor-Floor and Screen-Floor modality conditions results not so much from errors in the selection of the squares but from errors in reproduction of the sequences. One possible explanation of this finding is that in modality conditions with floor-recall, subjects adopt an erroneous strategy requiring less spatial updating, in which all squares are still visited however at a simplified sequence. This interpretation is well in line with the general idea of spatial updating and reference frame transformations as a factor in walking Corsi experiments. The analysis of partial set correct resulted in different outcomes compared to the analysis of the correct trials and the correct initial sequence. Thus, it can be concluded that for representation lacking sequence information a different memory is required than for representations containing sequence information.

A more detailed analysis of sequence length revealed a strategy change between the two shortest sequences (three and four) and the two longest ones (seven and eight) for those two modality conditions demanding two cost factors (i.e., Floor-Floor and Floor-Screen; see Fig. 7.24). Here, the modality condition requiring spatial updating in addition to visuo-spatial and temporal sequence learning (Floor-Floor) was found with higher performance values for the short sequences and lower values for the long ones compared to the modality condition which additionally required reference frame transformations (Floor-Screen). Such interaction is visible for the analyses of correct trials and correct initial sequence length and significant for the former one (Fig. 7.24 a) and b)). For the other two modality conditions (Screen-Screen and Screen-Floor) no such strategy change could be identified. These modality conditions showed a similar reduction between the two sequence lengths for all analyses (see Fig. 7.24 a) - c)). The interaction of the Floor-Floor and the Floor-Screen modality conditions may indicate a larger effect of reference frame transformations on working memory resources during shorter sequence lengths and spatial updating having a larger influence on working memory resources in longer sequence lengths.

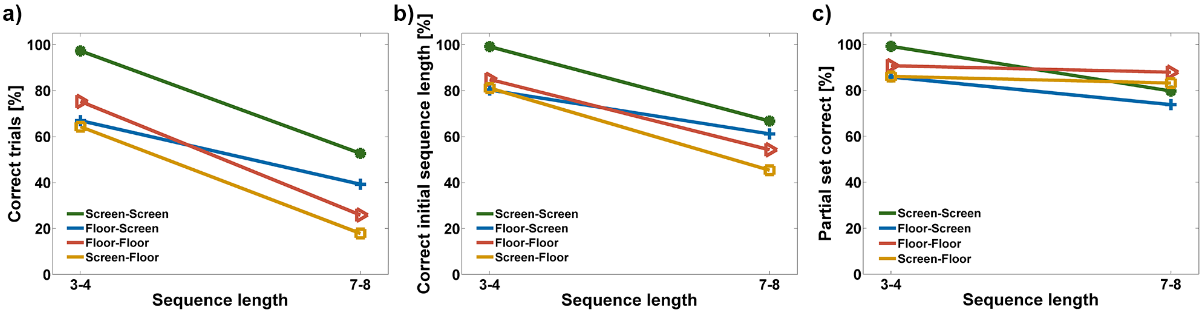

Figure 7.24.: Interaction plots for a) correct trials, b) correct initial sequence length and c) partial set correct. The mean performance in percent (y-axis) of all participants in the sequence lengths three and four and seven and eight (y-axis) is depicted. In a) the modality conditions Screen-Screen (green lines) and Screen-Floor (orange lines) showed a similar decrease (parallelism of the lines) in performance. The modality conditions Floor-Floor (red lines) and Floor-Screen (blue lines) showed crossing transitions regarding the performances between short and long sequence lengths and this interaction was significant ($F(1, 108) = 6.26$; $p < 0.05$, $\eta_P^2 = 0.055$). b) This interaction was also visible for the correct initial sequence length, but did not reach significance for this variable. c) In contrast to the results where the correct order of reproduced squares was relevant, in this case there was no change in performance in the modality conditions Floor-Screen and Floor-Floor. Except for the modality condition Screen-Screen (green line) the other modality conditions kept their same descending order in the different sequence lengths.

The overall findings of the experiment fit well with previous results by Perrochon et al. (2014). They also found that performance in a walking version of the Corsi task was poorer than in an electronic version with similar results like in the Screen-Screen modality condition. In terms of absolute performance levels, however, performance in the walking condition was better than found for the modality condition Screen-Floor. A possible reason for this could be that they used a smaller carpet size (2.5 x 3 m) than the carpet used here (5 x 5 m). Another reason for the differences could be different sequences, because also sequences which appear equally difficult in terms of the same sequence length and number of crossings, can result in different performances (Orsini et al. 2001).

For the modality conditions Floor-Floor and Screen-Floor participants' walking speeds were measured (cf. Fig. 7.8, p. 119). Like in Experiment 1 and Experiment 2 for both modality conditions a decrease of walking speed with increasing sequence length was found, though, there was no difference between the walking speeds. Again, this decrease could be caused by the additional load on working memory, since in longer sequence lengths more square tiles had to be remembered and also more spatial updating during recall was necessary.

The walking speed was once more split up into correct and false trials. In contrast to the former experiments a difference of walking speed in correct and false trials was found for the modality condition Floor-Floor, showing that participants walked slower in the false trials. For the modality condition Screen-Floor no difference between the walking speeds was observed (cf. Fig. 7.9, p. 120). A possible reason for the lower walking speed in the false trials of the modality condition Floor-Floor could be that participants were more unsure of the upcoming square tile and therefore made more rehearsal in the false trials to remember the next square. This increased rehearsal could cause additional working memory load which is not available for walking anymore. Though, in the other experiments and also in the modality condition Screen-Floor no difference between the walking speeds in correct and false trials was found, thus, the difference in the modality condition Floor-Floor could be

merely a random effect.
To investigate if the decrease of walking speed was caused by additional working memory load of longer sequences, the walking speeds in distances with equal lengths were analyzed for the different sequence lengths. For the modality condition Floor-Floor 19 out of 28 segments were analyzed. Only for two of these segments a significant decrease of walking speed was found with increasing sequence length (cf. Fig. 7.10 top, p. 122). These two segments had lengths of 1.32 m and 2.81 m. In the modality condition Screen-Floor 21 out of 28 segments were analyzed further and in five of these segments a significant decrease of walking speed with increasing sequence length was found (cf. Fig. 7.10 bottom, p. 122). The distances of these five segments lay between 1.61 m and 3.13 m. So similar to Experiment 2 and contrary to Experiment 1, the differences were found for segments with longer distances. Again, this could be an evidence that working memory processes, which are involved in walking a known route, have a greater influence on longer distances. In the modality condition Floor-Floor only two of the segments had significant differences of walking speed over the sequence lengths. Therefore, it could also be that the reference frame transformation from screen to floor has an influence on walking speed while walking a known route, too.

In both modality conditions (Floor-Floor and Screen-Floor) a correlation between walking speed and length of the walked distance was found, the longer the distances the faster the walking speeds were (cf. Fig. 7.11, p. 123). The second arm with a higher increase of walking speed in short distances, which was already found in the experiments 1 and 2, was also present in the two modality conditions and it seemed again to be caused by fast steps on nearby squares.
Participants' walking profiles were again equal to the one shown for Experiment 1 (see Fig. 3.13, p. 36). Similar to the Traveling Salesman task and the Walking Corsi task, it could have been shown that the walking speed was influenced by the additional working memory load caused by longer sequences to remember. But another reason for the slower walking speed could be again the distances between the square tiles. Reaching the maximum walking speed needs some time and on short distances, which appeared more often in longer sequence lengths, participants had to slow down again, before their maximum walking speed was reached.

In contrast to the Walking Corsi task, this time no difference between the standing times on a square tile was found for the sequence lengths. Though, there was a trend that with increasing sequence length the standing time got longer, too. No difference in standing time over the sequence lengths was found but a difference between the standing times of the two modality conditions was observed. In the modality condition Screen-Floor participants stood longer on a single square tile than in the modality condition Floor-Floor (cf. Fig 7.12, p. 124). This difference might be caused by the reference frame transformation from screen to floor and might took longer than only rehearsing the sequence within the same reference frame.
For both modality conditions an apparent increase for the first squares of a sequence and a decrease for the last squares of a sequence was observed (cf. Fig. 7.13, p. 126). For the modality condition Floor-Floor differences of the standing times on the squares within the sequence were found in half of the sequence lengths. For the modality condition Screen-Floor four of the six sequence lengths had significant differences of standing times on the squares. A similar standing time course with increasing standing time at the beginning and a decrease of standing time at the end of a sequence was observed. Again it is assumed that this standing time course resulted from participants recall behavior of the sequence. Probably

they remember the first squares of a sequence very well but needed longer to recall the middle squares of a sequence. The decrease of standing time was present in all sequence lengths about two to three squares before the end. This is again an evidence that participants recall the squares not one by one but in chunks of about two to three squares. Therefore, from the third square before the end participants did not have to make any further recalls of the sequence and thus did not have to stand long on the square tiles. This resulted in a decrease of standing time at the end of a sequence.

In this experiment, participants started from two additional starting positions compared to the experiments 1 and 2. Each of the four starting position was used six times per participant and once per sequence length. Neither in the modality condition Floor-Floor nor in the modality condition Screen-Floor a difference of performance was found between the four starting positions. A similar evaluation was also made for the modality conditions Screen-Screen and Floor-Screen. The pattern configurations oriented similar to the four starting positions were evaluated for differences in performance. But again no difference between the orientation was found in both modality conditions. Since the experimental setup and the pattern configuration was equal to the experiments 2 and 3, in which no differences between the starting positions and pattern orientations were found, it was not expected to find any differences between the starting positions and pattern orientations for the four modality conditions.
To figure out the difficulty of the sequences not only the minimal number of crossings was counted but also the minimal rotation angle per sequence was evaluated. Sequences with a lower number of crossings were more often reproduced correctly. These findings are in line with the results reported by Orsini et al. (2001) and Parmentier & Andrés (2006). There was not only a correlation between the number of crossings and the percentage of correctly reproduced trials but also sequences with small rotation angles led to a better performance than sequences with large rotation angles (cf. Fig. 7.14, p. 128). Larger rotation angles resulted from more or larger turnings of the participants. The more turnings participants had to make during the sequence recall the more often they had to update their position relative to the pattern configuration. This required more spatial updating and therefore a greater load on working memory resources, which resulted in a decrease of performance.

Once more in all modality conditions the performances were analyzed for differences between the genders. In contrast to Experiment 3, in which no differences between the genders were found, there were differences between genders in the modality condition Screen-Screen. Male participants had a better performance in percentage of correct trials. They also had a longer correct initial sequence length as well as higher number of partial set correctly reproduced square tiles. These findings are in line with studies of Piccardi et al. (2008 and 2016). They reported that male participants had a better performance in a classical version of the Corsi task than female participants. Also Capitani et al. (1991) and Shah et al. (2013) reported a higher Corsi span for males in a classical Corsi version. Fournet et al. (2012) reported a better performance of males in a computerized Corsi version and Brunetti et al. (2014) found a better performance of male participants in a tablet version.
In the modality condition Floor-Screen the same three factors as in Screen-Screen were analyzed for differences between the genders. In contrast, this time no differences between the genders were found.
In the modality condition Floor-Floor no differences between the genders were found for the percentage of correct trials and the standing time on a square tile; but the results showed that males had a longer correct initial sequence length than females and they also reached a

higher number of partial set correct squares compared to females. Further, likewise to the findings in Experiment 2, males had a faster walking speed than females. A generally higher walking speed for men than women was reported by Himann et al. (1988) and Öberg et al. (1993). The longer correct initial sequence and higher number of partial set correct squares of males could be a result of better mental rotation abilities of males compared to females. Some studies reported weaker performances of females in mental rotation tasks (e.g. Linn & Petersen 1985, Richardson 1994, Voyer et al. 1995). However, for floor recall better mental rotation abilities should be helpful because participants have to adjust their positions on the floor according to the sequence shown before.

Similar to the modality condition Floor-Floor no differences between the genders were found for the percentage of correct trials and the standing time in the modality condition Screen-Floor. In contrast to Floor-Floor also no difference between the genders was found for the factor partial set correct square tiles in Screen-Floor. Again, male participants had a longer correct initial sequence than female participants and they also had a faster walking speed.

Comparison with Corsi task 1 and Corsi task 2

Because this experiment was meant to be designed in a within-subject design, too, participants had to solve the four modality conditions only in six and not in eight sequence lengths like the experiments before. Having again eight sequence lengths would have taken more time and the whole experiment should be kept in temporal reasonable bounds. Another reason was that in the experiments before there were not many changes in the performances of the longer sequence lengths and therefore it seemed to be a good compromise to have only six sequence lengths. So all of the further comparisons between the experiments were done for the sequence lengths three to eight.

The results of the modality conditions Screen-Screen and Floor-Screen were compared with the results of Corsi task 1 and Corsi task 2. This was done for the factors percentage of correct trials, the correct initial sequence length and the number of partial set correct square tiles.

For the percentage of correct trials no difference between Screen-Screen and the two Corsi tasks was observed. This also indicates that there should not have been any advantage for the participants of Experiment 3 in solving the Corsi task always after the Walking Corsi task, although they recalled the same sequences the second time. Otherwise they should have reached a better performance than the participants in the Corsi task 2 and the Screen-Screen modality condition. Furthermore, the calculation of the time delays between the mouse clicks with an averaged walking speed and not with the specific walking speed of each sequence length also seems not to affect participants' performance.

The modality condition Floor-Screen differed highly significant from all of the three other tasks (cf. Fig. 7.15 b), p. 130). The performance in the modality condition Floor-Screen was lower than in the other tasks. In Floor-Screen there were not only demands on working memory caused by the sequence to remember, but also a reference frame transformation from floor to screen in the recall phase. This additional demand on working memory resources could be a reason for the lower performance in the modality condition Floor-Screen compared to the three other experiments.

Similar results were found for the length of the correct initial sequence, again, no differences were found between Screen-Screen and the two Corsi tasks, but Floor-Screen had a significantly lower correct initial sequence length than the other three tasks (cf. Fig. 7.16 b),

p. 131). Once more the reference frame transformation could be an explanation for the lower performance.
For the number of partial set correct squares differences between Corsi task 2 and Screen-Screen, as well as between Corsi task 2 and Floor-Screen were found (cf. Fig. 7.17 b), p. 132). In Corsi task 2 a higher number of partial set correct square tiles was reached. In none of the three experiments participants received feedback, therefore in none of the tasks any helpful cues should have been present. That is why the differences could be caused simply by individual differences of the participants who took part in the experiments.
In contrast to the comparison of the number of partial set correct squares between Corsi task 1 and Corsi task 2 in Experiment 4, in which a significant difference between the two tasks was found, this time no difference between the two experiments was observed. This converse result could be explained by the fact that the number of partial set correct squares increased more in the sequence lengths seven to ten in Corsi task 2 than in Corsi task 1. This resulted in a significant difference between the two experiments. Here in Experiment 5, the comparison between the experiments was done only up to sequence length eight, therefore the stronger increase of Corsi task 2 in the longer sequence lengths had no or less effect on the comparison of the experiments and resulted in no difference between the two Corsi tasks.

For all of these three factors participants' percental performance was compared between the two shortest sequence lengths (three and four) and the two longest sequence lengths (seven and eight). For the percentage of correct trials Corsi task 1 and Corsi task 2 showed about the same decrease. The modality conditions Screen-Screen and Floor-Screen had a similar decrease, too, but the performance in Floor-Screen in the short as well as the long sequence lengths was below the performance in Screen-Screen. The decrease of performance in these two modality conditions was lower than the performance decrease of the two Corsi tasks (see Fig. 7.25 a)).
For the correct initial sequence length the percental performance was identical for Corsi task 1, Corsi task 2 and Screen-Screen. Floor-Screen had a lower performance in the short sequence lengths (three and four) but about the same like the other three tasks in the long sequence lengths (seven and eight; see Fig. 7.25 b)).
The decrease in performance of Corsi task 2 was similar to the decrease of the modality condition Floor-Screen for the percental partial set correct squares (parallel lines in Fig. 7.25 c)), though, the general performance was lower in Floor-Screen. Corsi task 1 and Screen-Screen had the same performance as Corsi task 2 in the short sequence lengths, but they had a stronger decrease which resulted in a lower mean performance of the sequence lengths seven and eight.

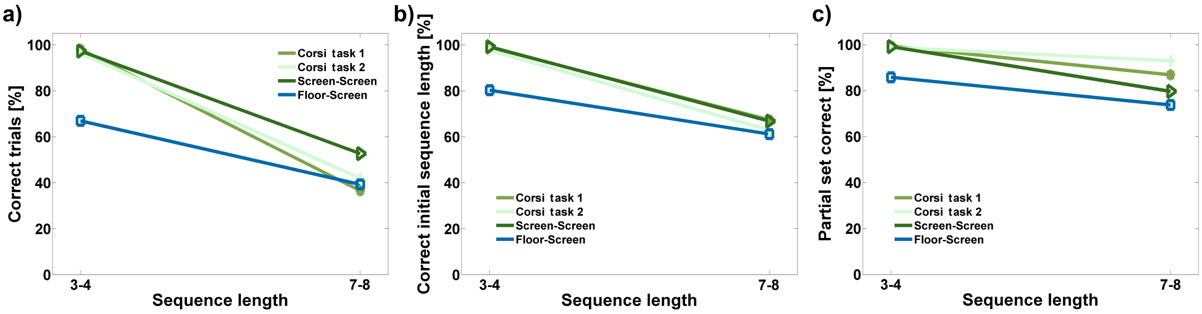

Figure 7.25.: Interaction plots for correct trials (a), correct initial sequence length (b) and partial set correct (c). The mean performance in percent (y-axis) of the participants in the sequence lengths three and four and seven and eight (y-axis), is depicted for Corsi task 1 (green lines), Corsi task 2 (mint green lines), Screen-Screen (dark green lines) and Floor-Screen (blue lines). In a) the modality conditions Screen-Screen and Floor-Screen showed a similar decrease (almost parallel lines) in performance. Also the performance of Corsi task 1 and Corsi task 2 was similar, though, it showed a stronger decrease than Screen-Screen and Floor-Screen. b) There was no difference in performance between Corsi task 1, Corsi task 2 and Screen-Screen, all of the three showed the same performance decrease. The performance in modality condition Floor-Screen was lower in the mean of sequence lengths three and four, but decreased only little and was about the same as the performances in the other tasks in the mean of sequence lengths seven and eight. c) In Corsi task 2 and Floor-Screen the performance decrease was similar (parallelism of the lines). The decrease of performance in Corsi task 1 and Screen-Screen was a bit larger than the performance decrease in Corsi task 2. In this comparison there was no interaction between the experiments in any of the depicted factors.

Comparison with Traveling Salesman task and Walking Corsi task

The results of the modality conditions Floor-Floor and Screen-Floor were compared with the results of the Traveling Salesman task and the Walking Corsi task. This time five factors were compared (i.e., percentage of correct trials, correct initial sequence length, partial set correctly reproduced squares, walking speed and standing time). In the Traveling Salesman task there was no correct initial sequence length and also no number of partial set correct squares, therefore, these comparisons were only made between the Walking Corsi task and the modality conditions Floor-Floor and Screen-Floor.

