Spatial Working Memory of Out-of-Sight Places: Representational Perspective and Continuity

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Abstract

Spatial cognition enables humans to remember, imagine, and navigate their environments by integrating sensory input, spatial representations, and memory. A key feature of spatial memory is its dependency on viewpoint and position: mental representations of space are not static but are dynamically reconstructed depending on the observer's location, orientation, and imagined perspective. This thesis investigates the phenomenon of *position-dependent recall* — the idea that spatial recall varies systematically with the observer's physical or simulated position and heading — across two complementary experimental paradigms.

In the first study, participants engaged in a novel *immersive sketching* task in virtual reality (VR). While immersed in a VR simulation of familiar urban locations, they were asked to draw sketch maps of spatially remote but well-known places. The study examined how body orientation and simulated viewpoint influenced recall orientation, and whether position-dependent effects persisted after participants exited the virtual environment.

In the second study, participants performed a *free recall* task while situated at specific virtual starting positions and orientations. Without drawing or external spatial aids, they verbally listed familiar locations from memory. This experiment tested whether recall was influenced by the simulated viewpoint and whether retrieval sequences exhibited systematic spatial progression, reflecting dynamic organization of spatial memory based on proximity, familiarity, and imagined perspective.

Together, these experiments provide evidence that spatial recall is shaped by both egocentric (viewpoint-based) and allocentric (map-based) reference frames, and that immersive VR constitutes a valid methodological tool for investigating these processes. By combining controlled virtual environments with natural recall behavior, this thesis advances our understanding of how spatial memories are organized, accessed, and influenced by bodily orientation and imagined perspective.

Zusammenfassung

Räumliche Kognition ermöglicht es Menschen, sich an ihre Umgebungen zu erinnern, sie sich vorzustellen und sich in ihnen zu orientieren, indem sensorische Informationen, räumliche Repräsentationen und Gedächtnisprozesse integriert werden. Ein zentrales Merkmal des räumlichen Gedächtnisses ist seine Abhängigkeit von Startpunkt und Blickrichtung: Mentale Repräsentationen des Raumes sind nicht statisch, sondern werden dynamisch rekonstruiert, abhängig vom Ort, der Orientierung und der vorgestellten Perspektive der beobachtenden Person. Diese Dissertation untersucht das Phänomen des positionsabhängigen Abrufs — die Annahme, dass räumlicher Abruf systematisch mit der physischen oder simulierten Position und Blickrichtung der beobachtenden Person variiert — anhand zweier komplementärer experimenteller Paradigmen.

In der ersten Studie bearbeiteten die Teilnehmenden eine neuartige immersive Skizzieraufgabe in virtueller Realität (VR). Während sie in eine VR-Simulation vertrauter urbaner Orte eingebettet waren, wurden sie gebeten, Skizzenkarten räumlich entfernter, jedoch wohlbekannter Orte zu zeichnen. Die Studie untersuchte, wie Körperorientierung und simulierter Standpunkt die Abruforientierung beeinflussen und ob positionsabhängige Effekte auch nach dem Verlassen der virtuellen Umgebung bestehen bleiben.

In der zweiten Studie führten die Teilnehmenden eine freie Abrufaufgabe durch, während sie sich an spezifischen virtuellen Startpositionen mit vorgegebenen Startorientierungen befanden. Ohne zu zeichnen oder externe räumliche Hilfsmittel zu benutzen, nannten sie vertraute Orte aus dem Gedächtnis. Dieses Experiment prüfte, ob der Abruf durch den simulierten Standpunkt beeinflusst wurde und ob Abruffolgen eine systematische räumliche Progression aufwiesen, die eine dynamische Organisation räumlicher Gedächtnisinhalte auf der Grundlage von Nähe, Vertrautheit und vorgestellter Perspektive widerspiegelt.

Zusammen liefern diese Experimente Evidenz dafür, dass räumlicher Abruf sowohl durch egozentrische (standpunktbasierte) als auch durch allozentrische (weltzentrierte) Referenzrahmen geprägt ist und dass immersive VR ein valides methodisches Instrument zur Untersuchung dieser Prozesse darstellt. Durch die Kombination kontrollierter virtueller Umgebungen mit natürlichem Abrufver-

halten erweitert diese Dissertation unser Verständnis darüber, wie räumliche Gedächtnisinhalte organisiert, abgerufen und durch Körperorientierung sowie vorgestellte Perspektive beeinflusst werden.

Contents

Chapter 1

General Introduction[1]

The ability to mentally visualize distant places is a key aspect of human spatial cognition. This process relies on retrieving spatial information from long-term memory and temporarily storing it in a working memory system. This type of working memory, often referred to as "representational memory", enables individuals to construct mental images of specific locations by dynamically integrating spatial knowledge accumulated over time Bisiach and Luzzatti (1978); Guariglia, Palermo, Piccardi, Iaria, and Incoccia (2013).

While the spatial information in long-term memory remains stable, the imagined representation of a place is flexible and dynamic. It is influenced by several factors, including an individual's imagined direction of movement (heading), viewpoint location, and current physical position and body orientation at the time of recall Klatzky (1998); Shelton and McNamara (2001).

This dynamic relationship between mental representations and viewing direction has been vividly demonstrated in studies of representational neglect. Although representational neglect is a neurological condition, its hallmark finding—that recall of a familiar environment depends on the imagined viewpoint—reveals a general principle of spatial imagery rather than a deficit-specific phenomenon. In their seminal study, Bisiach and Luzzatti (1978) showed that patients with representational neglect could recall only the right side of a familiar city square when imag-

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[1] This section is based on the following publication: Grochulla, B., & Mallot, H. A. (2024). Perceived spatial presence and body orientation affect the recall of out-of-sight places in an immersive sketching experiment. *Psychological Research 88:509–522*, 2024

ining themselves facing in one direction, but recalled complementary details when imagining the opposite viewpoint. Crucially, what counted as “left” or “right” was defined entirely by the imagined viewing direction.

Importantly, the core mechanism revealed by representational neglect—the viewpoint-dependent activation of spatial memory—does not depend on pathology. Rather, neglect provides an exaggerated illustration of processes that are also present in normal cognition. The findings demonstrate that representational memory is selectively accessed from a perspective-dependent working memory stage, in which some spatial information is activated while other information remains temporarily inaccessible.

When asked to mentally shift their position to the opposite end of the square and look in the other direction, they were now able to recall details of the previously neglected side, while the other side became inaccessible. This remarkable shift underscores how imagined viewpoints influence the retrieval of spatial information.

Building on these findings, Guariglia et al. (2013) further investigated how representational neglect manifests in complex environments and how spatial scale affects recall. Their study examined whether neglect differentially impacts topological (large-scale environmental) and non-topological (object-based) representations, revealing that patients with right hemisphere damage exhibited selective impairments depending on the type of spatial representation. These findings reinforced the idea that imagined perspectives play a crucial role in representational memory, shaping what individuals can recall based on their mentally assumed viewpoint and the structural properties of the imagined space.

These studies highlight that spatial recall is inherently viewpoint-dependent, as the mental reconstruction of an environment is strongly influenced by the observer’s imagined perspective. This perspective plays a crucial role in determining which spatial features are activated and prioritized in working memory. This viewpoint dependency aligns with broader theories of spatial representation, which describe the interplay between egocentric (body-centered) and allocentric (environment-centered) frames of reference Klatzky (1998).

Evidence for such selective, viewpoint-dependent access to spatial memory is not limited to neurological patients. A broad range of behavioral studies with healthy participants has demonstrated comparable, though less extreme, perspective-dependent effects. Tasks such as the judgment of relative direction (JRD), sketch mapping, and building tasks show systematic biases depending on imagined heading, recall position, and body orientation. These findings suggest that the mechanisms revealed by representational neglect reflect general properties of representational working memory rather than clinical anomalies.

Egocentric representations encode spatial information relative to the observer's current position and orientation, continuously updating with movement. In contrast, allocentric representations store spatial relationships independently of the observer's viewpoint, maintaining a fixed structure regardless of changes in perspective. This flexibility in perspective-taking highlights the dynamic nature of spatial imagery, where mental constructs continuously adapt based on task demands, environmental cues, and the observer's imagined orientation.

Representational space, the mental framework we use to imagine and navigate environments, can be understood through two complementary models. The first is the local chart model, which represents the imagined environment as a spatial map centered on the observer. In this model, the observer remains stationary at the center of the imagined space, while objects, landmarks, and scene elements are positioned in their egocentric positions – that is, relative to the observer's perspective Bicanski and Burgess (2020).

Bicanski and Burgess (2020) developed a computational model describing how spatial representations are formed in the hippocampal-entorhinal system, supporting the idea that egocentric spatial processing relies on neurons encoding an object's position relative to the observer. For such neurons, they introduced the term "vector-cells".

This model is based on vector-based coding, where each object is mentally represented at a specific distance and direction from the observer. As a result, spatial relationships are dynamically structured around the observer's orientation and physical position at the time of recall. This framework aligns with egocentric spatial processing theories, which suggest that spatial relationships are encoded and retrieved based on the observer's orientation and position at the time of recall.

Alternatively, representational space can be understood through the view-graph model, which organizes the environment as a network of stored visual viewpoints or "snapshots" Mallot (2024); Mallot, Ecke, and Baumann (2020); Röhrich, Hardiess, and Mallot (2014); Schölkopf and Mallot (1995). This model was initially introduced by Schölkopf and Mallot (1995) as a framework for view-based navigation and has since been expanded upon in studies of spatial memory and recall Röhrich et al. (2014). More recent work by Mallot (2024); Mallot et al. (2020) further refines this approach, emphasizing how stored visual viewpoints contribute to spatial orientation and wayfinding.

In this model, each viewpoint corresponds to a specific vantage point in the environment, while the connections between these viewpoints define the egocentric movements — such as rotations or translations — needed to transition from one view to another. Rather than encoding a complete spatial map, the model focuses on sequences of familiar views, emphasizing how individuals mentally navigate between stored perspectives.

This approach suggests that navigation and spatial recall depend on retrieving familiar visual perspectives and understanding how to transition between them, rather than constructing a precise metric map of the environment. Instead of storing an environment as a single, unified spatial representation, the view-graph model prioritizes viewpoint-based memory, allowing for efficient recall of spatial relationships based on prior experience and familiar transitions.

While both models provide largely similar predictions regarding spatial memory and recall, the view-graph model offers distinct advantages for certain tasks. For example, it naturally supports the generation of pictorial imaginations, where mental images of the environment are reconstructed based on familiar viewpoints. Additionally, the view-graph model can accommodate anisotropies in representational space, meaning that certain views may be more salient, accessible, or frequently recalled depending on task demands, environmental distinctiveness, or prior experience (Röhrich et al. (2014)). These anisotropies reflect an uneven distribution of spatial representations, where some directions or views are prioritized over others due to their relevance or visual clarity.

Together, these frameworks provide complementary perspectives on how humans mentally organize and recall spatial information. While the local chart model emphasizes an egocentric, observer-centered approach, the view-graph model highlights the role of stored viewpoints and transitions in spatial navigation. Crucially, both the local chart and the view-graph model make specific predictions for unconstrained recall. If representational working memory is loaded with a particular imagined viewpoint, recall should proceed in a spatially coherent manner rather than as an arbitrary list of locations. In particular, when one remembered location is activated, subsequent recall is expected to follow spatial relations that are locally consistent with that imagined perspective. This predicts that recall may progress stepwise through nearby or directly connected locations, effectively treating each recalled place as the reference point for the next.

In behavioral studies involving normal participants, the structure of spatial imagery and representational space has been extensively investigated through various experimental paradigms. One of the most widely used methods is the judgment of relative direction (JRD) task, which examines how individuals mentally reconstruct spatial relationships from memory Shelton and McNamara (2001). In a typical JRD task, participants are asked to imagine themselves at a specific location within a familiar environment, facing a particular reference point, and then determine the direction of another object relative to that imagined perspective.

Performance in JRD tasks provides critical insights into the interplay between egocentric and allocentric spatial representations. Egocentric representations encode spatial relationships relative to the observer's body position and orientation, whereas allocentric representations store spatial information independently of the observer's viewpoint. Research has shown that systematic biases emerge in JRD performance, based on the alignment between the imagined viewpoint and the intrinsic spatial frames of reference within the environment Montello (1991); Mou and McNamara (2002).

Shelton and McNamara (2001) demonstrated that JRD performance is influenced by the presence of intrinsic environmental axes, such as the dominant orientation of a room or a well-defined landmark structure. Mou and McNamara (2002) further expanded on these findings, showing that participants exhibit superior accuracy in JRD tasks when their imagined perspective aligns with one of these intrinsic axes. Similarly, Montello (1991) explored how larger-scale spatial structures, such as urban street networks and building layouts, impose intrinsic frames of reference that shape spatial recall. These studies collectively suggest that spatial memory is not only influenced by an individual's imagined perspective but is also constrained by structural elements within the environment.