In the percentage of correct trials participants reached a highly significant better performance in the Traveling Salesman task compared to the three other tasks (cf. Fig. 7.18 b), p. 134). In the modality condition Floor-Floor participants had a significantly better performance than in the Walking Corsi task and in the modality condition Screen-Floor. These results indicate that in the chosen experimental designs finding the shortest route was easier than recalling a sequence which had been memorized before. The better performance in Floor-Floor compared to the Walking Corsi task and the modality condition Screen-Floor can be explained with additional working memory load in the two latter experiments caused by reference frame transformations from screen to floor, whereas in Floor-Floor no such reference frame transformation was present.
For the length of the correct initial sequence no difference between the three tasks was observed (cf. Fig. 7.19, p. 135).
For the number of partial set correct square tiles a significant difference between the Walking Corsi task and the modality condition Floor-Floor was found, showing that the number of partial set correct squares in Floor-Floor was higher than in the Walking Corsi task

(cf. Fig. 7.20 b), p. 136). Once more the lower performance in the Walking Corsi task could be caused by the reference frame transformation from screen to floor.

For the factor walking speed a significant difference was observed between the four tasks, though, a post hoc test revealed no differences between the single tasks (cf. Fig. 7.21, p. 137). This result can be caused by the individual walking speeds of the different participants who took part in the Traveling Salesman task as well as in the Walking Corsi task and the participants who solved the Corsi tasks in the modality conditions Floor-Floor and Screen-Floor.

The standing times on a square in the Walking Corsi task differed highly significant from the standing times in the Traveling Salesman task and also significantly from the standing times in the modality condition Floor-Floor (cf. Fig. 7.22 b), p. 138). The longer standing times in the Walking Corsi task compared to the standing times in the Traveling Salesman task could be the result of different working memory processes which were required for solving the tasks. In the Walking Corsi task participants had to recall a sequence and this seemed to require more time, e.g. for rehearsal, than finding the next square of the shortest route and thus resulted in longer standing times on the squares. The difference between the Walking Corsi task and the modality condition Floor-Floor might again be caused by additional working memory resources used for the reference frame transformation from screen to floor in the Walking Corsi task.

Once more the percental performances of the shortest route and sequence lengths (three and four) were compared to the percental performances in the longest route and sequence lengths (seven and eight).

In the percentage of correct trials the Walking Corsi task and the modality conditions Floor-Floor and Screen-Floor had about the same decrease of performance (parallel lines in Fig. 7.26 a)), although participants differed in performance. The performance decrease in the Traveling Salesman task was lower compared to the three other tasks and the overall performance was best.

There was no difference between the Walking Corsi task and the modality conditions Floor-Floor and Screen-Floor in the length of the correct initial sequence; all showed a similar decrease and reached comparable performances with a slightly higher performance in Floor-Floor (see Fig. 7.26 b)).

For the percental number of partial set correct square tiles all three tasks had about the same performance in the shorter as well as in the longer sequence lengths (see Fig. 7.26 c)).

The walking speed decreased in all four tasks similarly (see parallel lines in Fig. 7.26 d)). The walking speeds were equal for the Traveling Salesman task and for the Walking Corsi task. They were also equal for the modality conditions Floor-Floor and Screen-Floor. The difference between the walking speeds should be caused by the different participants who took part in the Traveling Salesman task as well as in the Walking Corsi task and the participants who attended to the modality conditions Floor-Floor and Screen-Floor. The walking speeds of the participants of the experiments 1 and 2 apparently were higher than the walking speeds of the participants who took part in the modality conditions Floor-Floor and Screen-Floor.

The standing time increased in the Walking Corsi task and a similar increase was present in the modality conditions Floor-Floor and Screen-Floor. In contrast, the standing time in the Traveling Salesman task decreased from short to long route lengths.

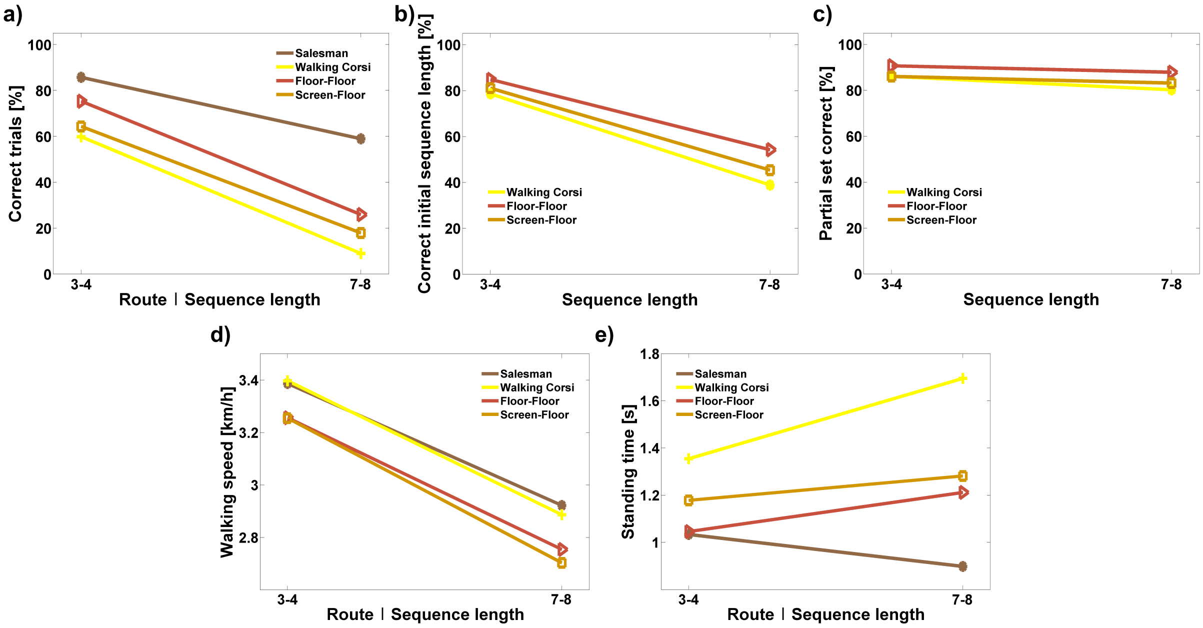

Figure 7.26.: Interaction plots for correct trials (a), correct initial sequence length (b), partial set correct (c), walking speed (d) and standing time (e). Participants' mean performance (y-axis) in the route and sequence lengths three and four and seven and eight (x-axis) is depicted. In a) the modality conditions Floor-Floor (red lines) and Screen-Floor (orange lines) as well as the Walking Corsi task (yellow lines) showed a similar decrease (parallelism of the lines) in performance. The Traveling Salesman task (brown lines) showed a lower decrease of performance and a better performance overall. b) The performance of the correct initial sequence length is shown only for Walking Corsi task, Floor-Floor and Screen-Floor. All of them showed about the same decrease of performance. c) All of the three experiments (Walking Corsi task, Floor-Floor and Screen-Floor) had the same performance in the averaged short and long sequence lengths. d) For the walking speed all four experiments had the same decrease of performance (parallel lines), but walking speed was higher in the Traveling Salesman task and in the Walking Corsi task. The standing time in e) increased in the longer sequence lengths for the Walking Corsi task and the modality conditions Floor-Floor and Screen-Floor. Whereas the standing time of Traveling Salesman decreased. For none of the shown factors an interaction between the experiments was found in this comparison.

In all four modality conditions the predicted decrease of performance with increasing sequence length was observed. Also the hypothesized performances in the modality conditions, with best performance in the modality condition Screen-Screen, intermediate performances in Floor-Screen and Floor-Floor and the lowest performance in Screen-Floor, were found. In the modality condition Floor-Screen a reference frame transformation from large or vista space (floor) to small or figural space (screen) required similar working memory resources as the spatial updating, with body turns, mental rotation of the pattern configuration, walking itself and so on, in the floor-recall of the modality condition Floor-Floor.

The comparisons with the experiments 1 to 4 revealed similar results for the equal tasks. With these experiments it could be shown that different demands on working memory resulted in different performances and that probably different components of the working memory are involved in the different tasks.

Conclusion

As predicted the performance in all four modality conditions decreased with increasing sequence length. Depending on the modality condition and thus the different additional demands on working memory a different performance decrease was found. It was shown that the demands on working memory caused by spatial updating and by reference frame transformations demand similar costs on working memory. The more additional demands on working memory load were present the more the working memory resources had to be split up on the different demands and the greater was the influence on general task performance.

8. General discussion[1]

The five experiments of this thesis were designed to investigate the differences in performance and walking speed between planning a route while walking and walking an already known route (Experiment 1 and 2) and to investigate whether performance of a task depends on the modality of task presentation and recall (Experiment 2 to 4).

In the first experiment a Traveling Salesman task had to be solved by the participants. Like in several other studies (e.g. Dry et al. 2006, Tenbrink & Wiener 2009, Wiener et al. 2007 and 2009, Blaser & Ginchansky 2012, Blaser & Wilber 2013) it was shown, that participants were quite good in finding the shortest route between marked locations in the experimental room. With more demands on working memory, caused by increasing route lengths, a decrease of performance over the route lengths was found. Since not only the performance was analyzed in the different route lengths but also participants' walking speeds were measured it could be shown that the walking speed decreased with increasing route length, too.
Because of the experimental design and the size of the experimental room the distance between two locations within the optimal route was shorter in the longer route lengths than in the shorter route lengths. Results showed that participants needed about 2 s to accelerate to their maximum walking speed. On shorter distances the maximum walking speed could not be reached since participants already had to slow down to stand on the next square tile. Nevertheless, it could be shown that route segments with the same distance were walked slower in longer route lengths. This was found for segments with relatively short distances between 1 and 2 m. The average standing time on a square decreased from short to medium route lengths and remained similar in long route lengths. For the standing time course per route length it was found that the standing time increased during the first squares of a route in the shorter route lengths (three to six) and decreased at the end of a route. For the longer route lengths (seven to ten) the standing times on the squares were similar at the beginning and middle part of a route and slightly decreased at the end. Since participants just had to go back to the start and did not have to plan any further steps of the route this decrease at the end is not surprising. For the Traveling Salesman task no differences between male and female participants were found for any of the analyzed variables.

In the second experiment a walking version of the Corsi task was designed. Similar to other studies (e.g. Fischer 2001, Busch et al. 2005, Cornoldi & Mammarella 2008) a performance decrease with increasing sequence length was found. This decrease was likely caused by the capacity limit of the working memory and the higher demands on working memory resources in the longer sequence lengths. With a mean Corsi span of about four participants were a little bit below the Corsi span of five reported by Corsi (1972) and Orsini et al. (1987). Though, in these studies participants solved a classical version of the Corsi task

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[1] Some parts of this chapter have been used and were published in the paper Röser et al. (2016) and were adopted here almost one to one. The final publication is available at link.springer.com/article/10.1007%2Fs00221-016-4582-z.

and here participants solved a walking version which required also working memory resources for spatial updating and walking itself. Further, due to the experimental setup participants had to transfer the shown sequence from screen to the pattern configuration on the floor. This reference frame transformation required also working memory resources which could not be used for rehearsal and recall of the sequence and probably were co-responsible for the performance decrease. In several studies it was shown that the space of scale has an influence on spatial coding (Wolbers & Wiener 2014, Jiang & Won 2015), which could make it more difficult in the Walking Corsi task to memorize the sequence that was shown on a small screen and transferred to the large floor. This might also be an explanation for the shorter Corsi span. During recall phase participants could not see the whole pattern configuration all at once; this means they sometimes had to move their head and turn around to find the next square of the sequence. This spatial updating also required working memory resources and led to a decrease of performance.

The mean correct initial sequence length was similar for all eight sequence lengths. This is another evidence for splitting the working memory resources between sequence memorizing and sequence recall as well as spatial updating and reference frame transformation, since the mean initial sequence was with about three below the working memory capacity of about five items (Cowan 2000). When the temporal factor was ignored for the analysis and only the square tiles, which were shown in the sequence, were counted regardless of their order the number of partial set correct squares increased with increasing sequence length up to eight squares in sequence length ten and was above the limited capacity of the working memory. This indicates that the chosen sequences were not the reason for the lower Corsi span but from errors in the recall phase. Though, it has to be admitted that there was a good chance to step on a square tile which was included in the sequence by chance, especially in the longer sequence lengths since the pattern configuration contained only fifteen squares. For sequence length ten this chance was 66.7 %. So this might be another reason for the better value in partial set correct.

Participants' walking speeds decreased with increasing sequence length. Similar to the findings of the Traveling Salesman task this decrease could be the result of the small experimental room and the smaller distances between square tiles in the longer sequence lengths. Though, again a decrease of walking speed with increasing sequence length was found for sequence segments with the same distance. This indicates that not only the size of the experimental room but especially the additional working memory load led to a decrease of walking speed. Contrary to the Traveling Salesman task this time the decrease was observed for longer segments with distances between 2 and 3.5 m. The standing time on a single square tile increased with increasing sequence length. This seems to be caused by the longer sequences which had to be remembered and hence, the additional working memory load. The standing time course tended to increase at the beginning of the sequences and decrease at the end of the sequences. Interestingly, the decrease of standing times appeared in each sequence lengths about three squares before the end. This finding provides evidence that participants did not memorize the sequence square by square, but it seems they grouped about three squares into a chunk. This chunking would facilitate remembering longer sequences since the squares were not recalled one by one. Therefore, the capacity limit of the working memory was reached later in longer sequence lengths.

For the two different starting positions no differences in performance were found. There was also no correlation between the minimal number of crossings of a sequence and participants' performances. Though, a correlation between the minimal rotation angle of a sequence and the performance in this sequence was observed showing that with increasing rotation angle the performance decreased. The more turnings participants made the more they had to update their current position in relation to the pattern configuration. For the percentage of correct trials, the length of the correct initial sequence and the partial set correctly reproduced square tiles no difference between males and females was found. Though, there was a difference in walking speed which was faster for males. Generally, faster walking speeds for males have been reported by e.g. Himann et al. (1988) and Öberg et al. (1993), which could be caused by the physical characteristics of males and females. Females not only walked slower but they also stood longer on the single square tiles than males. If the standing time on the squares was used for recall of the sequences and updating the own current position in relation to the pattern configuration, this longer standing time could be explained by weaker performances in mental rotation of females, which were found in studies by e.g. Linn & Petersen (1985), Richardson (1994) and Voyer et al. (1995).

A computerized version of the Corsi task was developed in Experiment 3. Similar to the findings of the Walking Corsi task, again, a decrease of performance was found with increasing sequence length. This decrease was caused by the longer sequences which had to be memorized. The Corsi span participants reached in the computerized Corsi task was above six and therefore higher than the reported Corsi span of five in a classical version (Corsi 1972, Orsini et al. 1987). An explanation could be that the presentation on a screen in 2D has less spatial information to remember than a classical version with wooden blocks in 3D. Though, in other classical Corsi versions Corsi spans of about six were mentioned (Kessels et al. 2000, Monaco et al. 2013), still, they were a bit lower than the Corsi span found here. The length of the correct initial sequence increased with increasing sequence length up to a sequence length of six shown squares. Then it remained the same in the longer sequence lengths with about five and was in line with the reported working memory capacity limit. Like for the Walking Corsi task the number of partial set correctly reproduced squares increased with increasing sequence length. And once more this could be explained by the excluded temporal factor of the sequence but also by the possibility to click on a correct square by chance in particular in the long sequence lengths. No differences in performance were found for the comparison between the two pattern orientations as well as for the comparisons between the genders.

In the fourth experiment participants were asked to solve a computerized version of the Corsi task and a Pattern Copying task in which no sequence but only locations had to be memorized.

For this computerized Corsi task similar results as for the Corsi task in Experiment 3 were found. Again, the percentage of correct trials decreased with increasing sequence length and the Corsi span participants reached was equal to the one of Experiment 3. The length of the correct initial sequence increased up to a sequence length of six and remained similar with about five in the longer sequence lengths which is also equal to the findings in Experiment 3. Furthermore, the number of the partial set correctly reproduced square tiles increased over the sequence lengths. The analysis for possible gender effects did not reveal any differences between male and female participants.

In the Pattern Copying task the percentage of correct trials was similar in all sequence lengths and participants' Copy spans were between 9 and 10. For the correct initial sequence lengths participants reached mostly the maximum number up to a sequence length of eight and still in the sequence lengths nine and ten the mean correct initial sequence length was close to the maximum. Also for the number of partial set correctly reproduced square tiles an increase with increasing sequence length was found; this time the maximum possible number was reached in all sequence lengths. Similar to the Corsi task, there was no difference of performance for the two different pattern orientations and there were also no differences between the genders. Participants' click patterns were analyzed for possible strategies, but none of the participants kept the same click strategy for the whole experiment. Nevertheless, it was observed that the squares were clicked in consecutive ways for most of the time.

In the last experiment four Corsi tasks with different modality conditions were solved by the participants. Again, a performance decrease with increasing sequence length was found. However, the strength of the decrease depended on the modality condition and particularly on the different types and amounts of requirements needed in each modality condition. Therefore, the best performance was reached in the modality condition Screen-Screen, followed by Floor-Screen and Floor-Floor. The lowest performance was found for the modality condition Screen-Floor. The Corsi span for the modality condition Screen-Screen was similar to the Corsi spans of Corsi task 1 and 2. Also the Corsi span of Screen-Floor was equal to the Corsi span of the Walking Corsi task. The Corsi spans of the modality conditions Floor-Screen and Floor-Floor were between the two other modality conditions. The length of the correct initial sequence increased in all modality conditions with increasing sequence length, except for the modality condition Screen-Floor in which no difference of the length of the correct initial sequence was found over the sequence lengths. Again, the longest correct initial sequence was found for Screen-Screen followed by Floor-Screen and Floor-Floor. The shortest mean initial sequence length was observed in Screen-Floor. These results are in line with the different demands on working memory resources of each modality condition. Similar to the first experiments the number of partial set correctly reproduced square tiles increased in all four modality conditions with increasing sequence length.

For the modality conditions Floor-Floor and Screen-Floor a decrease of walking speed with increasing sequence lengths was found, like it was found for the walking speeds of Experiment 1 and 2 before. For both modality conditions the walking speeds on equal distances in different sequence lengths were analyzed. In Floor-Floor a significant decrease of walking speed with increasing sequence length was only found for two segments which had a length of 1.32 m and 2.81 m. In Screen-Floor five segments revealed a significant decrease of walking speed with increasing sequence length for segments with the same distance. Similar to the Walking Corsi task this decrease was found for segments with longer distances; this time the lengths were between 1.61 m and 3.13 m. In the Walking Corsi task the standing times on a square tile increased with increasing sequence lengths, though, here in Experiment 5 only a tendency for longer standing times in longer sequence lengths was found. Further, it was found that participants stood longer on the square tiles in the modality condition Screen-Floor than in the modality condition Floor-Floor. These longer standing times could be caused by the reference frame transformation from screen to floor which makes it more difficult for the participants to rehearse the sequence in the recall phase, compared to sequences in Floor-Floor which were shown and reproduced in the same reference frame. Again, the standing time course showed an apparent increase of the standing times for the first squares of a sequence and a decrease of standing time for about the last three squares of a sequence. This is another evidence that at least in walking versions of the Corsi task participants chunk about three squares of a sequence together and later recall these chunks which resulted in a shorter standing time at the end of the sequence.