Beyond JRD, position-dependent recall has been extensively examined through tasks such as the production of sketch maps and three-dimensional neighborhood models, where participants reconstruct spatial layouts from memory Röhrich et al. (2014). These methods provide valuable insights into how spatial representations are retrieved and structured, revealing that recall is not static but instead dynamically shifts based on the individual's physical or imagined viewpoint at the time of retrieval.

Findings from these studies reinforce the idea that spatial memory is shaped by both long-term cognitive maps and momentary egocentric perspectives Basten, Meilinger, and Mallot (2012); Meilinger, Frankenstein, Simon, Bülthoff, and Bresciani (2016). Röhrich et al. (2014) demonstrated that participants' recall orientations in sketch map tasks are systematically influenced by their position at the time of retrieval, aligning with the dominant airline direction or intrinsic axes of the environment. Similarly, Basten et al. (2012) found that priming effects from imagined travel influence the way individuals reconstruct distant locations, suggesting that mental travel and spatial updating play a role in recall orientation. Further supporting this, Meilinger et al. (2016) showed that both position and body orientation significantly affect how participants reconstruct spatial configurations, underscoring the interaction between egocentric and allocentric frames of reference in spatial memory retrieval.

Judgment of Relative Direction (JRD)

The judgment of relative direction (JRD) task is a widely used paradigm for investigating how individuals mentally reconstruct spatial relationships from memory. In this task, participants are instructed to imagine themselves at a specific location within a familiar environment, facing a particular reference object, and then determine the relative direction of another remembered object from that imagined perspective Shelton and McNamara (2001).

Recall accuracy in JRD tasks is highly dependent on the alignment between the imagined heading direction and intrinsic spatial reference frames. Performance is generally highest when the imagined viewpoint aligns with the dominant intrinsic axis of the environment, such as the long axis of a room or a well-defined structural feature Mou and McNamara (2002).

Intrinsic reference axes naturally emerge from the spatial layout of an environment. For instance, Mou and McNamara (2002) found that when participants were presented with a regular grid of objects, their JRD performance was superior when mentally orienting themselves along one of the two primary grid axes, reinforcing the idea that spatial memory organizes information relative to dominant structural cues. On a larger scale, Montello (1991) and Werner and Schmidt (1999) demonstrated that urban street networks and architectural layouts establish intrinsic reference frames, which influence how spatial relationships are encoded and retrieved.

In complex environments such as university campuses or multi-level buildings, multiple reference axes may coexist. This means that spatial recall depends not only on local structural elements but also on the hierarchical organization of representational space Wang and Brockmole (2003). The interaction between these multiple reference frames highlights the dynamic nature of spatial memory retrieval.

These findings emphasize the interplay between egocentric and allocentric representations in spatial cognition. Spatial recall is shaped by both the individual's imagined viewpoint and the underlying structure of the environment. The JRD paradigm provides critical insights into how spatial information is dynamically retrieved and restructured, further informing research on position-dependent recall, spatial navigation, and cognitive mapping in both real-world and virtual environments.

Sensorimotor Alignment in Judgment of Relative Direction (JRD)

Performance in the judgment of relative direction (JRD) task is not solely determined by cognitive spatial representations; it is also influenced by the subject's actual body orientation during recall. Studies have shown that spatial judgments are more accurate when the participant's physical body posture aligns with their imagined viewpoint, a phenomenon known as the sensorimotor alignment effect Kelly, Avraamides, and Loomis (2007); May (2004); Riecke and McNamara (2017). This effect suggests that even when engaging in mental imagery, individuals continue to track their real-world bodily position, leveraging sensorimotor cues to enhance spatial recall. The persistence of this effect highlights the role of path integration and spatial updating mechanisms, which allow the brain to dynamically represent self-location relative to the environment.

Research by May (2004) demonstrated that participants performing JRD tasks exhibit systematic improvements in accuracy when their real-world bodily orientation matches their imagined viewpoint, reinforcing the idea that sensorimotor congruence enhances spatial recall. Kelly et al. (2007) extended these findings by investigating how this alignment effect is modulated by movement-related cues, revealing that sensorimotor feedback, such as physical rotation before recall, can further strengthen spatial memory. Similarly, Riecke and McNamara (2017) explored how vestibular and proprioceptive cues contribute to spatial orientation, demonstrating that even subtle bodily misalignments can impair performance in spatial judgment tasks.

Interestingly, sensorimotor alignment effects persist even in virtual environments, where both the actual and imagined body poses are defined within a simulated space. Marchette, Vass, Ryan, and Epstein (2014) demonstrated that participants engaged in JRD tasks within virtual reality (VR) still exhibited superior recall when their virtual body orientation matched their mental perspective. This finding supports the idea that representational space is constructed from both intrinsic spatial cues (e.g., an environment's structural axes) and extrinsic directional tracking (e.g., alignment between imagined and actual bodily posture) Julian, Keinath, Marchette, and Epstein (2018); Meilinger and Vosgerau (2010).

In essence, spatial recall is not purely a cognitive process but an embodied experience, integrating sensory feedback, physical orientation, and imagined viewpoints. These insights have significant implications for navigation, spatial cognition, and VR-based research. Understanding how sensorimotor alignment interacts with mental spatial representations can inform the development of more effective spatial learning tools, improve wayfinding strategies, and enhance virtual training environments by optimizing the alignment of perceived and actual body orientation.

Sketch Maps and Building Tasks

Representational memory is structured along preferred reference axes, even when such axes are not explicitly defined by task instructions. Basten et al. (2012) demonstrated that imagined travel influences the orientation of spatial recall, shaping how distant places are mentally represented. In their study, participants situated on a university campus were asked to imagine walking between two familiar city squares, crossing a target square in one of two possible directions. When later instructed to produce a sketch map of the target square, their recall orientation was systematically aligned with the perspective of their previously imagined travel. These findings suggest that performing an imagined walk activates representational memory, either through automated spatial updating, mental travel mechanisms, or both.

In the study by Basten et al. (2012), priming effects in recall orientation were attributed to the activation of visual imagery during imagined travel, which may stem from visual memory representations. Alternatively, this effect could result from spatial updating, a process in which memories of nearby locations are automatically activated as an observer mentally approaches a target. To further investigate position-dependent recall, Röhrich et al. (2014) conducted an experiment in which passers-by in a city center were asked to produce sketch maps of nearby city squares that were not visible from their interview location.

Analysis of these sketch maps revealed a systematic variation in orientation based on the recall position. When participants recalled nearby squares (within walking distance), their sketch maps were predominantly aligned with the airline direction – as if they were able to see through intervening buildings. However, for more distant locations (approximately 2 km away), sketch maps were more homogeneous and conformed to a standard or "canonical" view of the target, independent of the interview location. The term "canonical" is used here in analogy to canonical views in object recognition Bülthoff, Edelman, and Tarr (1995), where certain perspectives are more naturally recalled due to cognitive familiarity and perceptual stability. Thus, the mental representation of a distant target square is influenced by two primary factors: (1) the airline direction, which reflects how the square would appear if visible through obstacles, and (2) an intrinsic axis of the target itself, which determines its canonical view.

In addition to these spatial dependencies, bodily orientation may also influence recall orientation. This was demonstrated by Meilinger et al. (2016), who used a building task instead of freely sketched maps to investigate spatial recall. In their study, participants were provided with a set of cards labeled with well-known locations and were asked to reconstruct the spatial configuration of these landmarks. The results confirmed the position dependence of recall orientation and further revealed a significant effect of body orientation, suggesting that participants' reconstructed layouts were influenced by their own bodily alignment during the task. However, it is important to note that Meilinger et al. (2016) focused on larger-scale landmark configurations rather than specific views of individual city squares.

Building tasks have also been adapted to virtual environments, allowing for controlled manipulation of spatial factors. Le Vinh, Meert, and Mallot (2020) extended these findings by investigating the reconstruction of a specific target square in a VR-based building task. Their study confirmed the overall effect of airline direction on recall orientation, supporting previous evidence that spatial memory is structured around egocentric navigation cues. However, unlike Meilinger et al. (2016), body orientation was not explicitly addressed in this virtual setup, leaving open questions about the interaction between physical posture, virtual immersion, and position-dependent recall.

Large-Scale Representational Memory

Unlike object configurations within a room, which can be perceived at a single glance, large-scale environments, such as a downtown area, must be explored sequentially through step-by-step navigation. This distinction has been conceptualized by Montello (1993) as the difference between vista space – small-scale environments that can be seen in their entirety – and navigational space – large-scale environments that require movement to fully comprehend. The cognitive representation of navigational spaces involves more complex spatial structuring, where multiple viewpoints and transitions must be integrated into memory.

To describe how large-scale spatial representations are organized, Meilinger (2008) proposed a network of local reference frames or spatial charts, each possessing its own intrinsic axis. In a simple JRD task, only one such local chart is activated, meaning that imagery and recall will primarily rely on the intrinsic axis of that specific reference frame, along with the observer's body orientation. However, in position-dependent recall, the actual environment and the imagined environment often belong to different local charts, each structured by its own intrinsic axis. As a result, the relative positioning of these charts introduces an additional factor affecting spatial recall.

Research on large-scale spatial memory suggests that relative positioning between local reference frames significantly influences recall accuracy and perspective alignment. In the studies discussed above, this relative positioning has been described through airline direction and distance to the target, both of which shape how spatial memory is reconstructed. Meilinger (2008) demonstrated that overlapping reference frames may create conflicts in recall, particularly when the transition between charts involves a shift in imagined heading direction. Furthermore, Montello (1993) emphasized that navigational spaces require a greater degree of spatial updating than vista spaces, as movement across a large environment involves continuous re-referencing of spatial landmarks.

The present study extends this framework by investigating the role of body orientation in position-dependent recall, examining how physical posture and viewpoint alignment interact with intrinsic spatial axes during recall processes. This approach aims to clarify how individuals mentally reconstruct large-scale environments and how bodily alignment influences the activation of local reference frames in recall tasks.

VR Methodology

With the exception of the study by Le Vinh et al. (2020), most previous research on position-dependent recall has been conducted in real-world environments. In the present work, we aim to further validate virtual reality (VR) as a research tool offering greater experimental control in spatial cognition studies. After years of debate, it is now widely accepted that VR can yield ecologically valid results in spatial cognition, both through non-immersive desktop setups Ruddle and Jones (2001) and through fully immersive environments utilizing motion tracking and head-mounted displays Avraamides and Kelly (2008); Kelly et al. (2007); Marchette et al. (2014).

Although visual fidelity does not appear to be the primary determinant of perceived presence – as discussed by Slater, Lotto, Arnold, and Sanchez-Vives (2009) – it remains crucial for tasks involving spatial navigation and the recognition of specific locations Lessels and Ruddle (2005). In this context, we adopt the more focused term "spatial presence" to refer to the participant's subjective sense of being at a specific virtual location, rather than a general sense of immersion. This dimension is one of the core components in the Presence Questionnaire developed by Sanchez-Vives and Slater (2005), although our study does not address other aspects such as immersion level or the long-term formation of VR-based memories.

Beyond visual realism, the quality of bodily motion feedback represents another critical factor in VR-based spatial research. In non-immersive VR setups, where participants interact via a desktop interface, the absence of full-body sensorimotor feedback may impair spatial recall and reduce experimental validity Kelly, Cherep, Klesel, Siegel, and George (2018). Therefore, understanding and accounting for these methodological factors is essential in the design of robust and ecologically valid VR-based experiments on spatial cognition.

Task Design in Virtual Position-Dependent Recall

One of the primary challenges in adapting the position-dependent recall paradigm to a virtual environment is identifying the most effective task for assessing spatial memory within immersive conditions. Le Vinh et al. (2020) employed an interactive building task in which participants used a joystick to manipulate virtual building blocks, selecting elements from a reservoir and placing them in a designated workspace. While this setup enabled detailed reconstruction of spatial layouts, it also introduced motor constraints and interface-specific interactions that may not reflect the natural recall process.

In the present study, we introduce a novel and more naturalistic method known as immersive sketching. In this approach, participants use a physical drawing board while fully immersed in a virtual environment. Their sketching process is captured by an external camera and projected into the VR simulation in real time as a live image. This method combines the intuitive, expressive advantages of traditional sketch mapping with the experimental control and spatial consistency of VR, allowing for a more direct and spontaneous representation of spatial memory. It also enables a closer approximation of how spatial imagery is used in everyday recall scenarios, while still operating within a controlled virtual context.