In this experiment four different starting positions were used, but no difference in performance was found between them, neither for the walking modality conditions (i.e., Floor-Floor and Screen-Floor) nor for the modality conditions in which the sequence was reproduced by mouse clicks (i.e., Screen-Screen and Floor-Screen). Similar to Experiment 2 the minimal number of crossings and the minimal rotation angle of each sequence were compared with participants'

performance in this sequence. In contrast to Experiment 2 this time a correlation between the minimal number of crossings and the performance was observed. Sequences with less crossings were recalled correctly more often than sequences with more crossings. Similar results were also reported by Orsini et al. (2001) and Parmentier & Andrés (2006). The minimal rotation angles also correlated with the percentage of correct trials - the larger the rotation angles were the lower the performance was. This result was similar to the findings in Experiment 2.
For all four modality conditions the results were analyzed for possible gender differences. There were no gender differences for the modality condition Floor-Screen. In the modality condition Screen-Screen males had a better performance than females. For Floor-Floor no differences between the genders were found for the percentage of correct trials and the standing time on a square tile; but it was found that males had a longer correct initial sequence length and also a higher number of partial set correctly reproduced squares than females. Again, it was found that males had a higher walking speed than females. This was also found by Himann et al. (1988) and Öberg et al. (1993). In the modality condition Screen-Floor no differences between the genders were observed for the percentage of correct trials, the number of partial set correctly reproduced squares and the standing time. Though, male participants had a longer correct initial sequence length and a faster walking speed than female participants. Better performances of male participants in a classical version of a Corsi task were also reported by Piccardi et al. (2008 and 2016).

In all five experiments a performance decrease with increasing sequence length was found. This decrease is caused by the limited capacity of the working memory (Miller 1956, Cowan 2000). If more than one task has to be solved simultaneously working memory resources and also attention have to be split up and provided to the involved subsystems of the working memory and switched between them (Barrouillet & Camos 2007). Such a splitting can lead to performance decrease in dual task setups and was found in all experiments.

In all of the different walking conditions a decrease of walking speed with increasing sequence length was observed. Further, in segments with equal distances participants walked slower in longer sequence lengths than in shorter ones. This decreased walking speed should not be simply the result of the size of the experimental room but should be caused by additional working memory demands in longer sequence lengths. Furthermore, it should be noted that participants probably used the time while standing on the square tiles for planning their next step, although they were instructed not to keep standing too long on the square tiles. If participants were not asked to stand on the square tiles with both feet but simply walk across them, there probably would have been a larger influence on walking speed caused by working memory resources needed for planning the route and recalling the sequence also for short distances between square tiles. Though, for a better data evaluation it was necessary to ask the participants to keep standing on the squares with both feet for a short time.

In the different Corsi tasks presented in this thesis participants' performance was also used to calculate the individual Corsi span of the participants. In most of the studies which investigated the performance in Corsi tasks Corsi's (1972) method to calculate the Corsi span was used. This means the maximum number of blocks participants reproduced in the correct order denotes their Corsi span (e.g. Kessels et al. 2000, Millet et al. 2009, Monaco et al. 2013, Piccardi et al. 2013 and 2016). Though, Smirni et al. (1983) reported in their study that participants sometimes failed in shorter sequence lengths but reproduced longer sequence lengths correctly. They suggested “that the test should be continued at least two lengths beyond the first failure in order to be sure of testing the real memory span and its stability” (Smirni et al. 1983). Since in the experiments presented here not only the performance but also the walking speeds in the different sequence lengths should be investigated it was necessary that participants solved the trials of all sequence lengths. Therefore, the task was not aborted if participants failed to complete a sequence length correctly but was continued up to a sequence length of eight and ten, respectively. For calculating the Corsi span the method by Smyth & Scholey (1992) and Lépine et al. (2005), in which the correct trials are proportionally rated to the total trial number, was adopted (for more details see explanation on p. 42).

The Corsi spans observed in the different experiments differed from Corsi spans found in other studies, e.g. Piccardi et al. (2010) reported a Corsi span of about five in a walking version of the Corsi task, whereas participants in the Walking Corsi task reached a Corsi span of only four. Reasons for this discrepancy could be different methods of calculating the Corsi span but also varying sequences which were tested in the different sequence lengths.

In several studies it was found that the difficulty of the sequences not only depend on the length of the sequence but also on the characteristics of the sequence. Orsini et al. (2001) found e.g. that the number of crossings also influences the difficulty of a sequence. Also Shah et al. (2013) reported that sequences without crossings were reproduced better than sequences containing crossings. Smirni et al. (1983) as well as Schellig & Hättig (1993) reported that the “spatial configuration” and thus the “figural complexity” of a sequence affects performance of the Corsi task.

Further, the presentation method of the sequences varied often in the studies. Often an experimenter presented the sequence to remember in a classical version by tapping on (wooden) blocks with the finger, though, the tapping speed varied in different studies, e.g. tapping speeds with one block per second (Della Sala et al. 1999, Kessels et al. 2000, Pagulayan et al. 2006, Shah et al. 2013, Robinson & Brewer 2016) or tapping speeds with one block per two seconds (Piccardi et al. 2010) were used.

Perrochon et al. (2014) used a plastic board with plastic blocks to present the sequences by illuminating the blocks. This presentation of the sequences was computer-controlled. There are also several studies which used a computer screen to present the sequences (e.g. Zimmer et al. 2003, Vandierendonck et al. 2004, Fournet et al. 2012, Shah et al. 2013, Higo et al. 2014, Woods et al. 2016). In the walking versions of Piccardi et al. (e.g. 2008) and Tedesco et al. (2017) an experimenter walked the sequences to present them to the participants and a virtual version of a walking Corsi task was tested by Nori et al. (2015). These examples show that there are several methods for presenting the sequences which all might influence the difficulty of the sequences. For example, participants of Piccardi et al.’s study of 2008 reported that they were “visualizing a pathway on the carpet” when the experimenter presented the sequence by walking on a carpet. This visualization was not present during a classical presentation of tapping on the blocks with the finger or at least to a lower degree. Finally, with computerized versions in which the blocks were only highlighted no pathway was shown by the experimenter.

The different Corsi spans might not only be caused by the varying sequences and presentation as well as recall methods but also by the participants’ age. The Corsi span increases in children (Orsini et al. 1987, Logie & Pearson 1997) up to an age of twenty years (Pagulayan et al. 2006) and decreases again from twenty years on (Orsini et al. 1987 and Monaco et al. 2013). So different Corsi spans in different studies could also be the result of participants with different age.

The comparison between males and females revealed no differences in performance (e.g. percentage of correct trials, correct initial sequence length and partial set correct squares) for the Traveling Salesman task, Walking Corsi task, Corsi task 1, Corsi task 2, Pattern Copying task and the modality condition Floor-Screen. For the modality condition Screen-Screen for all of the three factors mentioned above, a difference between male and female participants was found. Also in the modality condition Floor-Floor males had a better performance in the correct initial sequence length and in the number of partial set correct squares. A longer correct initial sequence for males was observed in the modality condition Screen-Floor, too. In several studies better performances of males were found in classical (e.g. Capitani et al. 1991, Piccardi et al. 2008 and 2016, Shah et al. 2013), computerized (e.g. Fournet et al. 2012), walking (e.g. Piccardi et al. 2008) or virtual walking versions (e.g. Nori et al. 2015). In contrast, other studies reported no gender differences in classical versions of a Corsi task (e.g. Kessels et al. 2000, Pagulayan et al. 2006, Monaco et al. 2013) or even a better performance of females in a walking version (e.g. Nori et al. 2015). Therefore, a large variety of performances for male and female participants have been reported. These results and also those of the gender comparisons between Corsi task 1 as well as Corsi task 2 and the modality condition Screen-Screen might be caused by the sequences used in the experiments as well as experimental designs and other parameters. In the floor-recall modalities the better results of males in the correct initial sequence length and in the number of partial set correct squares are supposed to be a result of better mental rotation capabilities.
Faster walking speeds of males were found in all of the Corsi tasks, and in the Traveling Salesman task a tendency for a faster walking speed of males was observed. Physical characteristics could contribute to this effect.

In many of the Corsi tasks designed for this thesis the sequences were presented on a screen. Brunetti et al. (2014) used a tablet version of the Corsi task to investigate participants' Corsi spans. They compared their results to the Corsi spans of other studies and found similar results, though, they made no within-subject comparison between the tablet and the classical version. Robinson & Brewer (2016) compared both a tablet version of the Corsi task and a classical version of the Corsi task. In their study they found no difference between the two tasks. In contrast, Claessen et al. (2015) found a better performance on a classical Corsi version compared to a tablet version. Because of these converse results it would have been interesting to have a direct comparison between the modality condition Screen-Screen in 2D and a classical version of a Corsi task in 3D.

With the design of the four different modality conditions it could be shown that participants' performance was impaired by reference frame transformation. As a fifth modality condition it would be interesting to measure participants' performance when they were recalling the sequences by mouse clicks on a large screen, e.g. by displaying the pattern configuration with a beamer in the recall phase. In an experiment investigating memory for spatial information Smyth & Scholey (1994) did not find a loss of performance when the size of the display was enlarged. Though, Guérard & Tremblay (2012) reported that a larger display had a small effect on participants' performance. They used screens with sizes of 15" and 64". Presenting the pattern configuration with a beamer would allow to compare the performances in conditions with larger differences in screen size and therefore possibly increase the effect found by Guérard & Tremblay.

In the Pattern Copying task of Experiment 4 the temporal factor of the sequences was eliminated by presenting all squares the same time and participants only had to memorize and reproduce the spatial information of the square locations. In a future experiment it could be interesting to investigate an elimination of the spatial factor, at least in the recall phase. Therefore, a sequence similar to the Corsi task could be presented in the encoding phase and participants would be asked to memorize the sequence. Though, in the recall phase all squares included in the sequence would be highlighted and participants only had to reproduce their order by mouse clicks or walking to the square tiles. So, participants would not have to memorize the locations of the squares but only their temporal order. With such an experimental design it could be investigated whether the spatial factor (locations of the squares) or the temporal factor (order of the squares) has a bigger influence on task performance.

Giving feedback to participants during an experiment can have different reasons, e.g. Vickers et al. (2003 b) gave participants feedback for motivation after each trial. Further it can be used to give cues to the participants when feedback is given immediately after an error. In a study by Acuña & Parada (2010) participants received feedback after each trial and were able to repeat the trial for unlimited times. They found that feedback and repetitions led to improved performance. Here, in the Corsi task of Experiment 3 (i.e., Corsi task 1) participants received feedback right after an error, whereas participants solving the Corsi task of Experiment 4 (i.e., Corsi task 2) received no feedback. Feedback was introduced in Experiment 3 to check whether cues can improve participants' performance in solving the task and compared with the results of Experiment 4 in which no feedback was given. Both experiments did not differ in the percentage of correct trials and in the length of the correct initial sequence. Though, participants of Corsi task 2 had a higher number of partial set correctly reproduced square tiles than participants solving Corsi task 1. In this case the feedback participants received in Corsi task 1 led to a decrease of performance. Probably the reason was that participants sometimes clicked into the same square for a second time after receiving feedback when they e.g. mixed up two squares of a sequence. In contrast in Corsi task 2 participants got no hint that the square was wrong and therefore clicked into another square, so if they had mixed up two squares of a sequence they nevertheless often reproduced both of the squares, albeit not in the correct order. This resulted in a higher number of partial set correctly reproduced squares in Corsi task 2. So, using feedback during an experiment can increase, but also decrease participants' performance depending on the specific feedback type and also on the way of analysis and therefore should be used deliberately.

Conclusion

Planning a route while walking and walking a known route require different amounts of working memory resources and also different working memory components are thought to be involved in solving the two tasks, as the differences in performance and standing time as well as the different standing time courses between the Traveling Salesman task and the Walking Corsi task revealed.

Further, it was found that presentation type and recall type of a Corsi sequence have different demands on working memory resources and influence participants' performance in various ways. The data showed that performance in the Corsi task depends not only on the mental ability to reproduce a visuo-spatial and temporal sequence of varying lengths but also on additional spatial requirements demanded by real walking. Furthermore, these different additional costs affect working memory processes differently as revealed by the different modality conditions in this setup. These new findings will help to characterize and understand the spatial component of working memory in a better way.

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Appendix

A. Experiment 1: Traveling Salesman task

A.1. Routes

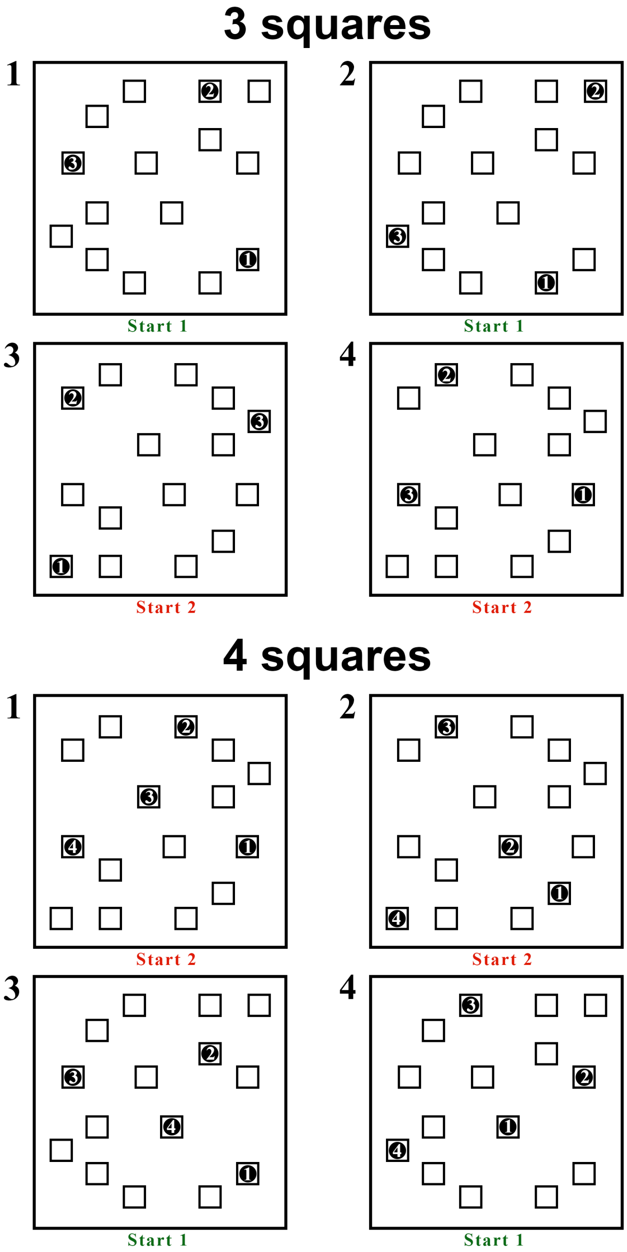
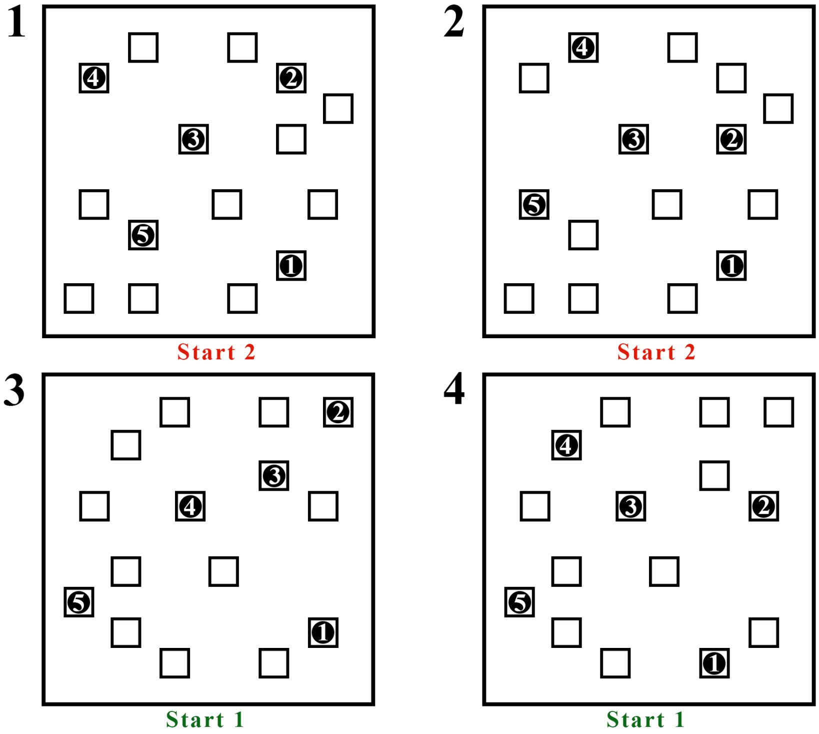


Figure A.1.: Traveling Salesman routes of route lengths three and four. The black circles mark the squares which had to be visited during the route. The numbers in the circles show one possible shortest route. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each route length.

5 squares



6 squares

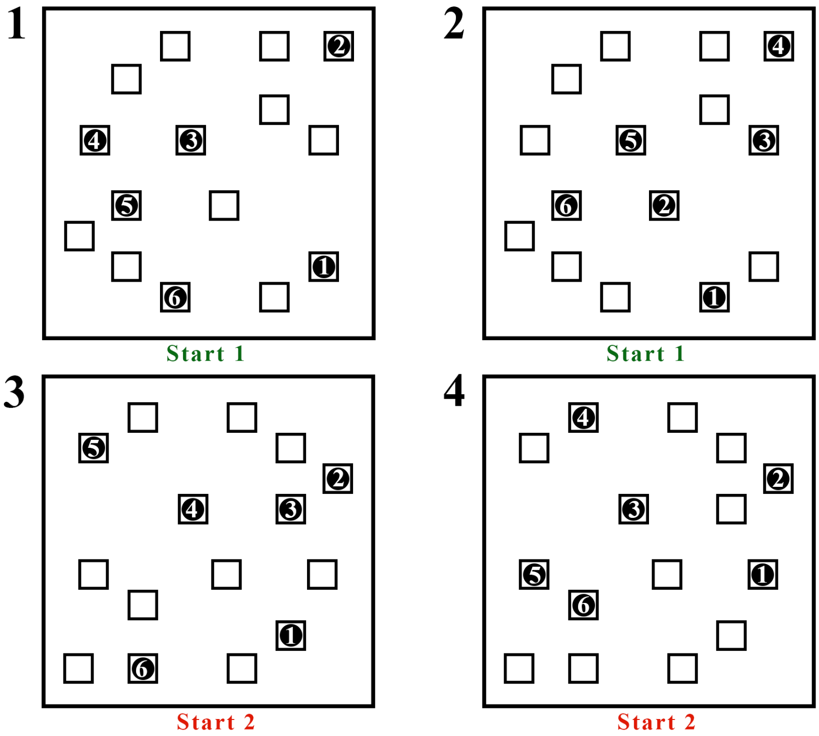


Figure A.2.: Traveling Salesman routes of route lengths five and six. The black circles mark the squares which had to be visited during the route. The numbers in the circles show one possible shortest route. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each route length.