A central prediction derived from the above framework is that free recall of familiar places will not be random but will exhibit structured spatial progression. Specifically, if each recalled location serves as a temporary viewpoint in representational working memory, subsequent recall should be biased toward locations that are spatially proximal or directly reachable from the previously recalled one. This implies that recall sequences may reflect imagined movement through the environment, even in the absence of explicit navigation instructions.

Plan of Study and Structure of the Thesis

The present thesis investigates the mechanisms of position-dependent recall in virtual environments. Specifically, we test the hypothesis that spatial recall is influenced by the participant's simulated location within the virtual space, rather than their actual physical position in the laboratory. Additionally, we examine the role of body orientation in modulating recall performance, both during and after virtual immersion.

To address these questions, the thesis is organized into two experimental chapters. In Chap. 2, we introduce a novel experimental paradigm called immersive sketching, in which participants draw sketch maps of familiar, remote urban spaces while fully immersed in a VR simulation of specific positions. This method allows us to assess whether the mechanisms of position-dependent recall, previously demonstrated in real-world settings, generalize to immersive virtual environments. We also investigate whether the recall orientation is influenced by body alignment during VR immersion.

In Chap. 3, we extend this investigation to a different mode of spatial recall—free recall without sketching. Participants were asked to verbally name familiar locations while situated at specific virtual starting positions and orientations, without any external spatial support. This task isolates the dynamics of representational working memory and allows us to test whether viewpoint-dependent organization persists across successive recall steps. In particular, we examine whether recall sequences show evidence of systematic spatial progression, such that each recalled location functions as the imagined reference point for the next.

Together, these two experiments aim to provide a comprehensive account of position-dependent spatial recall across different modes of memory access – from immersive, sketch-based tasks to abstract, internally driven recall – while also evaluating the methodological potential of VR for research in spatial cognition.

Chapter 2

Perceived Spatial Presence and Body Orientation Affect the Recall of Out-of-Sight Places in an Immersive Sketching Experiment[1]

2.1 Introduction

Spatial memory enables individuals to recall and navigate through environments by integrating sensory inputs, mental imagery, and learned spatial relationships O'Keefe and Nadel (1978); Tolman (1948). When mentally reconstructing distant locations, the imagined representation is shaped by several parameters, including the observer's body orientation, the airline or route direction to the target, and the activation of canonical views — those that are most familiar or structurally salient for a given place Röhrich et al. (2014).

These spatial recall processes highlight the interaction between egocentric and allocentric frames of reference, where egocentric cues are defined relative to the

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observer's current position and orientation, while allocentric cues remain fixed across viewpoints Klatzky (1998); Shelton and McNamara (2001). Previous studies in real-world settings have shown that position-dependent recall is a robust phenomenon: participants' sketch maps of unseen locations often align with either the airline direction from their current position or with a canonical view of the target Röhrich et al. (2014). However, these studies typically lacked precise control over key variables such as body orientation, which is known to influence spatial recall and mental imagery.

Virtual reality (VR) provides a promising methodological alternative by enabling immersive simulations of real-world environments while maintaining rigorous experimental control Meilinger (2008); Schölkopf and Mallot (1995). In particular, VR allows for the manipulation of both spatial position and body orientation, making it possible to isolate their respective contributions to position-dependent recall.

In this study, we extend the work of Röhrich et al. (2014) by introducing a novel immersive sketching paradigm. Participants are asked to produce sketch maps of familiar, but currently unseen, locations while immersed in a VR environment that simulates specific recall positions within a known urban space. By manipulating body orientation during immersion and retesting participants after they exit VR, the study aims to examine the relative contributions of immersion, body alignment, and representational memory to spatial recall. This approach allows us to test whether position-dependent recall effects generalize to immersive virtual environments and whether they persist beyond the immersive experience.

2.2 Methods

2.2.1 Participants

A total of 100 healthy adults, 37 male and 63 female, participated in our studies. All participants were students of the University of Tübingen aged at least 18 years. Further details were not recorded. All included participants had been living in Tübingen for more than two years and successfully passed a pre-experiment testing their knowledge of the experimental area. 80 participants were randomly assigned to 4 groups of 20 people each for experiment one and 20 participants were randomly assigned to 2 groups of 10 people each for experiment two.

Before beginning the study, all participants confirmed they had no issues with virtual reality equipment and were comfortable using the Oculus Rift head-mounted display. Participants were informed of their right to withdraw from the study at any time without needing to provide a reason. Written informed consent was obtained from all participants, and each received a payment of 8 Euros for their participation.

2.2.2 Experimental Setup

For this study, we used an Oculus Rift DK2 headset with a 100-degree field of view and a resolution of 960 × 1080 pixels per eye to create an immersive virtual environment. Participants were seated in a rotating chair, which allowed them to freely orient themselves within the VR setup. This rotating chair was specifically designed with modifications: it included a small desk behind the seat for the laptop, and a tablet-style arm desk in front where participants could draw sketch maps (shown in Fig. 2.1).

To ensure participants could draw while remaining immersed in the virtual environment, a camera was mounted on the tablet arm to capture live video of the sketching surface. This live video was displayed directly in the VR headset via a Unity WebCamTexture, allowing participants to see their hand and the drawing without having to remove the headset. The sketching paper was square to prevent any directional bias (horizontally or vertically) and was clipped securely to the desk to prevent movement during the task.

Videos for the pre-experiment were recorded on-site in Tübingen using a Canon PowerShot G7 camera. These recordings were subsequently presented using the Oculus Rift headset, which in this context served purely as a display device operating in an open-loop configuration. This approach allowed us to provide uniform presentation across all participants.

For the main experiment we have set up a virtual environment in Unity using C#. The virtual environment consisted of three well-known sketching location (S_1, S_2, S_3) in Tübingen, each represented by 360° panoramas. These panoramas were

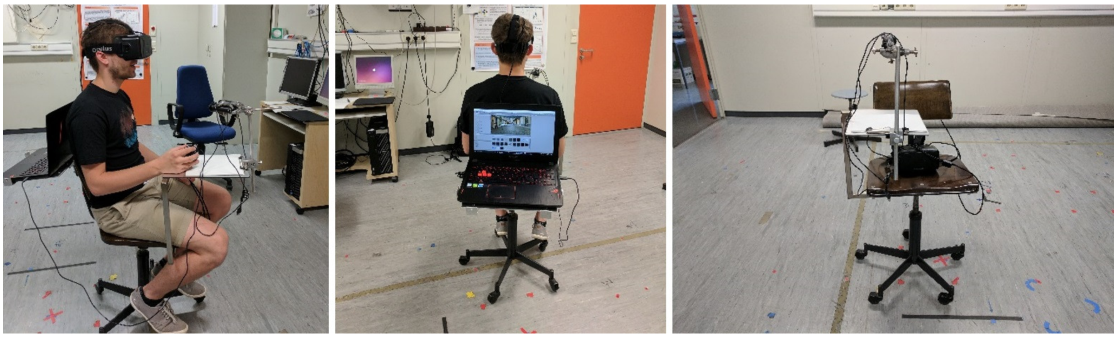


Figure 2.1: The setup for the experiments consists of a modified rotating chair. Attached to the chair is a small desk for carrying a laptop and a tablet arm desk for drawing the sketch maps. Attached to the tablet arm desk is a camera stand with camera that captures a live video from the sketch paper that is displayed in the virtual environment.

created by capturing images at 30° intervals using a Canon PowerShot G7 camera and then stitching the 12 pictures together to form a cylindrical representation using Microsoft Image Composite Editor. The three panoramas are shown in Fig. 2.2. All pictures and videos were taken during early morning hours to avoid imaging of passers-by.

The virtual cylinder was designed with realistic textures: the top showed a sky (either clear or cloudy), and the bottom displayed a matching ground surface, such as cobblestones. Participants were positioned at the center of each virtual cylinder and could explore their surroundings by rotating their heads. This setup aimed to replicate the visual experience of each real-world location as accurately as possible.

In the VR environment, participants were positioned at the center of each cylindrical scene. They could explore their surroundings by rotating their heads, but translational movement (i.e., moving from one place to another) was not tracked, to ensure stability of the visual experience. This meant that any movement produced by the participants' upper body did not affect the VR view; the scene appeared to move with them, maintaining a consistent perspective.

During the sketching phase, participants viewed their drawing as if it were positioned in a virtual square workspace at the base of the cylinder. This workspace

Figure 2.2: The panoramas of sketching locations S_1, S_2, and S_3.

was either set facing towards or away from the target area, allowing us to manipulate the participants' orientation relative to the target. The experimenter could change the participants' virtual location using the space bar on a laptop, effectively "teleporting" them from one location to another.

This immersive setup allowed participants to create sketch maps while fully immersed in the VR environment. The setup facilitated studying how body orientation and spatial context influence recall, while the controlled environment minimized variability across participants.

2.2.3 Task

In all experiments, we used three sketching locations, S_1, S_2, S_3 and two target areas T_1: Marktplatz (market square), T_2: Holzmarkt (timber market), see Fig. 2.2 and Fig. 2.3. Throughout this chapter, we use the German names for these locations since they are the commonly recognized names of these specific sites. All locations were well-known landmarks in the historic center of Tübingen, with each pair of locations being within walking distance but out of each other's line of sight. The goal was to evaluate how participants recalled spatial layouts from different perspectives and orientations in a virtual environment.

To gather meaningful data, we designed four main sketching tasks: sketching target T_1 from sketching location S_1 (S_1-T_1), sketching target T_1 from sketching location S_2 (S_2-T_1), sketching target T_2 from sketching location S_2 (S_2-T_2), and

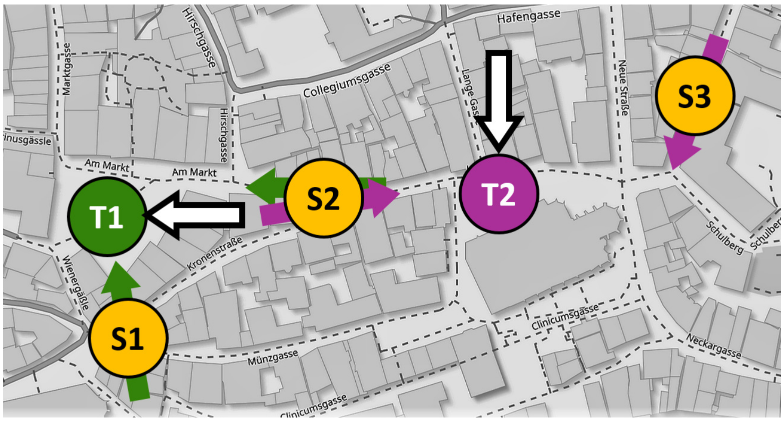


Figure 2.3: Map of Tübingen city center with the two target areas T_1 "Marktplatz" (green) and T_2 "Holzmarkt" (magenta) and the sketching locations S_1, S_2, and S_3 (yellow). Green and magenta arrows show route direction to target place T_1 (green) or T_2 (magenta), respectively. They coincide with the body orientation in the "towards" condition while the arrow tails mark the body orientation in the "away" condition. The heavy white arrows show the canonical viewing direction of the target areas as reported by Röhrich et al. (2014). The airline directions are not shown; they mostly coincide with the route directions except for task S_3T_2 where it is offset by some 30 degrees to the right. Map source: www.openstreetmap.org

sketching target T_2 from sketching location S_3 (S_3-T_2), see Fig. 2.3.

In addition, we varied the participants' body orientation by placing the live image of the sketching paper either towards the street leading from the sketching location directly to the target ("towards condition") or offset from this direction by 180° ("away condition"). In the "towards" condition, participants might therefore imagine to just move forward to walk to the target. The "exit direction" is generally similar to the airline direction, but slight deviations may occur due to the city street raster. In the "away" condition, participants were required to produce their sketches while imagining a target located behind them.

Each participant completed two sketching tasks, each involving a different target. Participants were randomly assigned to one of four groups based on body orientation and starting location: A-towards, A-away, B-towards, and B-away. Each group carried out a distinct combination of tasks. The tasks were designed so that no participant repeated the same sketching task twice, which minimized the potential for interactions or carry-over effects between repeated tasks.

In total, we evaluated eight distinct task variations, combining starting location, target area, and body orientation.

2.2.4 Data Analysis

The sketch maps were categorized by two independent raters into one of eight nominal categories: the cardinal directions (north, east, south, and west) and the intercardinal directions (northeast, southeast, southwest, and northwest). The raters were allowed to use any necessary aids, including their own local knowledge of the area, pictures, or maps, as well as the orientation of lettering included in the maps. The sketches were not evaluated for geometric accuracy, completeness, or other qualitative parameters. The raters worked independently from each other and both raters rated all sketch maps. Cohen's κ (Cohen (1960)) was used to assess inter-rater reliability.

Directional ratings were analyzed in two ways, first as categorical data using χ^2 tests, and, in a follow-up analysis, with the V-test of circular statistics. Circular statistics transforms angular data (α_i) into unit vectors of the form $\vec{x}_i = (\cos\alpha_i, \sin\alpha_i)$, see for example Batschelet (1981) and Berens (2009). In our data, the cardinal directions N, E, S, W correspond to the following vectors in the mathematical angle convention: $N = (0,1), E = (1,0), S = (0,-1)$, and $W = (-1,0)$. The average of a set of unit vectors, also called the resultant vector, is given by $\vec{r} = (\sum_{i=1}^{n} \vec{x}_i)/n$; its length $||\vec{r}||$ is close to zero if the individual $\vec{x}_i$ point into different directions and approaches one if the sample is uniform. For a given "theoretical" direction $\vec{x}_0 = (\cos\alpha_0, \sin\alpha_0)$ the V-test tests the hypothesis that the sample is drawn from a population not concentrated in the theoretical direction, i.e. that data cluster around another direction or do not cluster at all. It rejects the null hypothesis if the data are clustered around the theoretical direction.

2.3 Procedure

2.3.1 Pre-experiment

Before conducting the main experiment, a pre-experiment was performed to confirm participants' familiarity with the Tübingen city center and the specific locations used in the study. Participants viewed three videos, each showcasing one of the sketching locations (S_1, S_2, S_3). The videos were presented using video goggles in an open-loop setup.

Each video began slightly away from the respective sketching location and showed a walkthrough of its immediate surroundings, including views of streets connecting to the target areas. However, the target areas themselves were not visible in any of the three videos. After viewing each video, participants were asked the following questions to assess their familiarity with the areas:

- "Do you know this place?"
- "Do you know what this place is called?"
- "When was the last time you visited this area?"
- "Why did you visit this area?"

Participants who failed to correctly name all three sketching locations or reported having last visited them more than 30 days ago were excluded from further participation. As a result, three participants were removed from the main experiment.

2.3.2 Experiment 1

After completing the pre-experiment, participants received detailed instructions about the procedure, both verbally and in written form. The experimenter introduced them to the equipment, including the rotating chair, camera setup, and fixed square paper used for sketching. Participants were informed they could rotate the chair freely during the experiment whenever necessary and that they would be asked to draw sketch maps of Marktplatz ("Market Square", target T_1) and Holzmarkt ("Timber market", target T_2) on the paper while still wearing the goggles. They were advised about a relaxation room available for use if they felt unwell during the virtual reality (VR) session.

At the beginning of each sketching task, participants were virtually "teleported" to the respective sketching location within the VR environment, oriented to face north. They would then explore the environment by looking around (closed loop VR simulation for rotations only). Exploration duration was not recorded. Once they indicated familiarity with the location, the experimenter asked them to imagine the target area and produce a sketch on the virtual sketching board. To do so, participants needed to turn into the direction in which the virtual sketching board had been provided. Beyond the sketching board, they would still see the scenery of the current sketching location, facing either towards or away from the target.

Each participant completed two sketching tasks corresponding to two target areas, "Marktplatz" (T1) and "Holzmarkt" (T2). They were randomly assigned to one of four groups of 20 participants: A-towards, A-away, B-towards, and B-away, with each group performing a distinct combination of tasks as summarized in Tab. 2.1. The second sketching task was initiated immediately after completing the first.

2.3.3 Experiment 2

To explore the effect of immersion and spatial presence on representational memory, we conducted a second experiment in which participants repeated the sketching tasks after a delay and outside the virtual environment. A total of 20 participants (gender not recorded) were randomly divided into two groups: C-towards and C-away, with 10 participants in each group.

Procedure

Experiment 2 was divided into two phases. Phase 1 followed the same protocol as Experiment 1 for groups A-towards and A-away, where participants completed sketching tasks S_2-T_1 and S_3-T_2. After completing the sketches, the experimenter collected the papers, and participants removed the video goggles. They were then

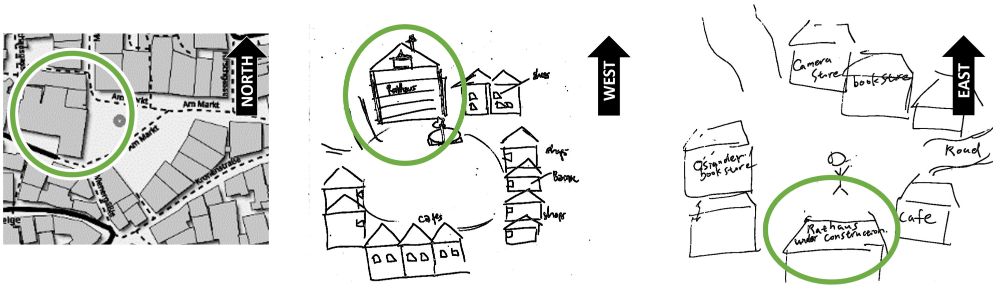
	Group			
Sketching task	**A-towards**	**A-away**	**B-towards**	**B-away**
1st sketch				
Starting location	S_2	S_2	S_1	S_1
Target area	T_1	T_1	T_1	T_1
Orientation	towards	away	towards	away
2nd sketch				
Starting location	S_3	S_3	S_2	S_2
Target area	T_2	T_2	T_2	T_2
Orientation	towards	away	towards	away

Table 2.1: Overview of assigned sketching tasks for participants in Groups A-towards, A-away, B-towards, and B-away in experiment 1. Each group was assigned the same target area T per sketching task, but different starting locations S and body orientations.

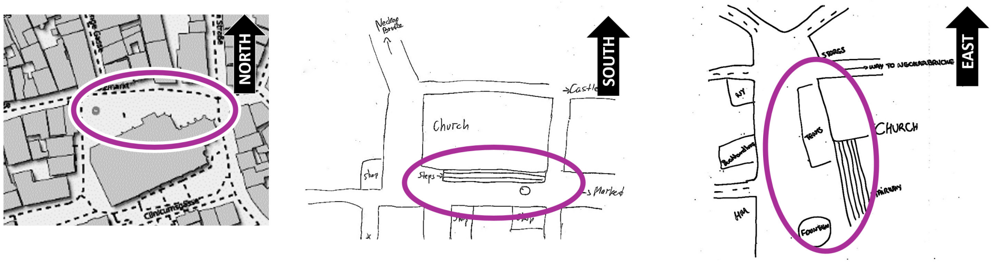
given a 10-minute break and asked to remain in the experiment room. During this time, they could access refreshments or have a look at unrelated reading material provided in the room, but they were instructed not to use the internet or engage in phone calls.

After the 10 minutes break, in Phase 2, participants were instructed to redraw the layouts of the same target areas (T_1 and T_2) from memory without the aid of the virtual environment or additional guidance from the experimenter. Once participants completed the sketches, the second phase of the experiment and the experiment itself concluded.

In total, each participant produced four sketch maps: two maps of locations T_1 and T_2 before the break and within the virtual reality environment, and again two maps of the two target areas after the break.



a: map of T1 **b: S2 to T1, towards** **c: S2 to T1, away**



d: Map of T2 **e: S3 to T2, towards** **f: S3 to T2, away**

Figure 2.4: Maps and sketch map examples. **a** – **c**: target area T_1. The green ellipses mark the city hall ("Rathaus"). **b** is oriented west (city hall up) and **c** is oriented east (city hall on bottom). **d** – **f**: target area T_2. The magenta ellipses mark the long axis of the square together with the church and a fleet of stairs in front of it. **e** is oriented south (church up) while **f** is oriented east (church right). Note that the paper orientation while drawing is also defined by the scribbling. Map source: www.openstreetmap.org

2.4 Results

2.4.1 Experiment 1

Fig. 2.4 provides four examples of the sketch maps produced by participants, along with their orientational ratings. Further examples of sketch maps are shown in Fig. A.3. Inter-rater agreement was 100 %, resulting in $\kappa = 1$ (Cohen's κ, see Sec. 2.2). The full set of map orientations is presented in the Appendix Fig. A.1. Fig. 2.5 shows the distribution of the orientational ratings for sketch maps produced at the three sketching locations S_1, S_2, and S_3, both for the towards and

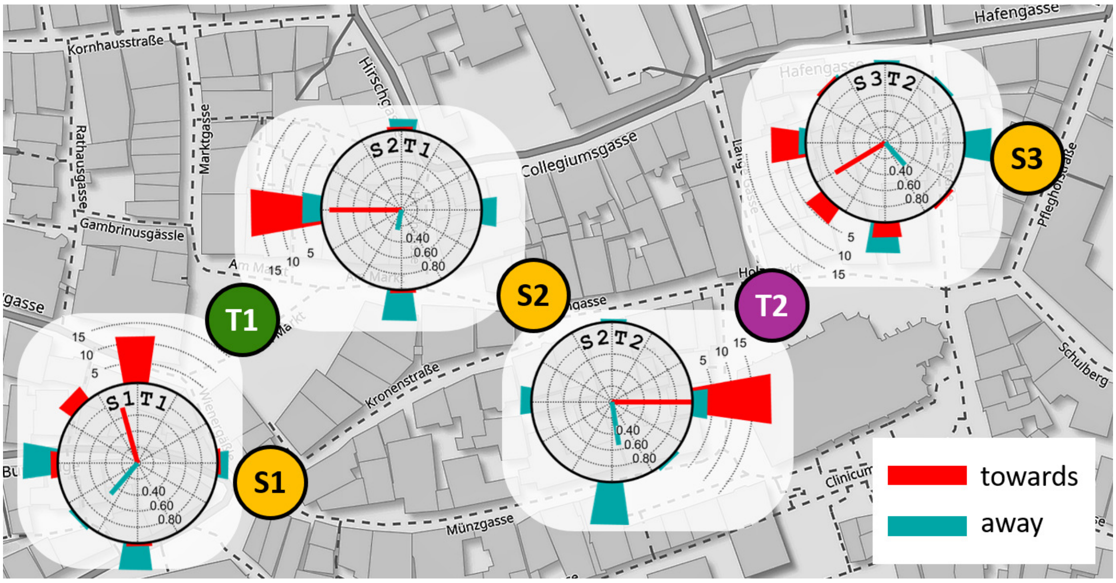


Figure 2.5: Results of Expt. 1. Sketching and target areas as in Fig. 2.3. The circular histograms show the frequency of sketch map orientations for the four tasks S_1T_1, S_2T_1, S_2T_2, S_3T_2 as indicated also by the location markers touching each panel. Red and cyan bars indicate towards and away condition; north is upwards. The red and cyan lines in the center of each histogram show the circular means. Each histogram shows data from 20 sketch maps. Map source: www.openstreetmap.org

away conditions. For the statistical analysis, the orientation ratings were binned into four classes north, east, south, and west. The rare intercardinal ratings were counted as 0.5 for each of the two adjacent cardinal directions.

In the "towards" condition, sketch map orientation for both target areas was significantly influenced by the sketching location, demonstrating position-dependent recall. This effect was revealed by two separate χ^2-tests comparing the orientation histograms for the two sketching locations used with each target area. Note that for each target area, the comparison is between different participant groups, as shown in Tab. 2.1. As shown in the first row of Tab. 2.2, the effect was highly significant for both target areas. However, this effect was absent in the "away" condition.

Additionally, sketch map orientations also depend on body orientation. Comparisons between the "towards" and "away" conditions for individual tasks (pairs

Orientation	**Target T_1**	**Target T_2**
towards	S_1-T_1 towards vs. S_2-T_1 towards $\chi^2(3, N = 40) = 36.19$, $p < .001$, $V = .95$	S_2-T_2 towards vs. S_3-T_2 towards $\chi^2(3, N = 40) = 38.05$, $p < .001$, $V = .98$
away	S_1-T_1 away vs. S_2-T_1 away $\chi^2(3, N = 40) = 4.56$, n.s.	S_2-T_2 away vs. S_3-T_2 away $\chi^2(3, N = 40) = 1.757$, n.s.

Table 2.2: Position dependent recall (experiment 1). The table shows test statistics for the data shown in Figure 2.5. Note that all comparisons are between different subject groups as specified in Table 2.1. V is Cramér's V indicating effect strength.