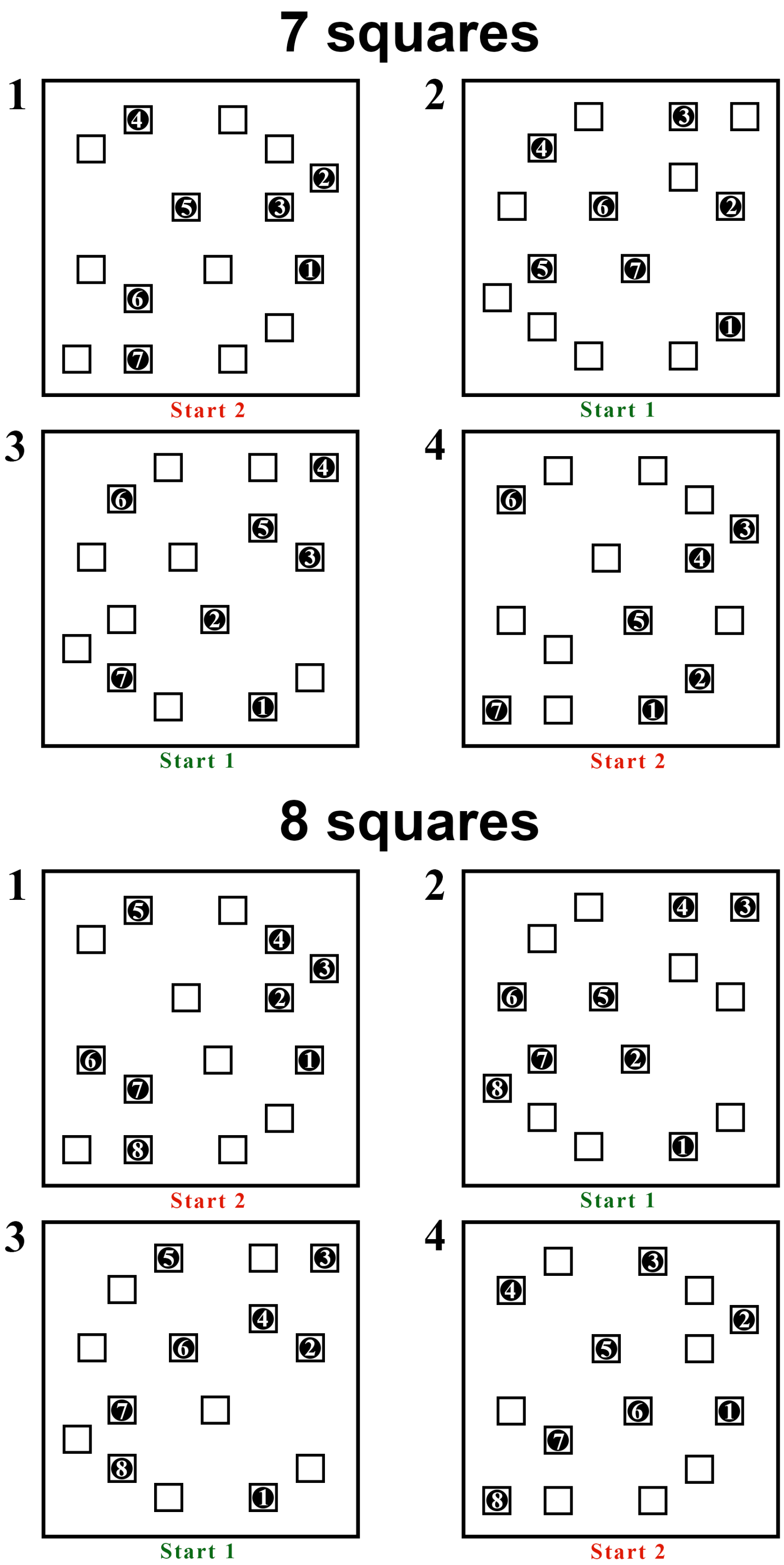


Figure A.3.: Traveling Salesman routes of route lengths seven and eight. The black circles mark the squares which had to be visited during the route. The numbers in the circles show one possible shortest route. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each route length.

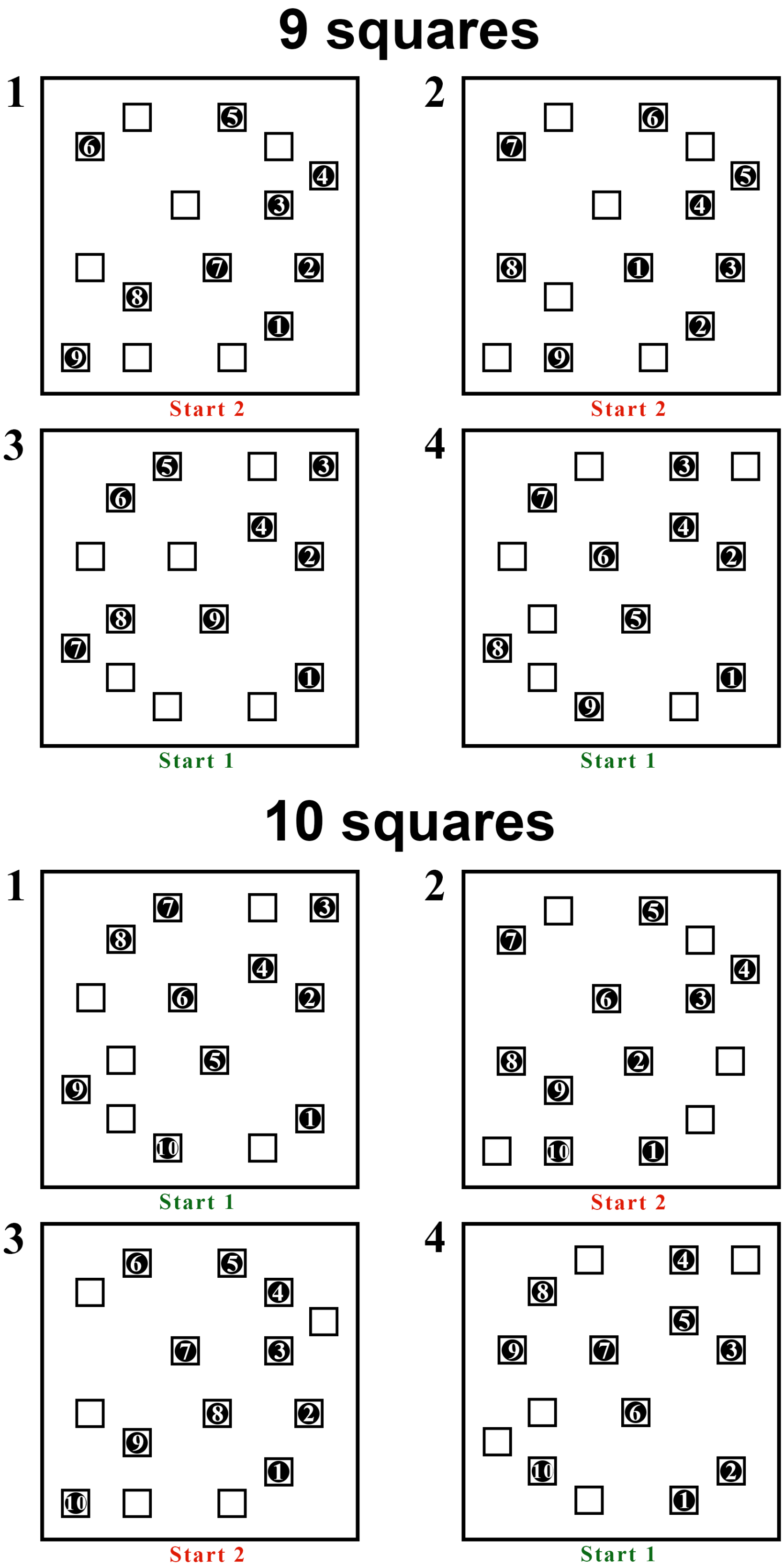


Figure A.4.: Traveling Salesman routes of route lengths nine and ten. The black circles mark the squares which had to be visited during the route. The numbers in the circles show one possible shortest route. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each route length.

A.2. Correct versus false trials

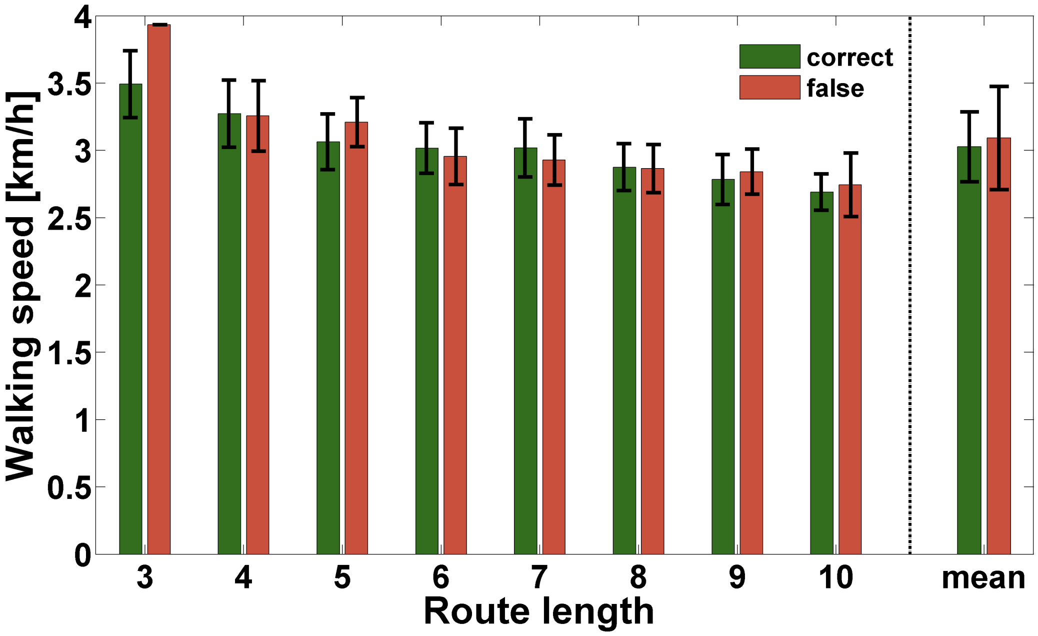


Figure A.5.: Comparison of walking speed in correct and false trials. Participants' mean walking speed (y-axis) is depicted for each route length (x-axis) for the correct (green bars) and false trials (red bars). The mean walking speed decreased significantly with increasing route length. Though, there was no difference between correct and false trials in walking speed. Also there was no interaction between the factors route length and performance (correct and false trials). The mean average over all participants and route lengths is depicted for both groups on the right. Error bars indicate the standard deviation.

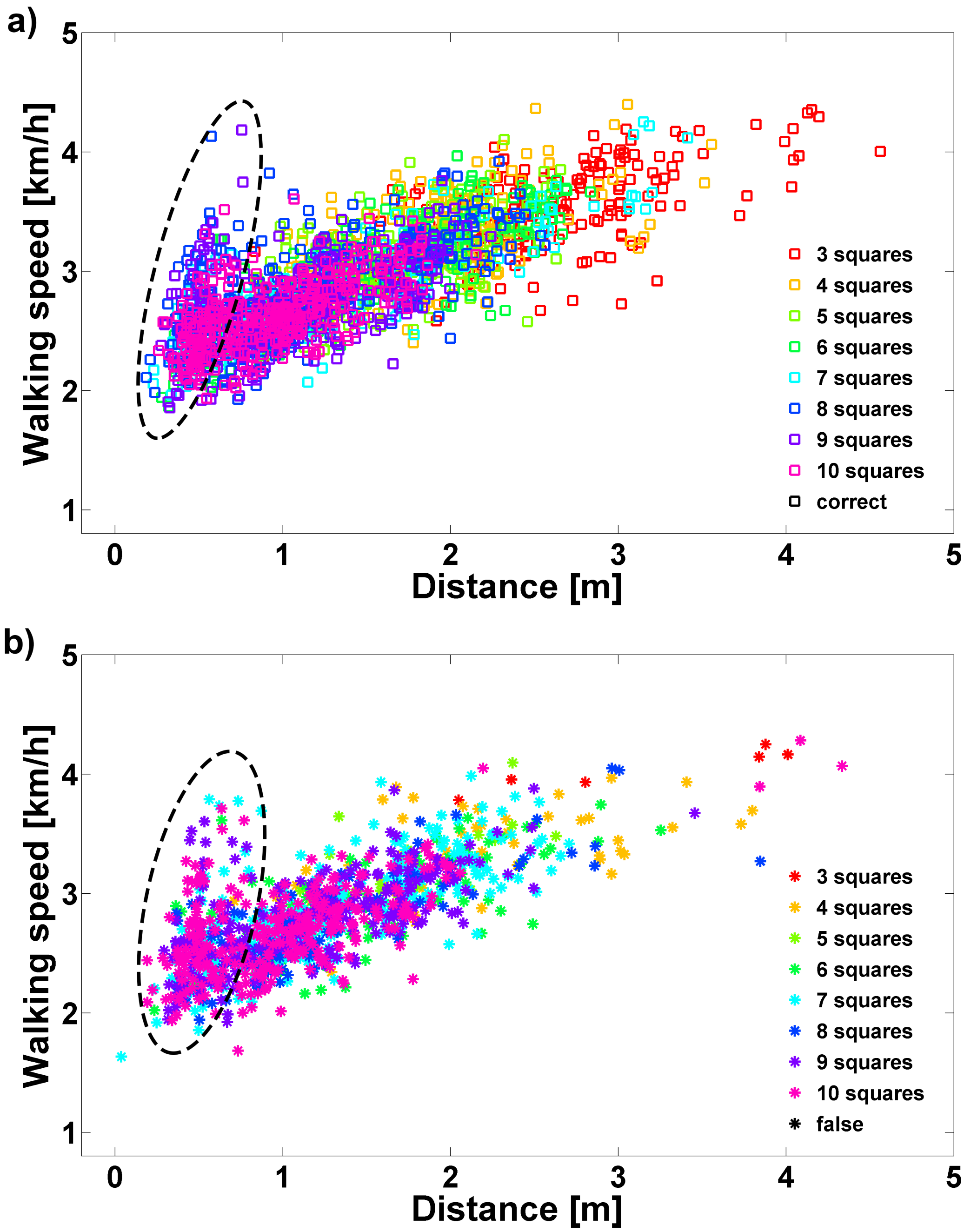


Figure A.6.: Correlations between the mean walking speed and the distance between two square tiles. a) The correct trials are depicted. b) The false trials are shown. In both figures the mean walking speed (y-axis) between two square tiles is plotted against the walked distance between these squares (x-axis) for each trial and participant. The walking speed increased with increasing distance. The dotted ellipses mark the “second arms”. Correct trials are depicted with squares (a), false trials with stars (b) and the different sequence lengths with different colors.

A.3. Numbering of pattern configuration and segment classification

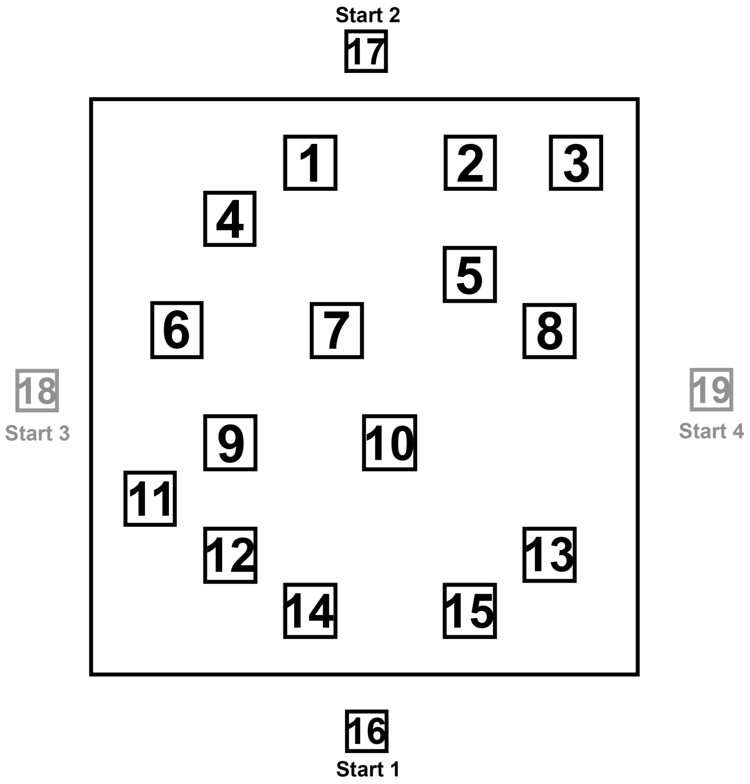


Figure A.7.: Numbering of the single square tiles in the pattern configuration. The squares of the configuration are numbered from 1 to 15. The two starting positions are numbered with 16 (Start 1) and 17 (Start 2). For Experiment 5 two additional starting positions Start 3 and Start 4 (square tiles 18 and 19, gray) were added.

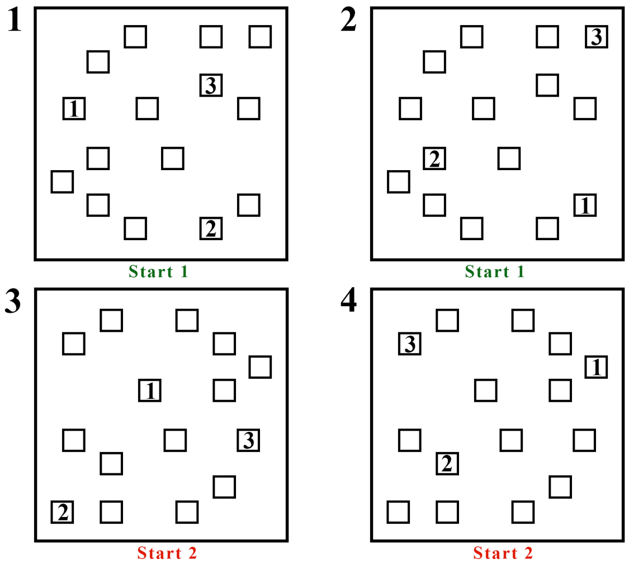
Table A.1.: Classification of the different route and sequence segments. The 28 segments are shown with their lengths and all distances between two square tiles which were pooled to the segments. Therefore distances which differed not more than about ± 5 cm were ranged in the same segment and segment's length was rounded. The arrows between the numbers illustrate that e.g. in Segment 1 the distances between square 1 and square 4 as well as between square 4 and square 1 are included.