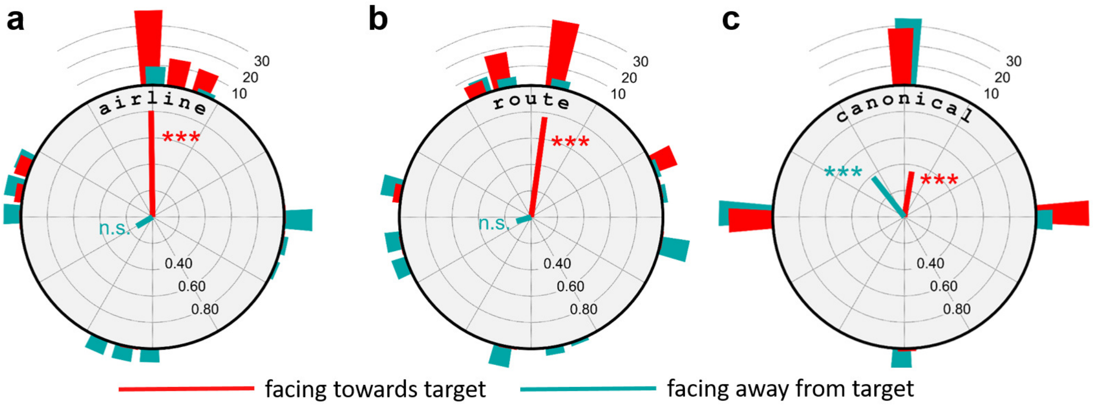


Figure 2.6: Deviation of sketch map orientation from the theoretical directions airline to goal (**a.**), route (**b.**), and canonical view (**c.**). red: towards condition, cyan: away condition. Same data as in Fig. 2.5, accumulated over all tasks. Radial lines are circular means, histogram bars show frequency data.

of sketching location and target area) revealed significant differences. Again, all χ^2-tests are between different participant groups as specified in Tab. 2.1. Test statistics for the effect of body orientation are shown in Tab. 2.3.

In summary, at least two main factors influenced sketch map orientation: the sketching locations and the participants' body orientation.

A further analysis of the data concerns the preferred orientations of the produced sketch maps in relation to three theoretical angles, (i) the airline direction

Sketching location	**Target T_1**	**Target T_2**
S_1	S_1-T_1 towards vs. S_1-T_1 away $\chi^2(3, N = 40) = 22.21$, $p < .001$, $V = .75$	—
S_2	S_2-T_1 towards vs. S_2-T_1 away $\chi^2(3, N = 40) = 17.80$, $p < .001$, $V = .67$	S_2-T_2 towards vs. S_2-T_2 away $\chi^2(3, N = 40) = 25.31$, $p < .001$, $V = .80$
S_3	—	S_3-T_2 towards vs. S_3-T_2 away $\chi^2(3, 40) = 13.32$, $p = .002$, $V = .58$

Table 2.3: Effect of body orientation (experiment 1). The table shows test statistics for the data shown in Fig. 2.5. Note that all comparisons are between different subject groups as specified in Tab. 2.1. V is Cramér's V indicating effect strength.

from the sketching location to the target are, (ii) the route direction heading into the street that most quickly leads from the sketching location to the target area (green and magenta arrows in Fig. 2.3), and (iii) the canonical view of the target as indicated by the white arrows in Fig. 2.3. Note that the route direction (ii) is also the body orientation of the participants in the towards condition. Fig. 2.6 shows the differences of the sketch map orientation and each of the three theoretical angles for all sketching tasks. Thus, if participants would exactly align their maps with the airline direction, Fig. 2.6a would show an ideal peak at angular difference 0. Significant alignment with the theoretical angles was tested with the circular V-test (for example Berens (2009)). Results show significant effects of all three theoretical angles in the towards condition (airline: $V(80) = 64.4, p < .001$; route: $V(80) = 60.8, p < .001$, canonical: $V(80) = 27.5, p < .001$), while in the away condition, significant map alignment was found only with the canonical viewing direction ($V(80) = 24.0, p < .001$). No meaningful distinction can be made between the airline and route directions, as these two theoretical angles were nearly identical in the sketching and target areas used in this study. Furthermore, all theoretical angles are virtually the same (in example west) for the S_2-T_1 task as can be seen from Fig. 2.3.

In summary, the results of Experiment 1 show that sketch map orientation depends on sketching location in the towards, but not in the away condition. The preferred sketch map orientation in the towards condition is a mixture between the airline or route directions to the target area and a canonical view of the target area, while the sketch maps produced in the away condition show some alignment with the canonical view, but not with the airline or route directions.

2.4.2 Experiment 2

Experiment 2 investigated whether the representational memory formed during immersion in the virtual environment persisted when participants sketched from memory outside the VR setting.

Results of experiment 2 are shown in Fig. 2.7. Inter-rater agreement was 100 %, resulting in $\kappa = 1$ (Cohen's κ, see Sec. 2.2). All map orientations are listed in the Appendix Fig. A.2. Participants from the C-towards and C-away groups produced sketches of tasks S_2-T_1 and S_3-T_2 before and after the break, i.e., within and outside the virtual environment. In the "towards" and "away" groups, the number of sketch pairs produced with different orientations before and after the break was 12 out of 20 and 8 out of 20, respectively (see Appendix Fig. A.2.). We therefore conjectured that participants do not simply reproduce their frst sketch in the second drawing and tested this hypothesis with two approaches.

First, we analyzed the orientation changes of sketch maps produced by each subject before and after the break using Hotelling's T^2 test. For this, the angular deviations between sketches produced before and after the break were transformed into unit vectors with components given by the cosine and sine of the angular differences. This generated a set of bivariate data which were compared to the value $(\cos 0, \sin 0) = (1, 0)$ expected under the null hypothesis of equal map orientation. The test did not reach significance for any of the tasks or body orientation conditions (S_2-T_1 towards: $T^2(2,8) = 4.47, p = 0.20$; S_2-T_1-away: $T^2(2,8) = 4.10, p = 0.22$; S_3-T_2-towards: $T^2(2,8) = 5.11, p = 0.17$; S_3-T_2-away: $T^2(2,8) = 2.70, p = 0.35$).

Second, we conjectured that if participants would simply reproduce their sketches drawn during immersion also after the break, the effect of body orientation should

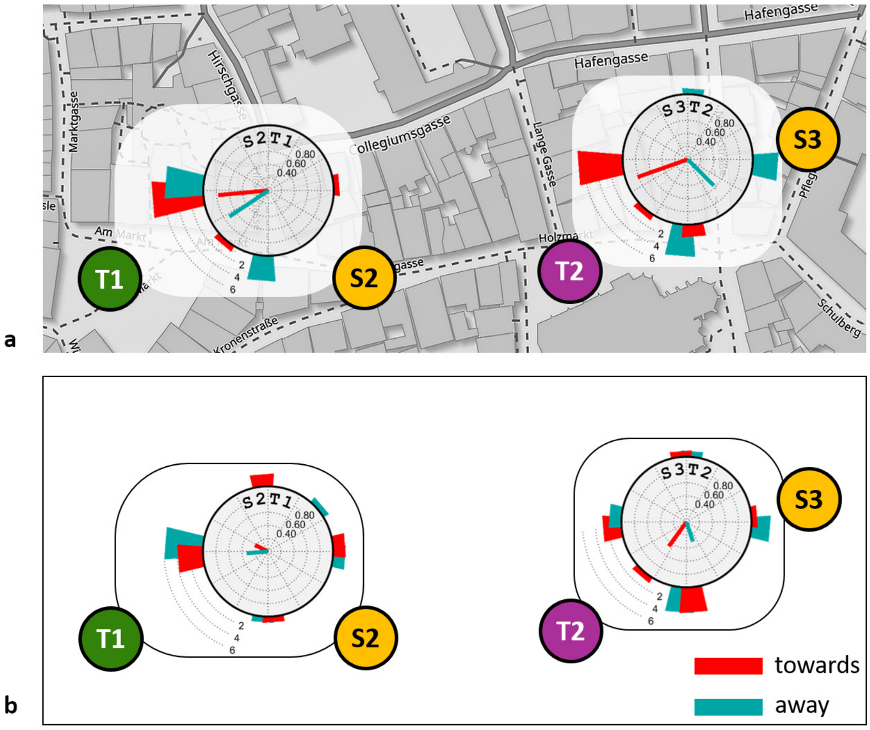


Figure 2.7: Results of experiment 2. **a.** Phase 1, immersed before the break, **b.** Phase 2, in office environment after the break. For explanations see Fig. 2.5. Map source: www.openstreetmap.org

be identical in the "before" and "after" conditions. In this approach, comparisons are made between the two subject groups C-towards and C-away, and are therefore again be analyzed by χ^2-tests. Data were collapsed for sketching task but kept separate for immersion. The "north" bin in task S_2T_1 was empty for both body orientations in the immersed condition and was therefore deleted. A significant effect of body orientation was found for the sketch maps produced during immersion (before the break, $\chi^2(6, 40) = 17.5, p = .0051, V = 0.66$), but not after the break ($\chi^2(7, 40) = 3.13$, n.s.). Indeed, after the break, when participants are tested in the lab environment, the definition of the "towards" and "away" body orientations is no longer apparent.

Fig. 2.8 shows the alignment of the chosen view orientations with the theoretical directions airline to target area, route to target area, and canonical view, each with and without immersion in the virtual environment. While immersed in the

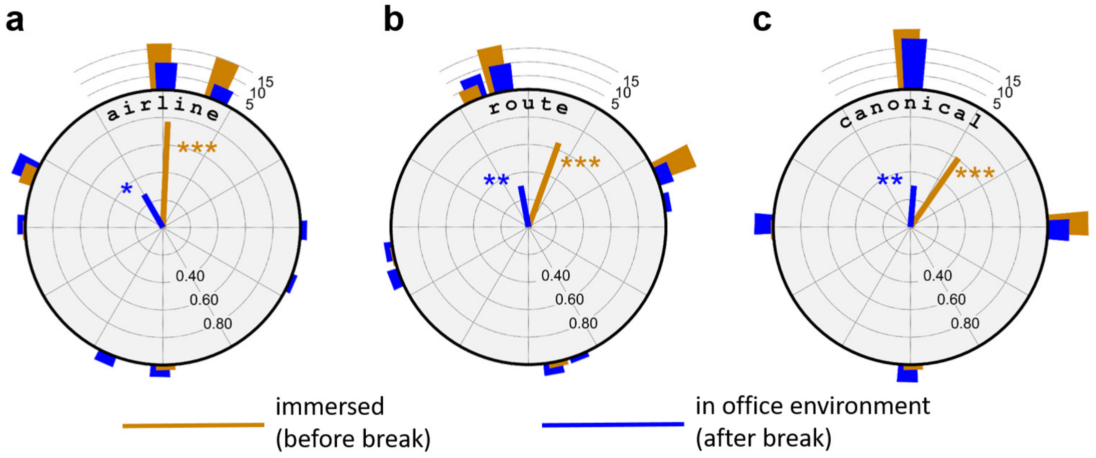


Figure 2.8: Deviation of sketch map orientation from the theoretical directions airline to goal, route to goal, and canonical view. Same data as in Figure 2.7, accummulated over all tasks and body orientations. Colors indicate immersion condition. Radial lines are circular means, histogram bars show frequency data.

virtual environment, highly significant alignment was found with all three theoretical directions (airline: $V(40) = 30.8, p < .001$; route: $V(40) = 24.4, p < .001$; canonical: $V(40) = 20.0, p < .001$). This pattern is unchanged after the break, when participants repeat their tasks in an office environment, although the significances are weaker (airline: $V(40) = 9.6, p = .016$; route: $V(40) = 11.9, p = .004$; canonical: $V(40) = 12.0, p = .004$).

In summary, the results of Experiment 2 suggest that the imaginary view point assumed during immersion in the virtual environment partially persists when the participants return to the physical environment of the lab.

2.5 Discussion

When participants produce sketch maps of distant target areas from memory, they tend to align their sketches with specific viewing directions. These depend on the airline or route direction from the sketching site to the target, the participants' body orientation at the sketching location, and a standard or canonical view of the target which is also activated when the distance to the target is large Röhrich et al. (2014). The canonical view is "allocentric" in that it does not change as the observer moves around, while the airline and route axes are of course dependent on observer position, in example, egocentric (see Klatzky (1998)). In our experiments, the airline direction was roughly identical with the direction of the shortest route connection to the target; thus, we can not distinguish the effects of these two factors.

The results confirm and extend earlier findings on position-dependent recall in a real urban environment by Röhrich et al. (2014) in two significant ways: First, the imaginary view point of position-dependent recall can be set by a virtual environment, while the participants are physically in the lab. Second, position-dependent recall is modulated by body orientation which was not controlled in the Röhrich et al. (2014) study. When participants' body orientation aligns with the route direction to the target, their sketch maps are oriented as though they could look directly through the intervening buildings to the target. ("towards" cases in Fig. 2.5). One possible interpretation of this result is that participants solve the task by mentally traveling to the target, imagining oriented views along the route, and sketching the final view envisioned upon "arriving" at the target (see Basten et al. (2012)). In the "away" condition, sketch maps are more preferably aligned with the target's canonical view (Fig. 2.6c), i.e., the view produced also at large distances (Röhrich et al. (2014)).

The difference in sketch orientations between the "towards" and "away" conditions suggests that participants have at least implicit knowledge of their current body orientation relative to the target. This cannot be a result of path integration (as in the sensorimotor alignment effect of Kelly et al. (2007)), as participants were teleported between sketching locations. Rather, this information must be derived from spatial memory. Relevant memory structures capable of providing such information include the view-graph proposed by Schölkopf and Mallot (1995) and Röhrich et al. (2014) as well as the network of reference frames described by Meilinger (2008). In both cases, the orientation changes stored for each view or reference frame transition would need to be accumulated along a path connecting the sketching and target areas. Alternatively, local orientation relative to a global reference direction could be memorized for each location (Mallot et al. (2020), Mallot (2024)). Of course, information about the egocentric bearing of the target area from a sketching site could also be derived from a complete metric map. In this case, however, position-dependent recall itself would be difficult to explain.

In the original study by Röhrich et al. (2014), body orientation was not controlled and varied substantially among participants. The fact that the strength of position-dependent recall was intermediate between the strong and absent effects found in the "towards" and "away" conditions in the present study may therefore result from averaging across participants with differing body orientations.

One key finding of this study is the overall equivalence between the real-world experiments conducted by Röhrich et al. (2014) and our immersive sketching task performed in a virtual environment. The role of immersion was further investigated in Experiment 2, which followed the same paradigm as Experiment 1 but included an additional phase where participants were retested outside the virtual environment in an office setting. Participants do not simply reproduce their previous drawings but still show the same pattern of orientational preferences, albeit with a higher level of noise. This suggests that immersion in the virtual environment is sufficient, but not necessary to induce position dependent recall. This is in line with the findings by Basten et al. (2012) who induced position-dependent recall simply using an imagined travel as a prime.

It is interesting to compare the various angles discussed in position-dependent recall with those studied in the literature on judgments of relative direction (JRD). The intrinsic axis of Shelton and McNamara (2001), i.e., the viewing direction in which an environment is most easily imagined, is a property of this environment. It does not change if the observer moves and is therefore allocentric in the sense of Klatzky (1998). The intrinsic axis is thus similar to our canonical view direction of the target place. In the JRD task, the imagined heading direction is determined by the instruction to imagine facing towards a particular object. In our experiment no such instruction is used, however, participants may have interpreted the sketching task in a similar manner. If so, the imagined heading would be the equivalent of our airline direction. It can, however, not be obtained from the imagery itself, but needs to take into account the current location and its remembered spatial relation to the target. Finally, sensorimotor alignment (Kelly et al. (2007)) does not seem to play a role in our virtual environment experiments where participants are teleported between sketching sites. Our angle of body orientation is defined by visual cues from the environment and knowledge of the spatial relations between sketching site and target. In real-world experiments, this may be combined with cues from path integration.

Conclusion

In conclusion, position-dependent recall aligns with the concept that spatial long-term memory is structured as a graph of local places, views, or reference frames. These can be "loaded" into a chart-like working memory stage for purposes of imagery and spatial planning. The representation within this chart possesses a specific orientation, resulting in view-like outputs in sketching tasks. These orientations are influenced by the current situation and task, likely in ways useful for spatial planning.

Chapter 3

Continuous Progression in Free Recall of Familiar Places: Insights into Spatial Memory Patterns

3.1 Introduction

Free recall of familiar places offers a unique window into the cognitive organization of spatial memory. Unlike structured tasks such as sketch mapping or directed navigation, free recall allows us to observe how individuals spontaneously access and sequence locations based on their internal memory structures. In this chapter, we investigate whether these recall patterns reveal systematic spatial progression—for instance, by clustering nearby places, following familiar paths, or aligning with certain directions. Our goal is to determine whether such patterns reflect underlying spatial schemas and whether they can be quantified to reveal general principles of spatial memory organization.

To explore this, we analyze how participants list familiar places from memory in an unconstrained order. By examining the sequential and spatial structure of their responses, we aim to identify patterns—such as proximity-based grouping or directional trends—that may reflect underlying cognitive strategies and memory processes guiding spontaneous spatial recall.

Prior research has shown that spatial recall is influenced by multiple factors, including spatial proximity, semantic associations, personal relevance, and frequency of experience with a place (Golledge (1992); Hirtle and Jonides (1985); McNamara (1988)). People tend to cluster nearby locations together in recall, a phenomenon known as spatial contiguity or spatial clustering, which is often interpreted as reflecting underlying spatial schemas (Montello (1999); Tversky (1993)). These schemas provide mental frameworks that structure memory and guide retrieval by organizing places hierarchically (e.g., buildings within streets, streets within neighborhoods).

Moreover, the cognitive maps underlying recall may combine egocentric (body-centered) and allocentric (environment-centered) representations (Klatzky (1998); Shelton and McNamara (2001)). Egocentric cues reflect the individual's current or imagined position relative to the recalled locations, while allocentric structures enable more flexible access across varying viewpoints. Free recall tasks provide a valuable opportunity to investigate how these reference systems may interact when spatial memory is accessed in a non-directed, internally guided manner.

While prior studies have explored place memory in structured recall and recognition tasks (Marchette, Yerramsetti, Burns, and Shelton (2011); Meilinger (2008)), fewer have investigated spontaneous recall of familiar locations. Our approach allows us to explore how people mentally organize geographic spaces by observing which places are retrieved first, which come later, and how they are organized spatially.

Based on this background, we test two central hypotheses. First, we hypothesize that freely recalled places are retrieved in a continuous, neighborhood-preserving manner, such that successive locations tend to be spatially close to one another and form coherent local progressions within the environment. Second, we hypothesize that recall order is influenced by the spatial context of retrieval, specifically the location from which recall takes place, leading to systematic differences in recall patterns depending on the starting position.

To test these hypotheses, recall was assessed from multiple predefined starting locations within a virtual representation of a well-known city. Participants recalled familiar places associated with specific target areas while positioned at different starting points and oriented toward the respective target area. By varying the starting location while leaving the recall task otherwise unconstrained, we were able to examine whether recall order reflects spatial proximity and whether systematic differences in recall patterns appear across starting locations.

In this study, we examine both the content and order of freely recalled locations in a well-known city. By comparing recall sequences across different starting locations, we aim to determine whether spatial progression and neighborhood preservation emerge reliably, and whether recall is modulated by the observer's spatial position even in the absence of explicit navigational or immersive cues. Through this work, we aim to deepen our understanding of how spatial memory is organized, accessed, and shaped by internal cognitive structure and spatial context.

3.2 Methods

3.2.1 Participants

A total of 40 healthy adults participated in the study. All participants were either students or staff members at the University of Tübingen, aged between 18 and 40 years. No additional information, such as gender or academic background, was collected. To ensure familiarity with key locations, all participants had lived in Tübingen for at least six months and successfully completed a pre-experiment.

Participants were randomly assigned to one of two groups of 20 individuals each. Before the experiment, they confirmed that they had no issues with virtual reality or the Oculus Rift headset.

It was also explained to participants that they were free to withdraw from the study at any time without providing a reason. Written informed consent was obtained from all participants before the experiment, and each participant received a payment of 10 Euros for their participation.

3.2.2 Setup

The setup in this study uses a similar, but not identical setup as in Sec. 2.2.2 and Fig. 2.1. For this study, we created a virtual environment using the Oculus Rift headset, simulating familiar locations in Tübingen to provide a controlled yet realistic experience. The virtual environment was created in Unity and implemented

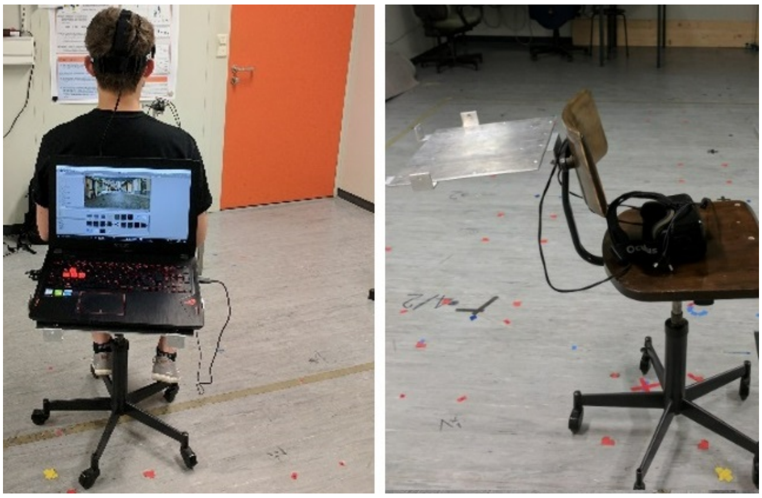


Figure 3.1: Experimental setup featuring a modified rotating chair with a small desk attached for holding a laptop.

with C#. The hardware setup included a rotating chair, as shown in Fig. 3.1. The chair was specifically modified for the experiment, with a small desk attached to the backrest to hold a laptop. This setup ensured that participants could rotate freely in the chair without interference from the cables connected to the video equipment.

The pre-experiment allowed participants to familiarize themselves with the virtual environment, ensuring that by the time the main experiment began, they were comfortable navigating the space and using the Oculus Rift.

To simulate the six starting locations (S_1, S_2, S_3, S_4, S_5, and S_6), we created 360-degree panoramic views. Panoramas were created by taking twelve photos at 30-degree intervals, providing participants with a smooth and comprehensive view of each starting location. These panoramas were generated using a Canon PowerShot G7 camera mounted on a tripod. The images were then stitched together into a seamless cylindrical panorama using Microsoft Image Composite Editor. Fig. 3.2 displays the six panoramas. To minimize distractions from people passing by, the photos were taken during off-peak hours when fewer pedestrians were present.

In the virtual environment, these starting locations were represented as textures mapped to the inner surface of a virtual cylinder. For each location, the top of

(a) S_1: The panorama at Stadtmuseum

(b) S_2: The panorama at Faules Eck

(c) S_3: The panorama at Kirchgasse

(d) S_4: The panorama at Pfleghofstrasse

(e) S_5: The panorama at Wohrdstrasse

(f) S_6: The panorama at Neckargasse

Figure 3.2: Panoramas representing all starting locations used in the experiment.

the cylinder displayed a sky image, such as a clear blue sky or a cloudy one, while the bottom showed a corresponding ground surface, such as cobblestone. A square was placed at the base of each cylinder, positioned so that when participants rotated toward the square, they were automatically oriented in the direction of the target area. This ensured that participants were facing the correct path when the experimenter instructed them to “turn toward the square” and recall the target area while physically oriented toward it.

The participant’s viewpoint was placed at the center of the virtual cylinder. The Oculus Rift provided accurate tracking of head movements, allowing participants to explore the panoramic environment by simply looking around. We tracked rotational head movements only, meaning that any minor translational movements of the upper body while seated were not translated into the virtual environment. In practice, if participants moved slightly, the virtual cylinder moved with them, leaving the visual scene unchanged.

To ensure participant comfort, a relaxation room was made available if needed, and participants were encouraged to take breaks or stop the experiment at any time if they felt unwell.

During the experiment, the experimenter controlled the transitions between starting locations. Using the spacebar on the laptop, the experimenter could instantly "teleport" participants from one starting location to another, ensuring smooth navigation between the six locations throughout the experiment.

Before the main experiment, we ran several test sessions to ensure the virtual environment and hardware worked consistently. This helped maintain a uniform participant experience and ensured reliable data collection.

3.2.3 Task

The aim of this task was to assess how well participants could recall landmarks and familiar locations from different starting points in a virtual environment. We wanted to understand if participants’ spatial memory was influenced by their starting locations, and whether proximity to the target affected the recall order. At the beginning of each recall task, participants were always facing the target direction to ensure consistency.