Segment 1	length: 0.76 m	1 ↔ 4	2 ↔ 5	5 ↔ 8	9 ↔ 11	9 ↔ 12	11 ↔ 12
		12 ↔ 14	13 ↔ 15				
Segment 2	length: 0.88 m	1 ↔ 17	2 ↔ 3	4 ↔ 6	6 ↔ 9	7 ↔ 10	14 ↔ 16
Segment 3	length: 1.32 m	1 ↔ 2	2 ↔ 8	5 ↔ 10	6 ↔ 7	9 ↔ 10	9 ↔ 14
		10 ↔ 14	10 ↔ 15	14 ↔ 15			
Segment 4	length: 1.52 m	1 ↔ 5	4 ↔ 9	8 ↔ 10	8 ↔ 13	10 ↔ 12	10 ↔ 13
		11 ↔ 14	13 ↔ 19				
Segment 5	length: 1.17 m	1 ↔ 7	2 ↔ 17	3 ↔ 5	3 ↔ 8	4 ↔ 7	5 ↔ 7
		6 ↔ 11	7 ↔ 9	15 ↔ 16			
Segment 6	length: 4.30 m	3 ↔ 11	3 ↔ 16	3 ↔ 18			
Segment 7	length: 1.61 m	1 ↔ 6	2 ↔ 7	4 ↔ 17	6 ↔ 12	12 ↔ 16	
Segment 8	length: 1.81 m	3 ↔ 19	4 ↔ 18	5 ↔ 17	5 ↔ 19	7 ↔ 8	7 ↔ 12
		12 ↔ 18					
Segment 9	length: 1.96 m	3 ↔ 17	6 ↔ 10	7 ↔ 11	7 ↔ 14	7 ↔ 17	10 ↔ 16
		13 ↔ 16					
Segment 10	length: 2.05 m	1 ↔ 9	1 ↔ 10	2 ↔ 4	2 ↔ 10	4 ↔ 5	4 ↔ 10
		4 ↔ 11	5 ↔13	8 ↔ 15	10 ↔ 11	12 ↔ 15	13 ↔ 14
Segment 11	length: 2.25 m	1 ↔ 3	2 ↔ 19	6 ↔ 14	7 ↔ 15	7 ↔ 18	9 ↔ 16
		10 ↔ 19	15 ↔ 19				
Segment 12	length: 2.37 m	1 ↔ 8	3 ↔ 7	4 ↔ 12	5 ↔ 9	5 ↔ 15	7 ↔ 13
		9 ↔ 15	11 ↔ 16				
Segment 13	length: 2.52 m	3 ↔ 10	5 ↔ 6	6 ↔ 17	8 ↔ 17	14 ↔ 18	
Segment 14	length: 2.72 m	1 ↔ 11	2 ↔ 6	3 ↔ 13	5 ↔ 14	7 ↔ 16	7 ↔ 19
		10 ↔ 17	10 ↔ 18	12 ↔ 13			
Segment 15	length: 2.81 m	1 ↔ 12	2 ↔ 9	2 ↔ 13	4 ↔ 8	4 ↔ 14	5 ↔ 12
		8 ↔ 9	8 ↔ 14	9 ↔ 13	11 ↔ 15		
Segment 16	length: 2.93 m	3 ↔ 4	9 ↔ 17				
Segment 17	length: 3.13 m	1 ↔ 14	1 ↔ 18	2 ↔ 15	5 ↔ 11	6 ↔ 8	6 ↔ 15
		6 ↔ 16	8 ↔ 12	8 ↔ 16			
Segment 18	length: 3.23 m	1 ↔ 19	3 ↔ 15	5 ↔ 16	14 ↔ 19		
Segment 19	length: 3.40 m	1 ↔ 13	1 ↔ 15	2 ↔ 12	2 ↔ 14	4 ↔ 15	9 ↔ 19
		11 ↔ 13					
Segment 20	length: 3.55 m	2 ↔ 11	2 ↔ 18	3 ↔ 6	3 ↔ 9	4 ↔ 13	6 ↔ 13
		8 ↔ 11	11 ↔ 17	15 ↔ 18			
Segment 21	length: 3.67 m	4 ↔ 16	4 ↔ 19	12 ↔ 17	12 ↔ 19		
Segment 22	length: 3.84 m	3 ↔ 14	6 ↔ 19	8 ↔ 18	13 ↔ 17		
Segment 23	length: 3.91 m	1 ↔ 16	14 ↔ 17				
Segment 24	length: 3.98 m	2 ↔ 16	3 ↔ 12	13 ↔ 18	15 ↔ 17		
Segment 25	length: 1.10 m	6 ↔ 18	8 ↔ 19	11 ↔ 18			
Segment 26	length: 1.42 m	9 ↔ 18					
Segment 27	length: 3.30 m	5 ↔ 18					
Segment28	length: 4.10 m	11 ↔ 19					

B. Experiment 2: Walking Corsi task

B.1. Sequences

3 squares



4 squares

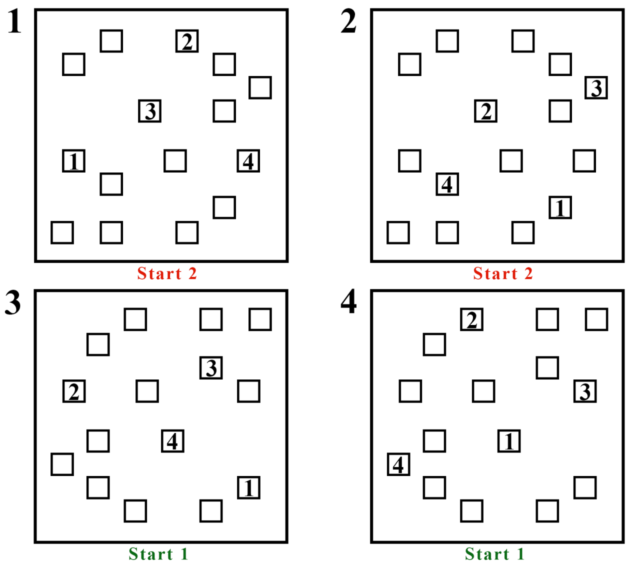


Figure B.1.: Corsi sequences of sequence length three and four. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

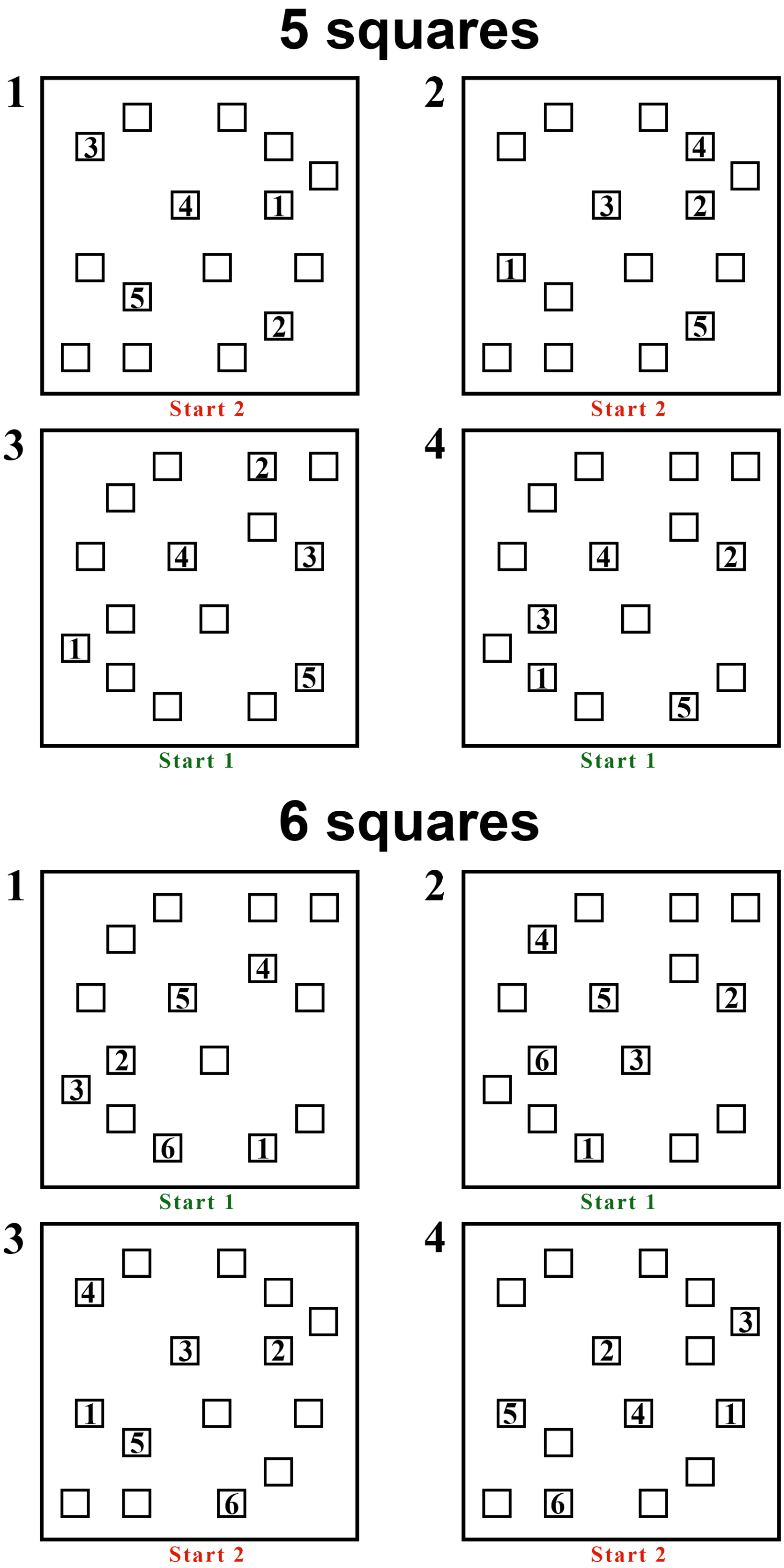


Figure B.2.: Corsi sequences of sequence length five and six. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

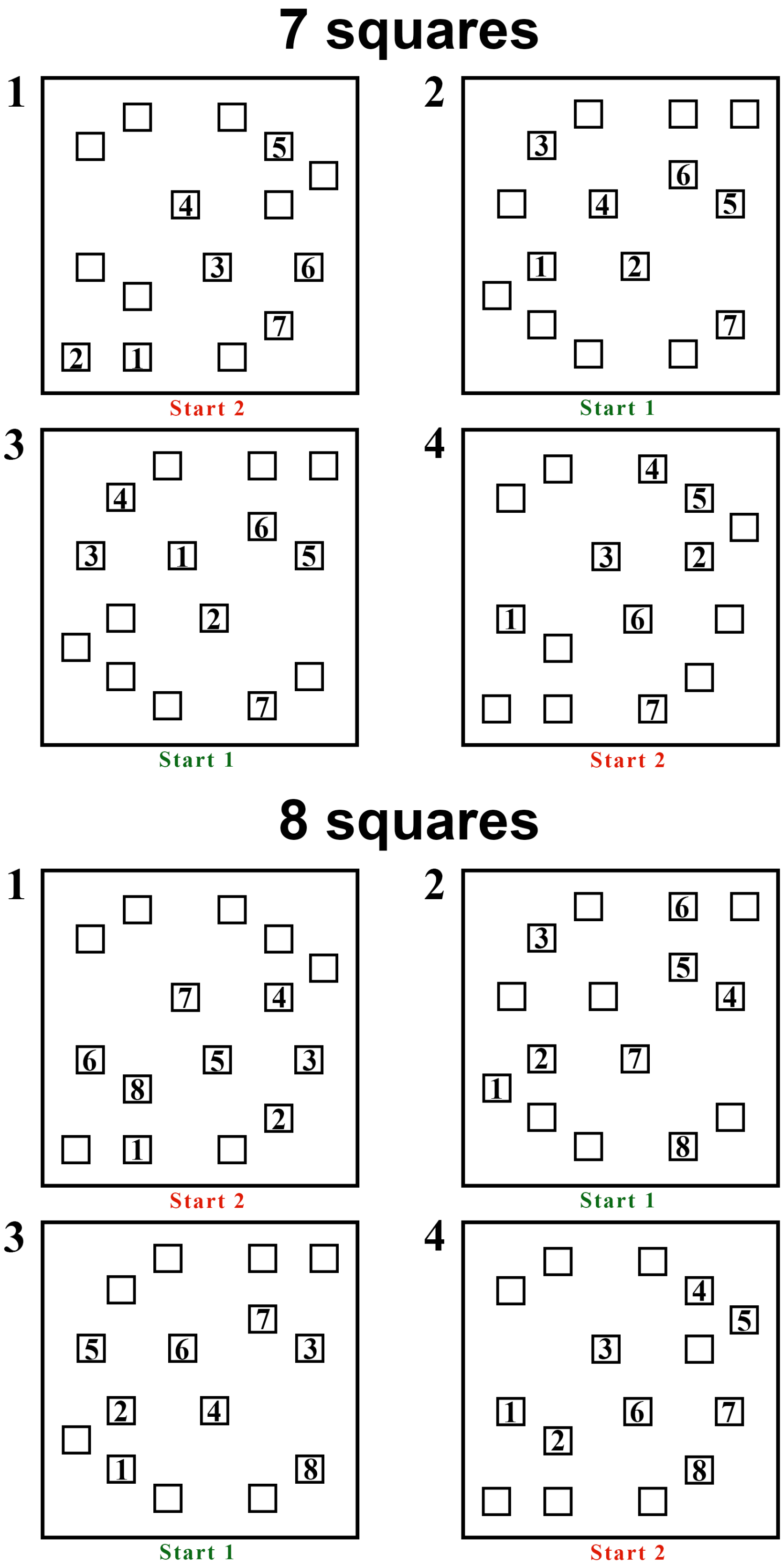


Figure B.3.: Corsi sequences of sequence length seven and eight. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

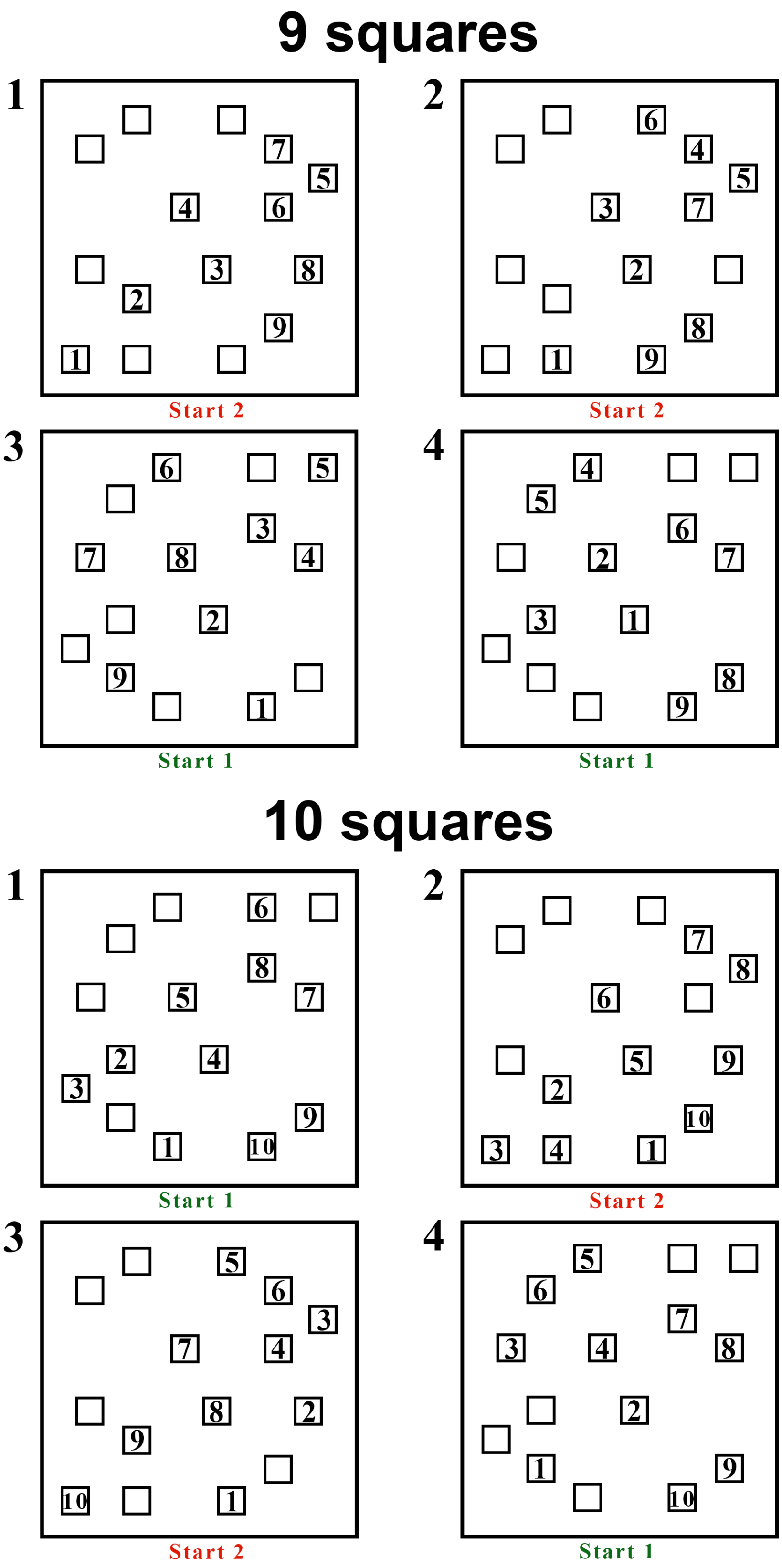


Figure B.4.: Corsi sequences of sequence length nine and ten. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

B.2. Correct versus false trials

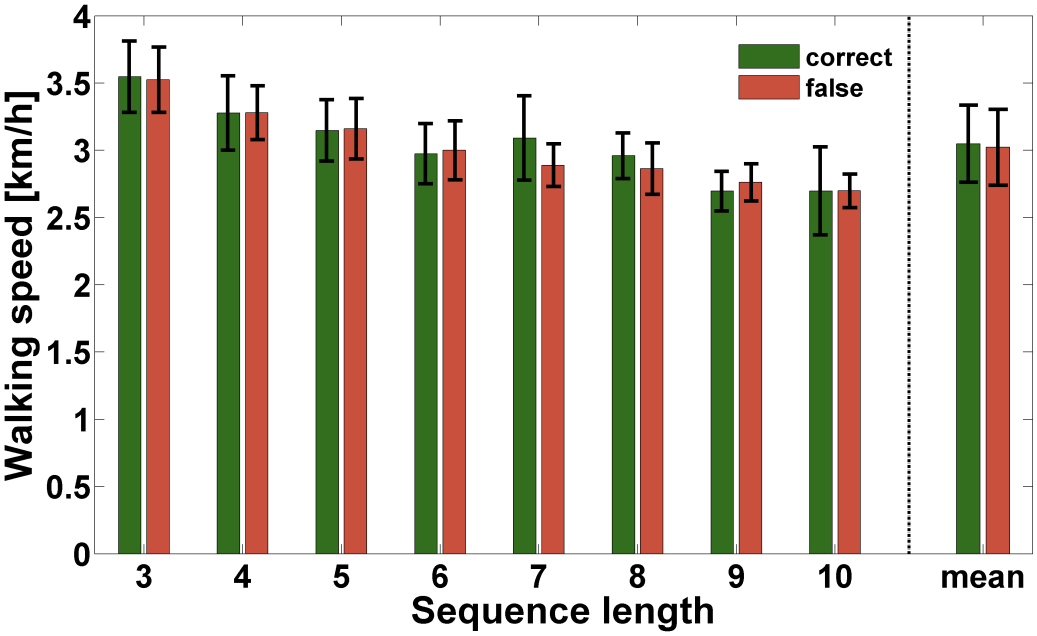


Figure B.5.: Comparison of walking speed in correct and false trials. The mean walking speed averaged over the participants (y-axis) is shown for the eight sequence lengths (x-axis) for the correct (green bars) and false trials (red bars). With increasing sequence length the mean walking speed decreased significantly. There is no difference between correct and false trials in walking speed, as well as no interaction between the factors sequence length and performance (correct and false trials). On the right the mean average over the fourteen participants and all sequence lengths is depicted for both groups. Error bars indicate the standard deviation.

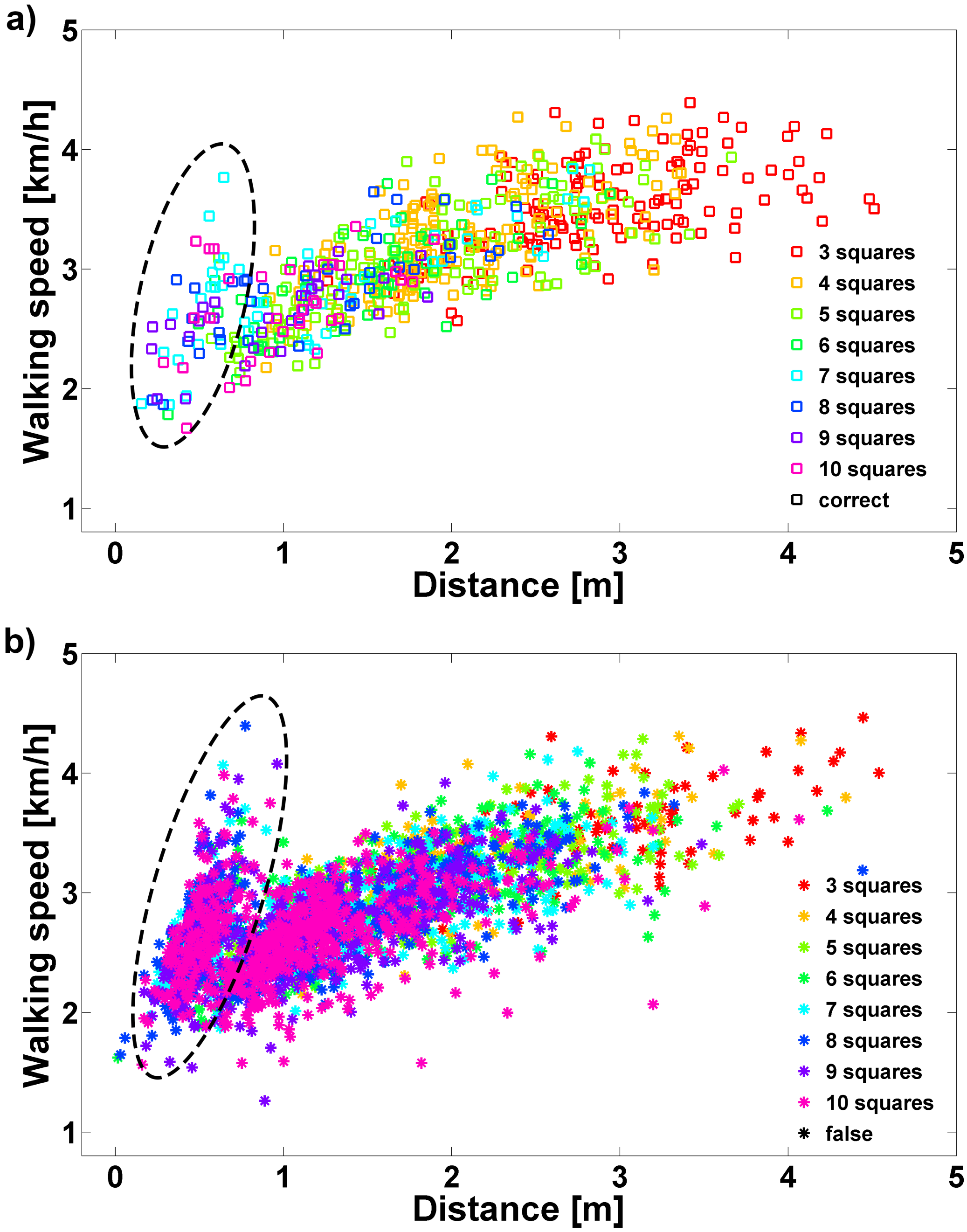


Figure B.6.: Correlations between the mean walking speed and the distance between two square tiles. a) The correct trials are depicted. b) The false trials are shown. For each trial and participant the mean walking speed (y-axis) between two square tiles is plotted in both figures against the walked distance (x-axis) between these squares. In both cases the walking speed increased with the walked distance. The dotted ellipses mark the "second arms". Correct trials are depicted with squares (a), false trials with stars (b) and the different sequence lengths with different colors.

B.3. Comparison between males and females

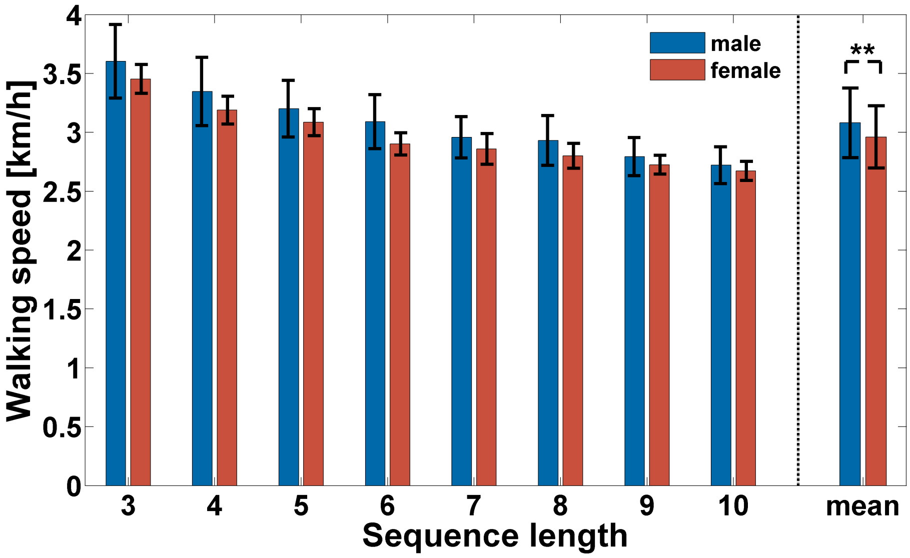


Figure B.7.: Comparison of gender differences in walking speed. The mean walking speed (y-axis) is depicted for all eight sequence lengths (x-axis) for seven males (blue bars) and seven females (red bars), also the overall mean of males and females is shown on the right. With increasing sequence length, the walking speed decreased in both groups. Males' walking speed differed significantly from females' walking speed (F(1, 7) = 10.827, $p < 0.01$, $\eta_P^2 = 0.101$; depicted with stars above the mean). Error bars indicate the standard deviation.

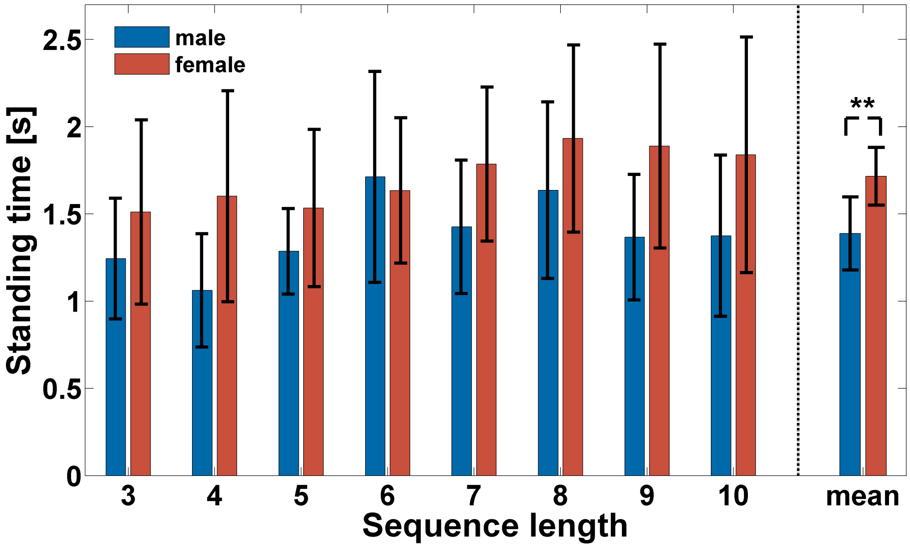


Figure B.8.: Comparison of gender differences in standing time. The mean standing time (y-axis) is shown for all sequence lengths (x-axis) for the two groups males (blue bars) and females (red bars) and also the mean over all sequence lengths is depicted on the right. With increasing sequence length the standing time on a single square tile increased for the female group. Standing time of the male group increased first, but stayed at the same level in the higher sequence lengths. Both groups differed significantly in standing time (F(1, 7) = 11.117, $p < 0.01$, $\eta_P^2 = 0.104$; depicted with stars above the mean). Error bars indicate the standard deviation.

C. Experiment 5: Corsi task in different modality conditions

C.1. Sequences of Set 1

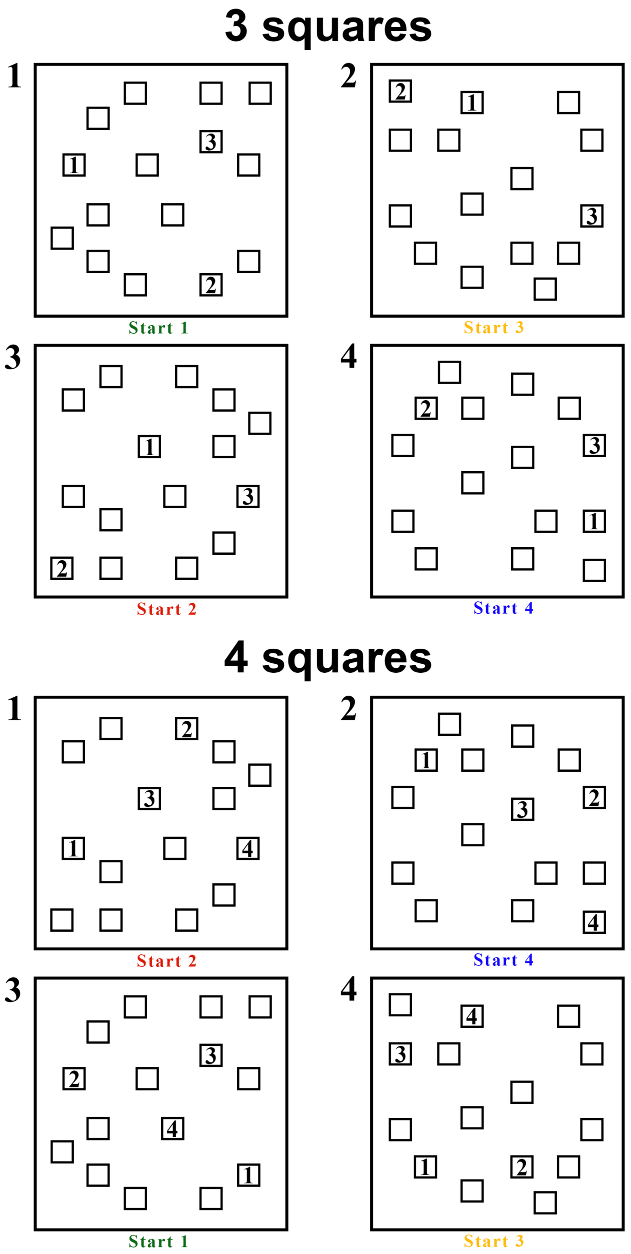


Figure C.1.: Corsi sequences of Set 1 of sequence length three and four. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

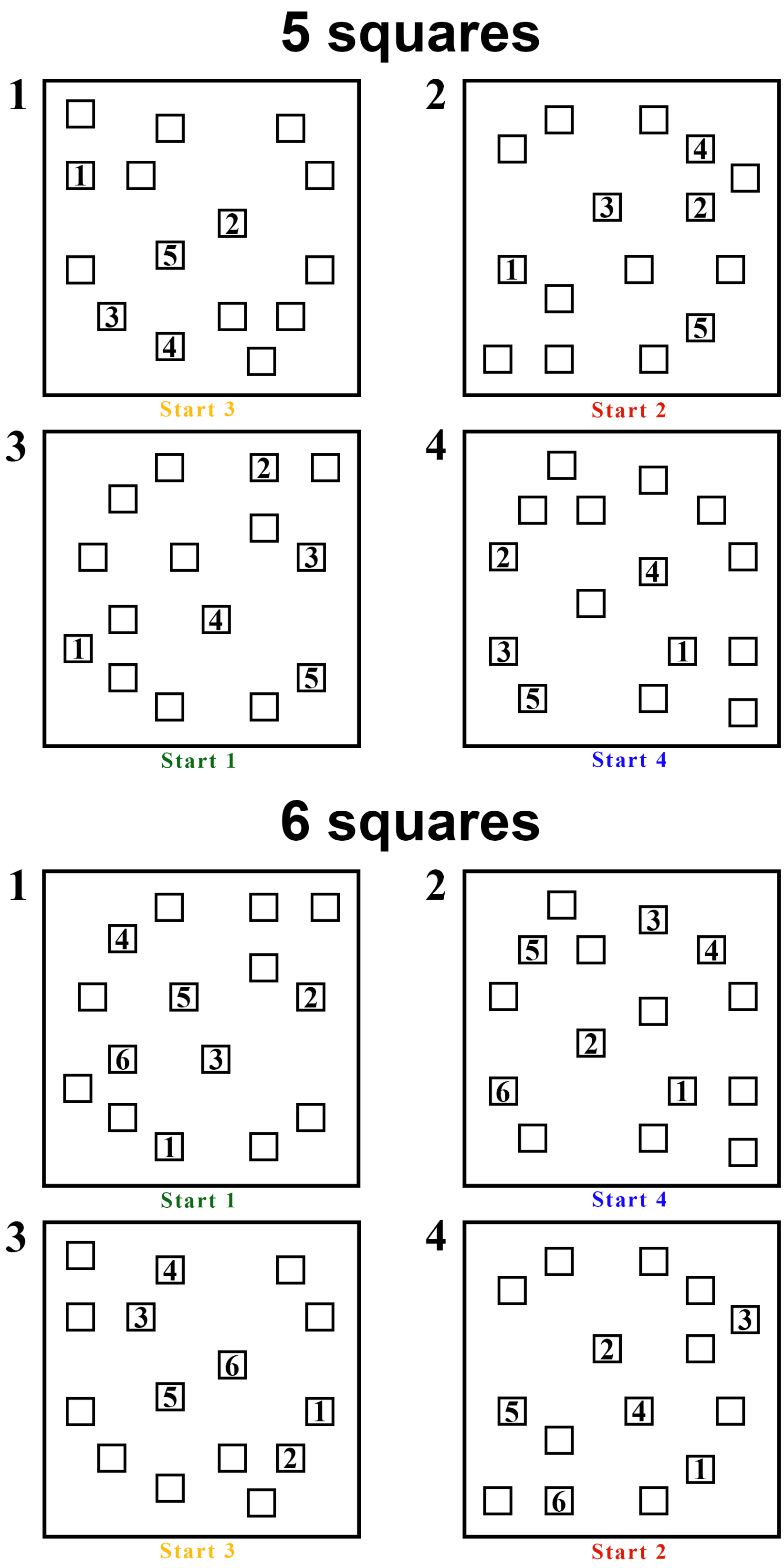
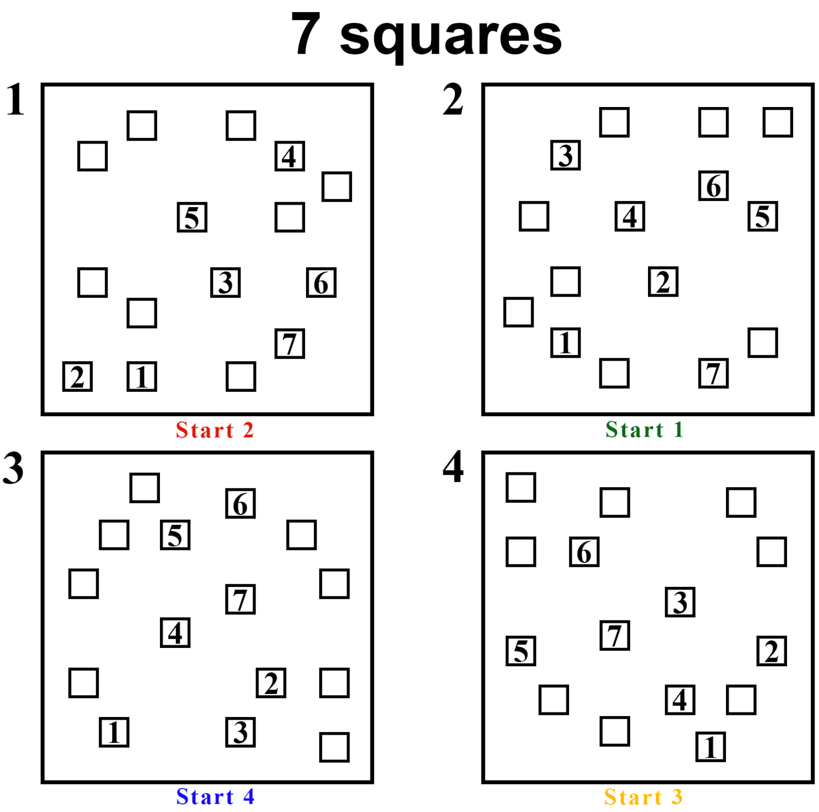


Figure C.2.: Corsi sequences of Set 1 of sequence length five and six. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.