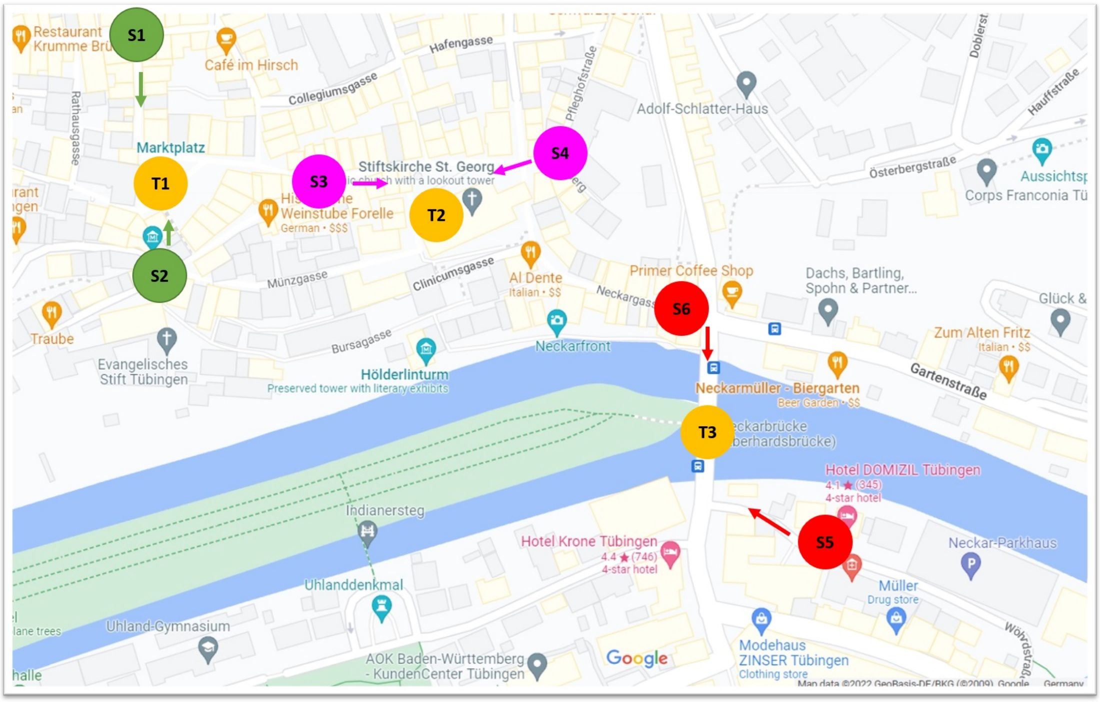


Figure 3.3: **Starting location S_1-S_6 and Target areas T_1-T_3.** The arrows indicate the direction participants were facing from their starting locations while recalling the corresponding target areas. The target areas are shown in orange, and the recall locations for each target are marked with the same color: green for T_1, magenta for T_2, and red for T_3. Map source: maps.google.com

We defined six starting locations ($S_1, S_2, S_3, S_4, S_5, S_6$) and three target areas: T_1: Marktplatz (market square), T_2: Holzmarkt (timber market), T_3: Neckarbrücke (Neckar bridge). All of these locations were situated in the historic center of Tübingen (see Fig. 3.3). Throughout this chapter, we use the German names for these locations since they are the commonly recognized names of these specific sites. Each group of participants was assigned three starting locations, one for each target area. Importantly, targets were not directly visible from any of the starting points, ensuring that participants could not simply see their target while recalling.

Each target area was recalled from two distinct starting points, dividing the participants into two groups: Group A recalled T_1 from S_2, T_2 from S_4, and T_3

from S_6 (S_2-T_1, S_4-T_2, S_6-T_3), while Group B recalled T_1 from S_1, T_2 from S_3, and T_3 from S_5 (S_1-T_1, S_3-T_2, S_5-T_3), as shown in see Fig. 3.4.

Participants were initially oriented toward the street leading to the target area, providing a consistent frame of reference across subjects. They were then asked to recall familiar places in the target area, without receiving any instruction to imagine movement or walking. However, we cannot rule out that some participants spontaneously engaged in mental travel during recall, meaning that they may have imagined walking the path towards the target as part of their recall process.

Participants were asked to recall and name as many landmarks, shops, or public places as they could at each target area. Their responses were recorded by the experimenter, who used a predefined list of well-known places specific to each target. The order of recall was also noted (e.g., '1' for the first place recalled, '2' for the second, etc). This structured recording method allowed for detailed analysis of recall patterns and proximity effects.

Participants were not given a time limit for each recall task to ensure consistency across trials. After each recall, they were transported to the next starting point to continue. If participants recalled fewer places than expected, these responses were still recorded for analysis.

The virtual environment allowed participants to rotate and orient themselves toward the direction of their target, but no physical movement was required, as only the orientation of the head was tracked. This setup helped them focus on the recall task without needing to navigate physically through the virtual environment.

3.2.4 Data analysis

All recalled locations named by participants were identified and marked on digital maps. For each target area, a map was created that covered a sufficiently large area, including both starting locations. Each map was stored as a high-resolution image, and the pixel coordinates of the target, the two starting locations, and all recalled places were determined.

These pixel coordinates were used to calculate distances between locations and to examine spatial relationships among recalled items. This method provided a clear and consistent basis for measuring spatial proximity and formed the founda-

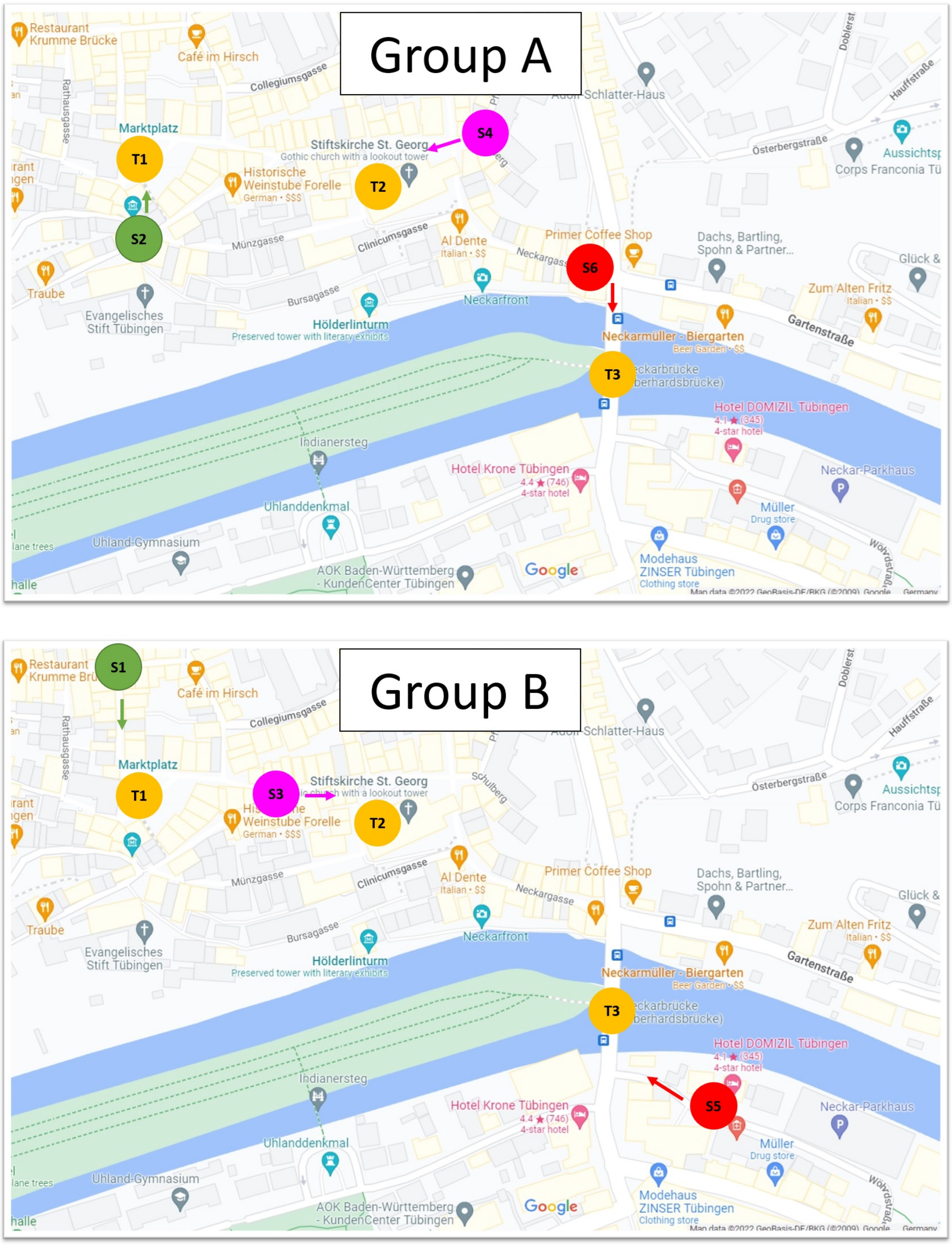


Figure 3.4: Group A: S_2-T_1, S_4-T_2 and S_6-T_3, and group B: S_1-T_1, S_3-T_2 and S_5-T_3. This figure shows the different starting and target area assignments for Group A and Group B. Map source: maps.google.com

tion for the subsequent statistical analyses.

The goal of this analysis was to understand how participants' starting points influenced their ability to recall landmarks in a virtual environment. Specifically, we wanted to see if participants tended to recall landmarks that were physically closer to where they started before recalling more distant locations. This helps us understand if spatial proximity plays a role in how people organize their recall of familiar places.

Length of Mental Scan Paths: To begin, we performed a fractile analysis to evaluate the efficiency of participants' recall. This involved comparing the distances between the recalled landmarks to all possible combinations of those same locations. By doing so, we aimed to see if participants tended to recall locations in a more efficient order compared to a random order. In this context, 'efficient recall' means recalling closer landmarks first, minimizing the overall distance traveled in their mental navigation.

$\boldsymbol{\chi}^2$ Tests: To assess whether participants' recall followed a systematic pattern, we examined the distributions of fractile values using χ^2 tests. These tests were used to determine whether the observed distributions deviated from a uniform distribution, which would be expected if landmarks were recalled in a random order. Separate χ^2 tests were conducted for Groups A and B to evaluate recall organization within each group. In addition, a χ^2 test was used to compare the fractile distributions between the two groups, allowing us to examine potential differences in recall behavior across starting locations.

Proximity-Based Recall Analysis: Next, to explore whether spatial proximity to the starting point influenced the sequence of recalled landmarks, we analyzed the distances of landmarks recalled in order from each participant's actual starting location. This analysis involved calculating the average distances of recalled landmarks across sequence positions, allowing us to examine whether participants tended to recall landmarks closer to their starting point before progressing to those further away. Additionally, these distances were recalculated relative to the alternate starting location used by the other group, in order to assess whether observed recall patterns were specifically tied to the participant's own starting position. This analysis was designed to investigate the role of spatial proximity and starting-point dependence in structuring recall order within the virtual

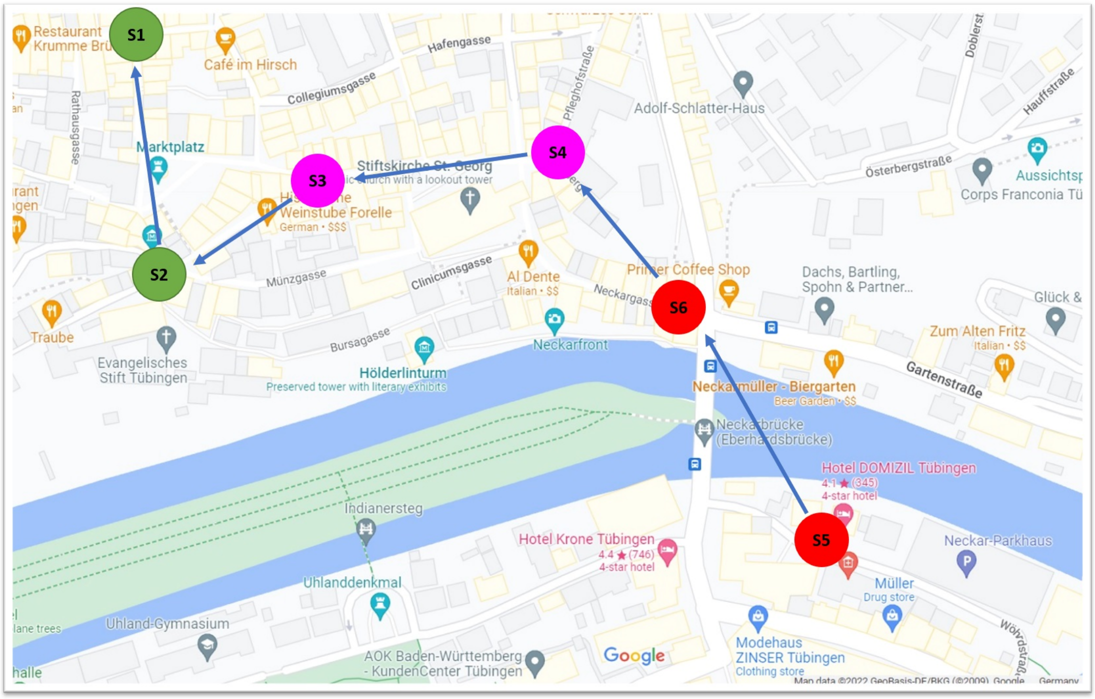


Figure 3.5: The six starting locations and their sequence in the pre-experiment are illustrated by the arrows. The arrows indicate the mental path that participants might take during the pre-experiment. The colors represent recall locations corresponding to different targets: green for T_1, magenta for T_2, and red for T_3. Map source: maps.google.com

environment.