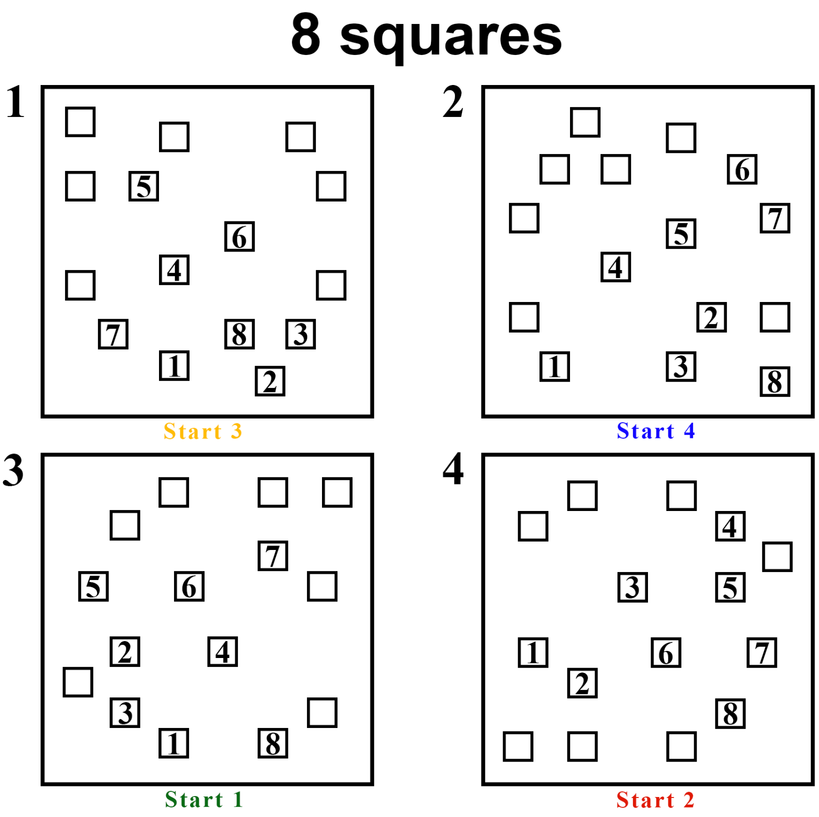


Figure C.3.: Corsi sequences of Set 1 of sequence length seven and eight. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

C.2. Sequences of Set 2

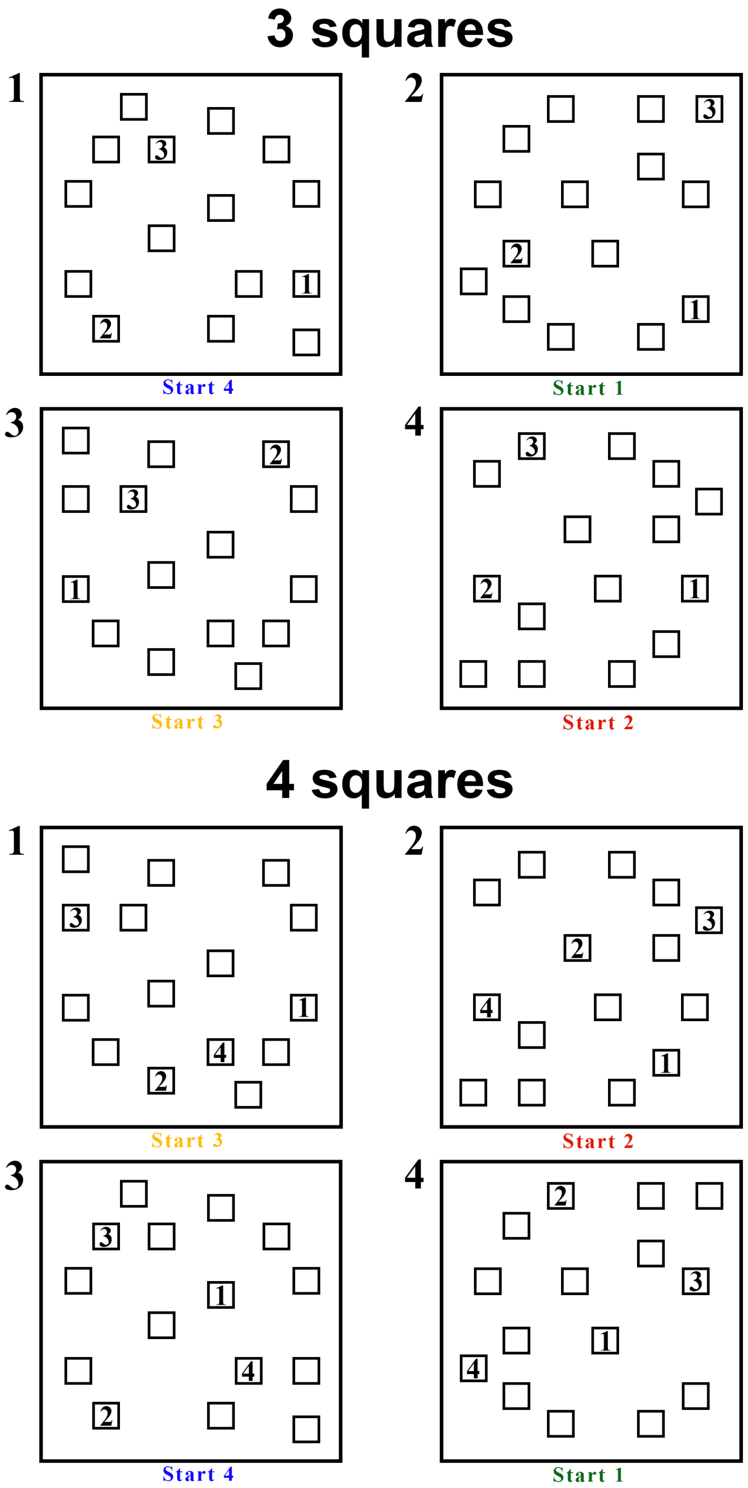


Figure C.4.: Corsi sequences of Set 2 of sequence length three and four. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

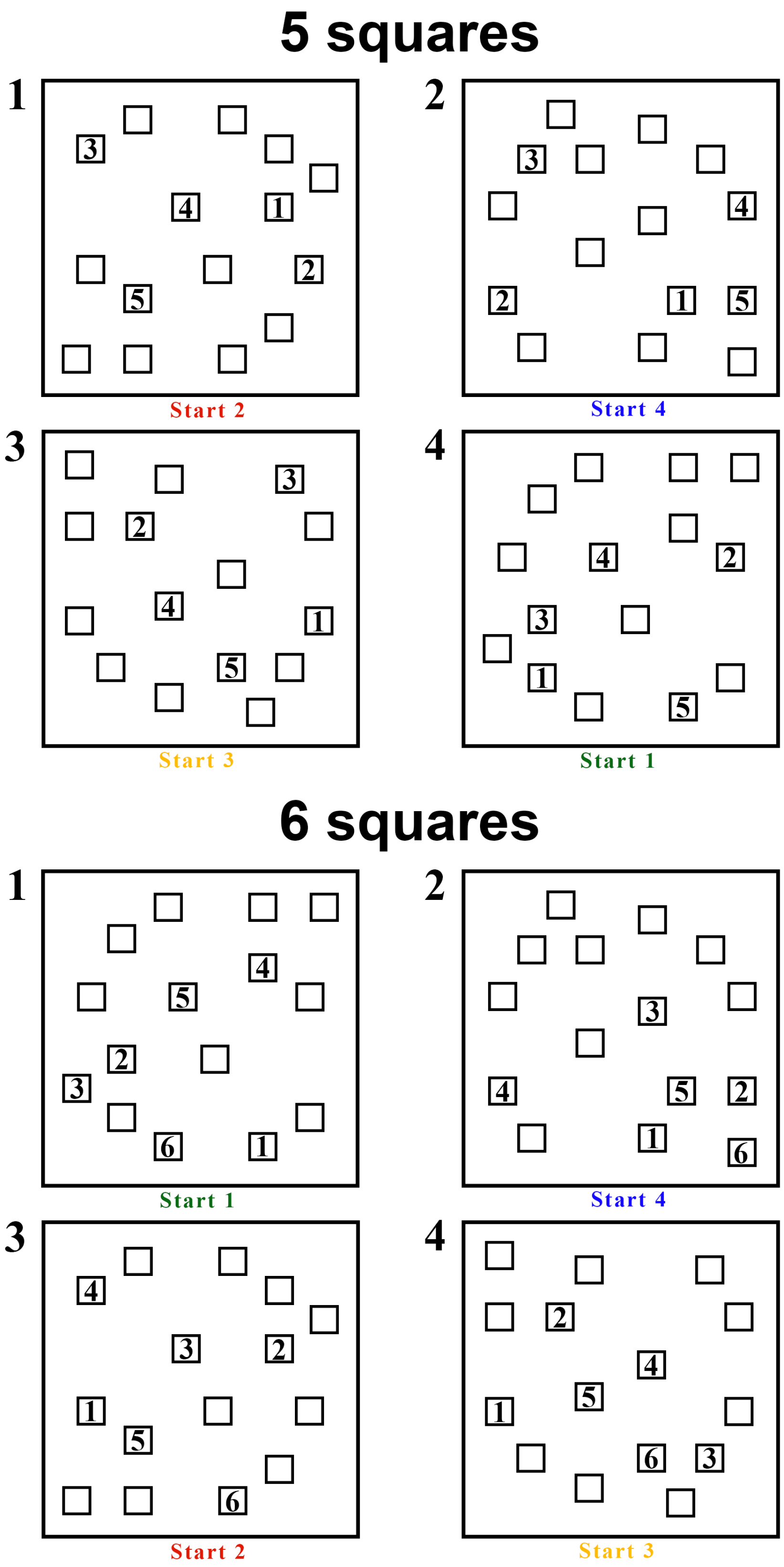


Figure C.5.: Corsi sequences of Set 2 of sequence length five and six. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

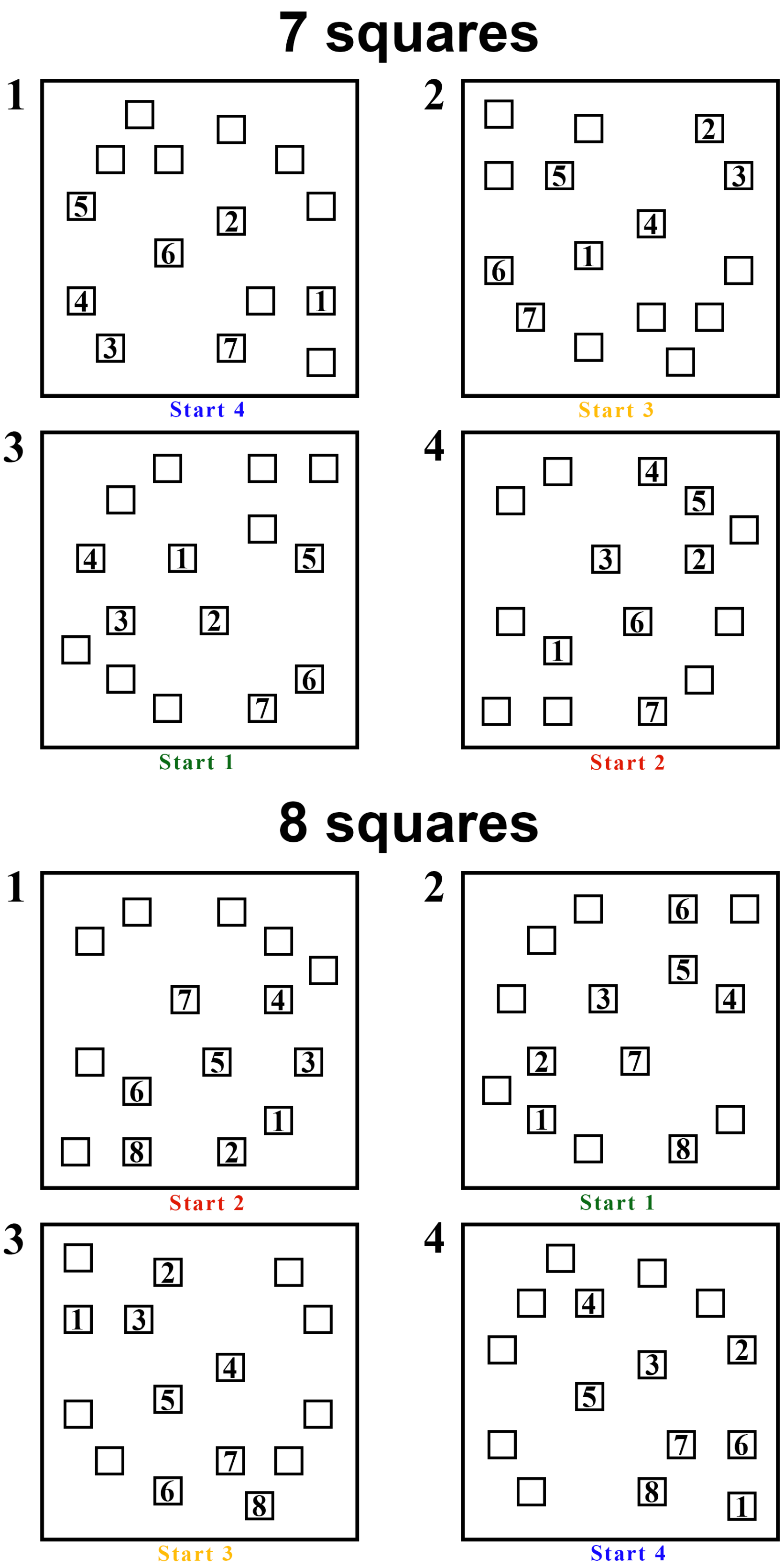


Figure C.6.: Corsi sequences of Set 2 of sequence length seven and eight. The numbers in the squares mark the square positions in the sequence. The numbers 1 to 4 outside the frames indicate the trials 1 to 4 of each sequence length.

C.3. Comparison between males and females

C.3.1. Screen-Screen

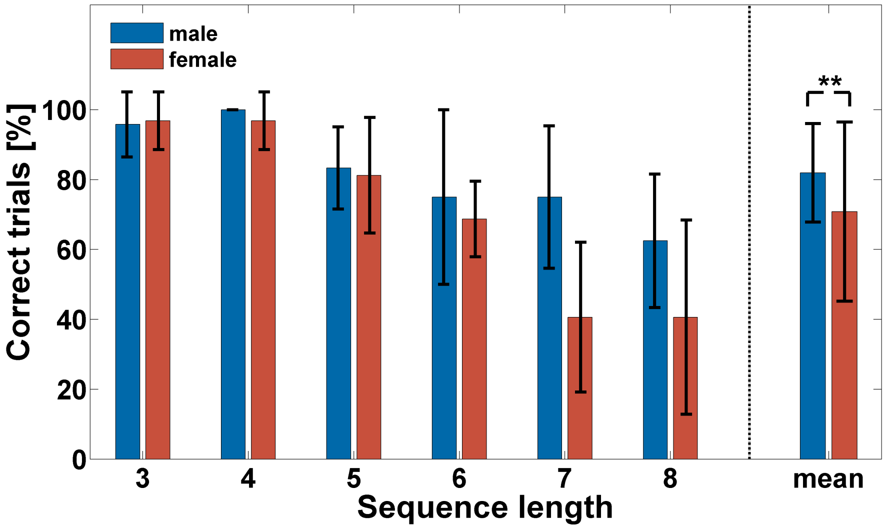


Figure C.7.: Comparison of gender differences in percentage of correct trials. The mean percentage of correct trials (y-axis) is shown for all sequence lengths (x-axis). For both groups the performance decreased with increasing sequence length. The six males (blue bars) performed better than the eight females (red bars), which is shown with stars above the overall mean on the right ($F(1, 72) = 7.666$, $p < 0.01$, $\eta_P^2 = 0.096$). Error bars indicate the standard deviation.

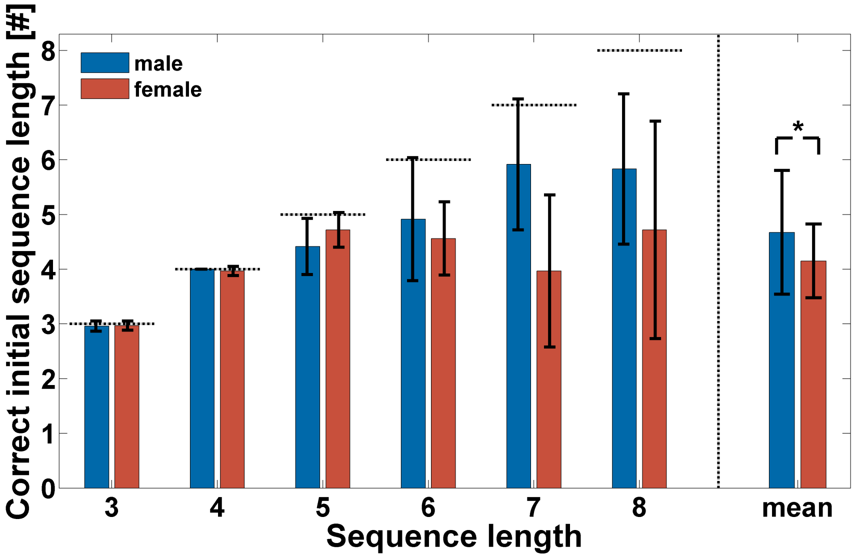


Figure C.8.: Comparison of gender differences in correct initial sequence length. For both groups (males: six participants, blue bars; females: eight participants, red bars) the mean length of the correct initial sequence (y-axis) increased with increasing sequence length (x-axis), though, for females the correct initial sequence length remained similar in the higher sequence lengths. On the right the mean over all participants and sequence lengths is depicted. Males had a longer correct initial sequence length than females ($F(1, 72) = 5.017$, $p < 0.05$, $\eta_P^2 = 0.065$; depicted with a star above the mean). Error bars indicate the standard deviation.

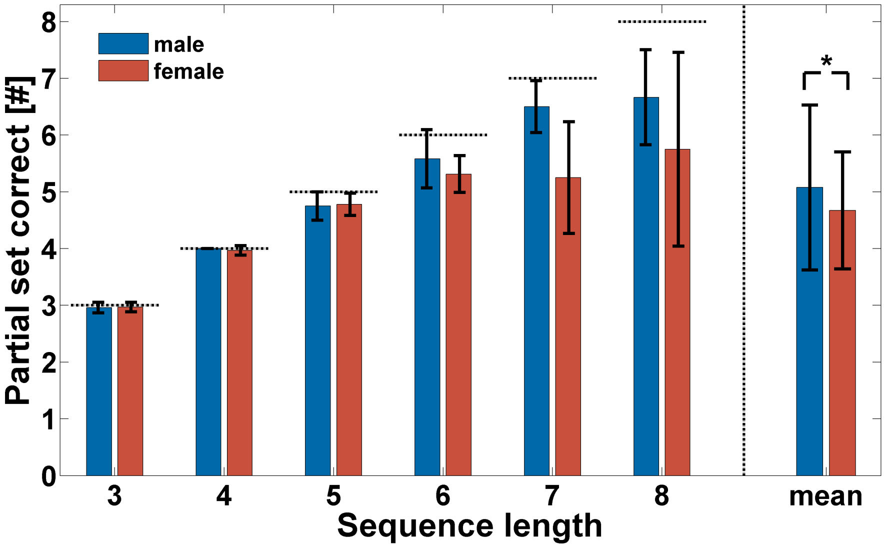


Figure C.9.: Comparison of gender differences in partial set correct. The six males (blue bars) had a higher number in partial set correct remembered square tiles (y-axis) than the eight females (red bars) in all sequence lengths (x-axis), though in both groups the number increased with increasing sequence length. The difference (F(1, 72) = 6.082, $p < 0.05$, $\eta_P^2 = 0.078$) is depicted with a star above the mean on the right. Error bars indicate the standard deviation.

C.3.2. Floor-Floor

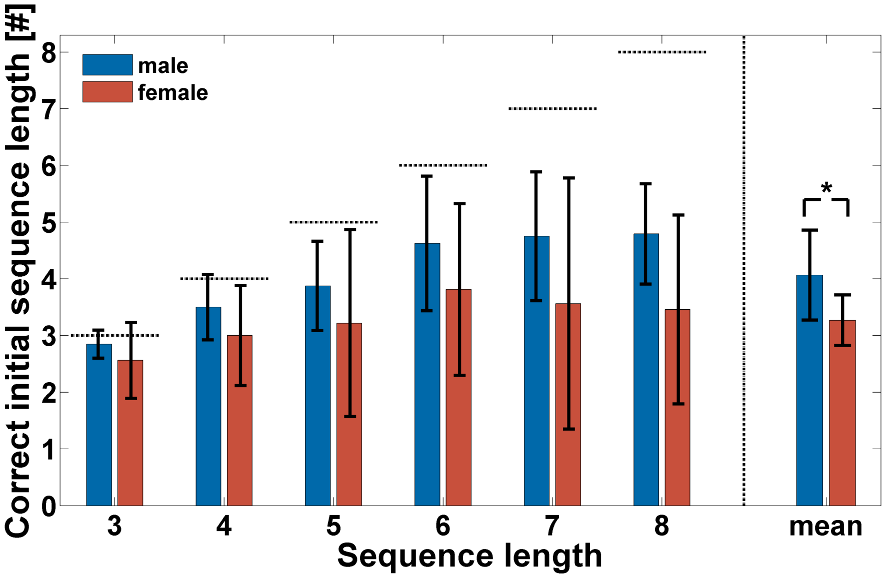


Figure C.10.: Comparison of gender differences in correct initial sequence length. The mean length of the correct initial sequence (y-axis) is depicted for six males (blue bars) and eight females (red bars) for the six sequence lengths (x-axis). The initial sequence length of the male group was longer than the one of the female group (F(1, 72) = 6.775, $p < 0.05$, $\eta_P^2 = 0.086$). This is depicted with a star above the mean. Error bars indicate the standard deviation.

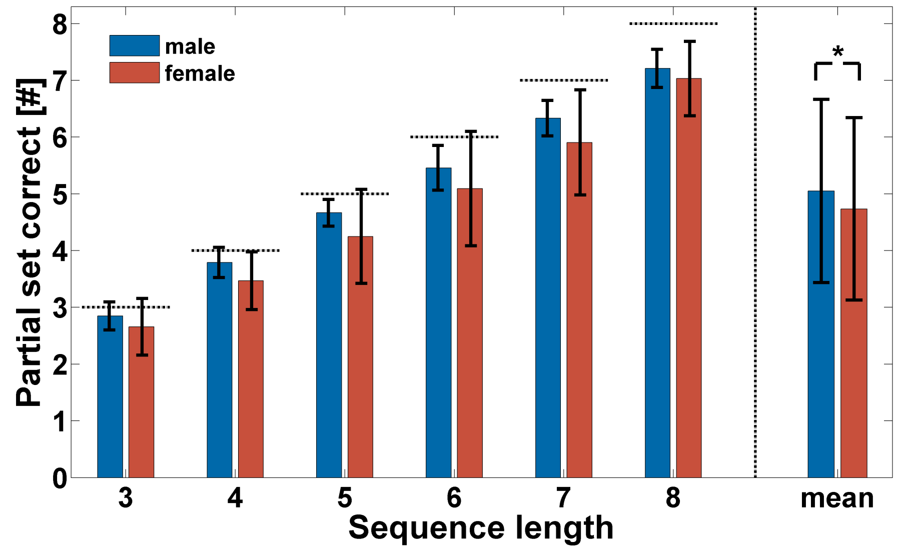


Figure C.11.: Comparison of gender differences in partial set correct. For six males (blue bars) and eight females (red bars) the mean number of partial set correct remembered squares (y-axis) is depicted for all sequence lengths (x-axis). With increasing sequence length the number of partial set correct square tiles increased. Males had a higher number than females (F(1, 72) = 4.745, $p < 0.05$, $\eta_P^2 = 0.062$), this is shown with a star above the over all mean on the right. Error bars indicate the standard deviation.

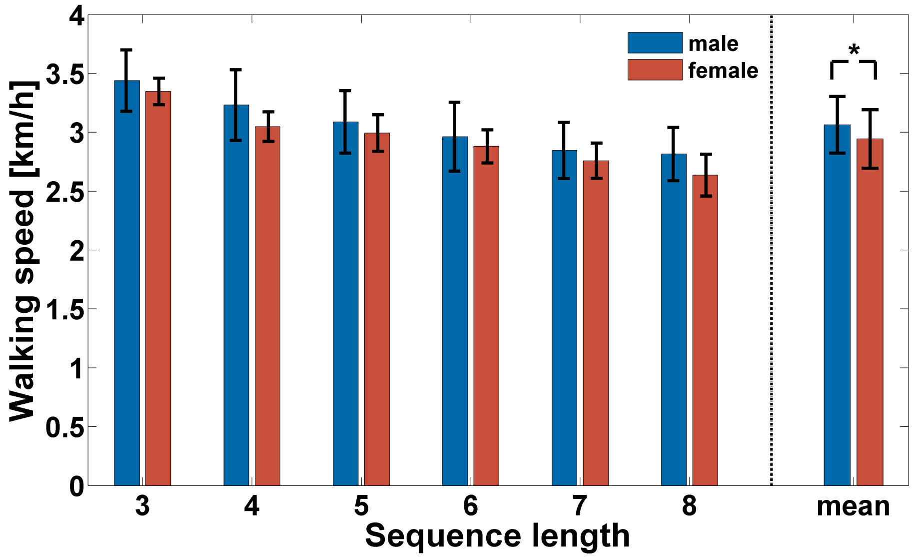


Figure C.12.: Comparison of gender differences in walking speed. The mean walking speed (y-axis) is depicted for the six sequence lengths (x-axis) for males (blue bars) and females (red bars). With increasing sequence length a decrease of walking speed was found. Males had a higher walking speed than females (F(1, 72) = 6.012, $p < 0.05$, $\eta_P^2 = 0.077$; depicted with a star above the mean on the right). Error bars indicate the standard deviation.

C.3.3. Screen-Floor

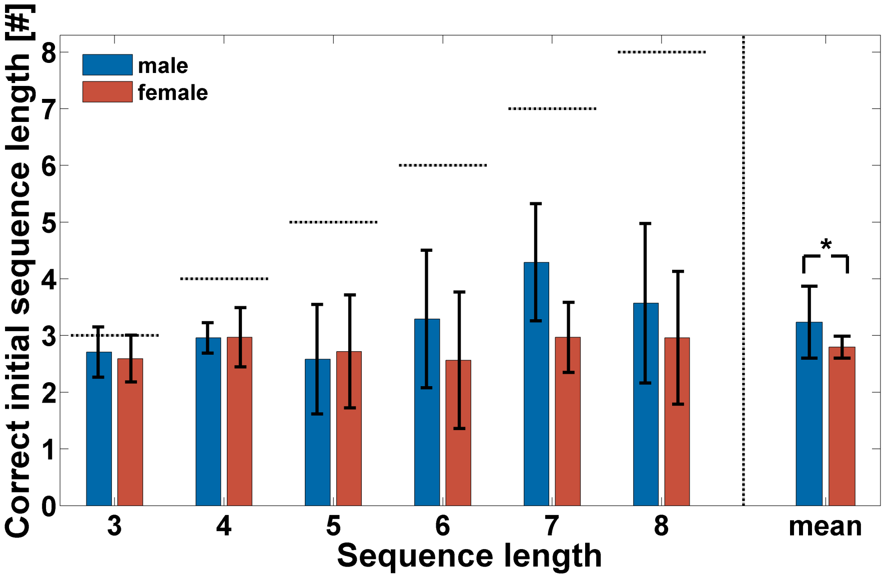


Figure C.13.: Comparison of gender differences in correct initial sequence length. The mean length of the correct initial sequence (y-axis) is depicted for all sequence lengths (x-axis). Males (blue bars) had a longer initial sequence length than females (red bars). This difference is depicted with a star above the mean on the right ($F(1, 72) = 3.991$, $p < 0.05$, $\eta_P^2 = 0.053$). Error bars indicate the standard deviation.

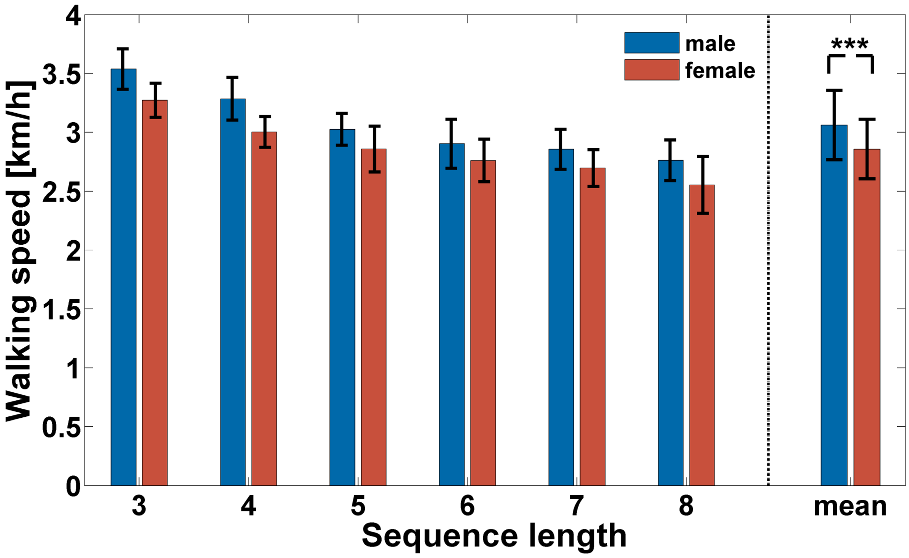


Figure C.14.: Comparison of gender differences in walking speed. For six sequence lengths (x-axis) the mean walking speed (y-axis) for males (blue bars) and females (red bars) is shown, it decreased with increasing sequence length. The walking speed of the males was significantly faster than the females' one ($F(1, 72) = 23.537$, $p < 0.001$, $\eta_P^2 = 0.246$). This is illustrated with stars above the mean on the right. Error bars indicate the standard deviation.

C.4. Correct versus false trials

Floor-Floor

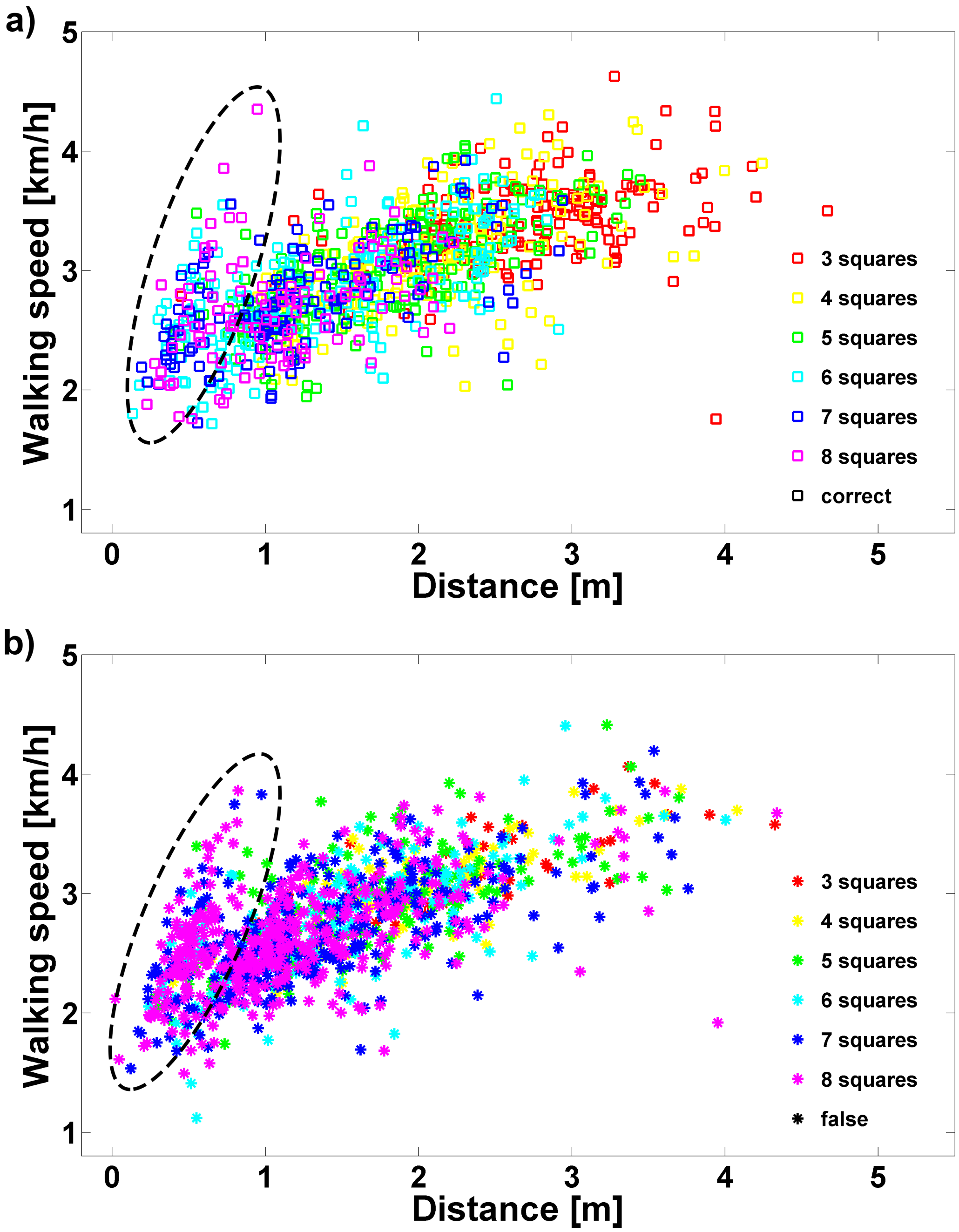


Figure C.15.: Correlations between the mean walking speed and the distance between two square tiles for Floor-Floor are shown. The correct trials (marked with squares) are depicted in a) and the false trials (marked with stars) in b). For each trial and participant the mean walking speed (y-axis) between two square tiles is plotted in both figures against the walked distance (x-axis) between these squares. With increasing distance the walking speed increased in the correct as well as in the false trials. The dotted ellipses mark the “second arms”. The different colors specify the six sequence lengths.

Screen-Floor

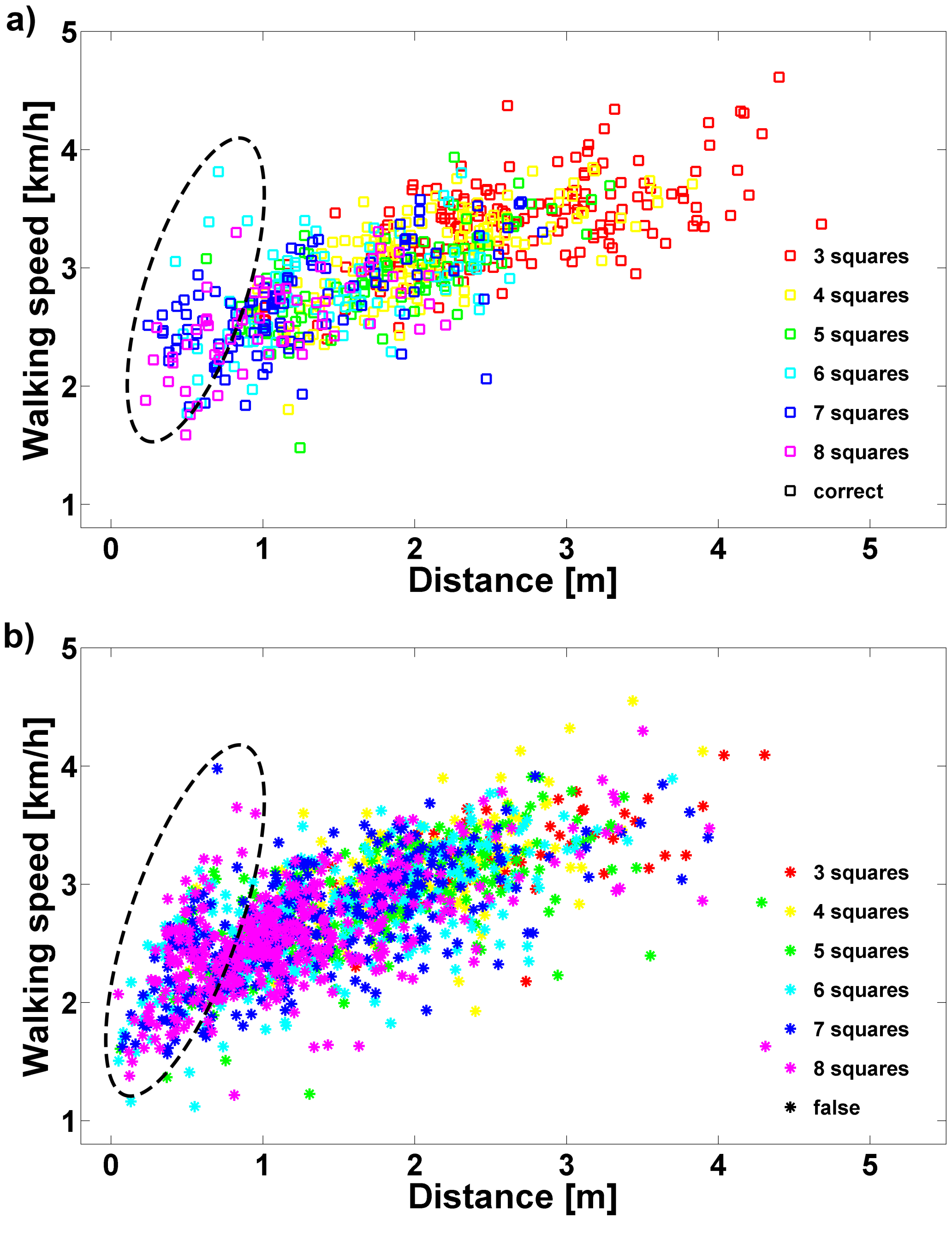


Figure C.16.: Correlations between the mean walking speed and the distance between two square tiles for Screen-Floor are shown. a) The correct trials are depicted. b) The false trials are shown. For each trial and participant the mean walking speed (y-axis) between two square tiles is plotted in both figures against the walked distance (x-axis) between these squares. The walking speed increased with increasing distance. The dotted ellipses mark the "second arms". Correct trials are depicted with squares (a), false trials with stars (b) and the different sequence lengths with different colors.

Contributions

All experimental designs and results of this doctoral thesis were designed together and discussed with PD Dr. Gregor Hardieß and Prof. Dr. Hanspeter A. Mallot.

In the experiments 1 to 4 all data collections, analyses, figures and written parts of these experiments were done by myself.

Experiment 5 is based on the publication “Modality dependence and intermodal transfer in the Corsi Spatial Sequence Task: Screen vs. Floor”, Experimental Brain Research 234(7):1784-1862 (link.springer.com/article/10.1007%2Fs00221-016-4582-z) and was extended by further results.
The publication was written by myself together with PD Dr. Gregor Hardieß and Prof. Dr. Hanspeter A. Mallot. Text and figures of this publication were used in the chapters Introduction (e.g. the subchapters Working memory, Spatial behavior, Corsi block tapping task and Scientific issue), General material and methods, Experiment 2: “Walking Corsi task” (subchapter Analysis), Experiment 5: “Corsi task in different modality conditions” and General discussion.
The idea for this experiment was developed by myself together with PD Dr. Gregor Hardieß and Prof. Dr. Hanspeter A. Mallot.
The data of Experiment 5 was collected by Dörte Kuhrt who used the data also for her bachelor thesis. The programs for data collection were written by myself and also all analyses were done by myself. No parts of the bachelor thesis have been used for this doctoral thesis, only the same raw data is underlying both theses.
In the publication most parts were written by myself with modifications and additions by PD Dr. Gregor Hardieß and Prof. Dr. Hanspeter A. Mallot.
Figures used in the publication as well as the analyses were done by myself with suggestions by PD Dr. Gregor Hardieß and Prof. Dr. Hanspeter A. Mallot.
The mathematical model presented in the publication and Experiment 5 (p. 140) was developed by Prof. Dr. Hanspeter A. Mallot.