Directional Progression Analysis: To further examine the structure of recall sequences, we analyzed the directional consistency of participants' mental navigation across recalled landmarks. While the previous analyses focused on proximity and efficiency, this step aimed to determine whether recall sequences followed systematic directional trends. For each participant, progression vectors were computed based on the ordered sequence of recalled locations. These vectors captured the dominant direction of spatial progression during recall. Participants were grouped according to starting-location condition (Group A vs. Group B) for each target area, and a multivariate comparison was conducted to assess whether directional progression differed between groups. This analysis allowed us to evaluate whether starting location influenced not only proximity-based organization but also the overall directional structure of recall.

3.3 Procedure

3.3.1 Pre-Experiment

To ensure that participants had a solid understanding of Tübingen's city center and were familiar with the specific locations used in the main experiment, a pre-experiment was performed, similar to the pre-experiment in Sec. 2.3.1. The goal of this preliminary session was to confirm that participants could recognize the six starting locations (see Fig. 3.5) and had recent experience with the surrounding areas. The pre-experiment took place in the same room as the main experiment, where participants were seated on a rotating chair equipped with an Oculus Rift head-mounted display (see Fig. 3.1). Using this setup, they viewed immersive panoramic representations of the six starting locations. Participants were placed inside these environments in the following order: S_5, S_6, S_4, S_3, S_2, and S_1.

While being placed in each virtual location, participants were able to freely rotate in the chair to explore their surroundings. Once they felt they had familiarized themselves with the environment, they were asked two key questions to check how well they recognized the area and if they had been there recently:

1. Are you familiar with this location?
2. Have you visited this location or the surrounding area within the last two months?

Participants who could not recognize all six starting locations or confirm recent familiarity were excluded from the main experiment, ensuring a consistent and reliable participant pool. This step was essential to minimize variability due to unfamiliarity with the tested environment. Additionally, the pre-experiment provided an opportunity for participants to become familiar with the experimental setup, including the rotating chair and Oculus Rift. This familiarization was intended to reduce any novelty effects that could affect participant comfort and ensure more reliable data collection during the main experiment.

3.3.2 Experiment

After participants completed the pre-experiment, they moved on to the main experiment. The experimenter explained the procedure to each participant using a prepared script, ensuring that everyone understood each step. This information was also provided in written form for future reference.

Since the pre-experiment took place in the same room with the same equipment, participants were already familiar with the rotating chair, Oculus Rift headset, and laptop setup. At the start of the main experiment, the experimenter briefly reintroduced the equipment to make sure everyone felt comfortable. Participants were informed that they could rotate freely in the chair as needed during the session and that they would be asked to recall and name well-known places while wearing the virtual reality goggles. A relaxation room was available in case anyone felt discomfort or nausea, and participants were reassured that they could leave the study at any time without needing to give a reason. We wanted everyone to feel comfortable and supported throughout the process.

At the beginning of each recall task, participants were virtually teleported to the respective starting location, facing north. They had the opportunity to explore their surroundings by looking around (using a closed-loop VR simulation that allowed for rotational movement only) until they felt sufficiently familiar with the location. To assist in the recall process, participants were instructed to turn towards a designated square marked on the virtual floor. This square was strategically placed so that when they oriented themselves towards it, they would automatically be facing the direction of the target area.

Once they felt oriented, the experimenter prompted participants to imagine a target area and to name as many well-known places as they could. These included a variety of landmarks such as shops, cafés, restaurants, bistros, bakeries, offices, historical sites, and monuments.

Each participant completed three recall tasks, corresponding to three different target areas. They were randomly assigned to either Group A or Group B, each with 20 participants. The specific tasks assigned to each group are shown in Tab. 3.1. After finishing each recall task, the next one began immediately, allowing for a smooth transition throughout the experiment.

Task	**Group A**	**Group B**
1st task		
Starting location	S_2	S_1
Target area	T_1	T_1
2nd task		
Starting location	S_4	S_3
Target area	T_2	T_2
3rd task		
Starting location	S_6	S_5
Target area	T_3	T_3

Table 3.1: Overview of assigned tasks for participants in Groups A and B. Each group was assigned the same target area T per recall task, but different starting locations S.

3.4 Results

This section presents the results of the experiments.

The analyses reported below were developed in an iterative and exploratory manner. Our aim was to describe how recall is organized by examining it from several complementary perspectives, including visual summaries, distance-based trends, path-length, fractile measures, and directional analyses. Some of these analyses overlap, as they address related aspects of the same underlying recall patterns. We include this broader set of analyses to show how consistent evidence was obtained across different approaches.

The statistical tests are used to quantify the strength of the observed patterns. Because the analyses were not defined in advance and several related tests were applied, we focus on the consistency of results across methods, the direction of effects, and their robustness across target areas and participant groups, rather than on individual test outcomes.

3.4.1 Visualizing Recall Sequences

Fig. 3.6 shows example trajectories recalled by participants from Groups A and B targeting the Neckarbrücke location (T_3), with starting locations S_5 and S_6, respectively. The arrows in the figure illustrate the order in which participants named landmarks at the target area. The red and green arrows represent the recall sequence for a single participant each. An arrow pointing from place X to place Y indicates that place Y was recalled directly after place X. The first place recalled is marked by an outgoing arrow, while the last place has no outgoing arrow. In addition, curved dotted lines (red and green) indicate the connection from each starting location to the first recalled landmark. Locations closer to the starting location of the participants are recalled earlier in the sequences, while locations farther away appear later in the recall sequences.

With three target areas, two starting locations per target area, and 20 subjects per starting location, we collected a total of 120 recall sequences. We denote the sequence of locations recalled by participant i from starting location S_j as $X_i^{S_j} = \left(x_{i,1}^{S_j}, x_{i,2}^{S_j}, \ldots, x_{i,l(i,S_j)}^{S_j}\right)$, and $l(i, S_j)$ represents the sequence length, therefore if $n = l(i, S_j)$ then $x_{i,n}^{S_j}$ represents the n-th named place by participant i in the sequence with starting location S_j.

Overview of Recall Sequences

Before delving into the mathematical analysis and detailed interpretation of the results, we first present Figs. 3.7 – 3.9 to provide an overview of how the recall patterns appear visually. These figures summarize the key relationships in the data: Fig. 3.7 shows the sequence positions of recalled locations relative to their distances in pixels, Fig. 3.8 illustrates the frequency of recall and the average positions of locations in the sequences, and Fig. 3.9 highlights the connection between the distance of locations from the target and how often they were recalled. Together, these visualizations offer an intuitive understanding of the results.

Distances between locations were calculated in pixel units to stay consistent with the visual representations used in the analysis. The maps were created by stitching together screenshots from Google Maps and saving them as JPEG files. Each map was carefully prepared to show the entire area around the target area

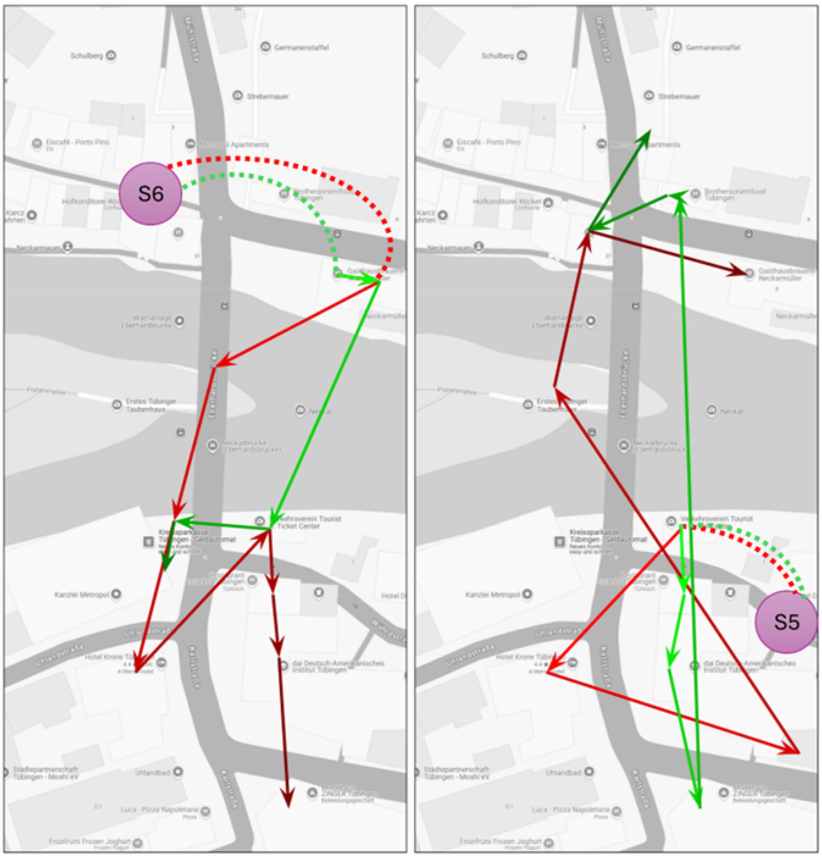


Figure 3.6: Recall sequences from two different starting locations (S_5 and S_6) to the same target area (T_3, Neckarbrücke), illustrated for two sample participants per starting location. Each trajectory is encoded using a color gradient to indicate the order of recalled locations: light red to dark red for one participant, and light green to dark green for the other. Arrows mark the direction of recall. Curved dotted lines (red and green) indicate the connection from each starting location to the first recalled landmark in the target area. The underlying map is shown in grayscale to emphasize the recall patterns. The participants recalled locations closer to their starting location first, locations further away from their starting location are recalled later in the recall sequences. Map source: maps.google.com

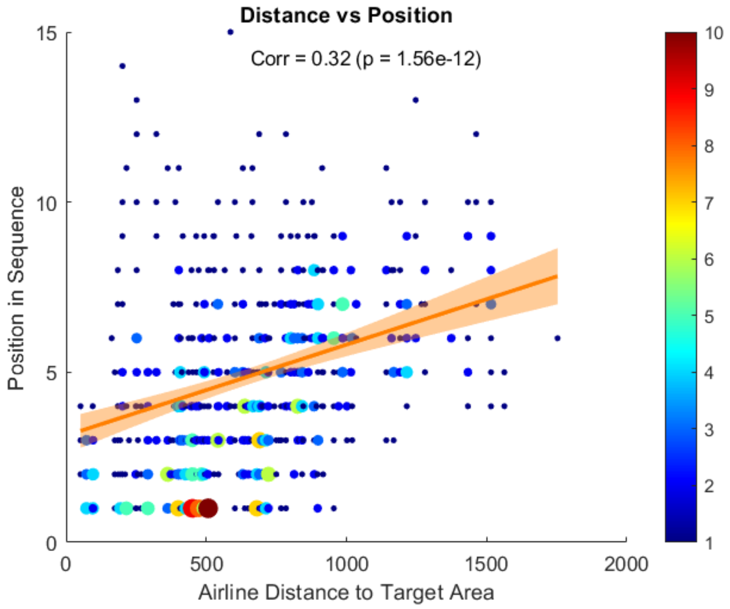


Figure 3.7: Scatter plot illustrating the relationship between the distance of each recalled location from the target area (x-axis, in pixels) and its position in the recall sequence (y-axis). Each dot represents a recalled location at a given sequence position. Dot color reflects the frequency with which that location was recalled at the same position across participants, transitioning from blue (low frequency) to red (high frequency). Similarly, dot size indicates recall frequency independent of recall position. A linear regression line with a 95 % confidence band is overlaid.

and for all maps the same scale was chosen. The screenshots were taken so that all relevant parts of the target and its surroundings were fully visible in a single image, ensuring that every recalled location mentioned by participants was within the map boundaries. The pixel coordinates of the target, starting locations, and recalled landmarks were manually extracted using Microsoft Paint. This coordinate-based method allowed for precise distance calculations between recalled locations and enabled a systematic analysis of spatial proximity patterns, maintaining consistency between the visual and numerical data.

We begin with Fig. 3.7, which presents a unified scatter plot, combining data for all six starting location - target area pairs S_j-T_k into a single figure. Each dot in the plot indicates a location that participants recalled at a given position in the recall sequence, with the x-axis showing the distance to the target area

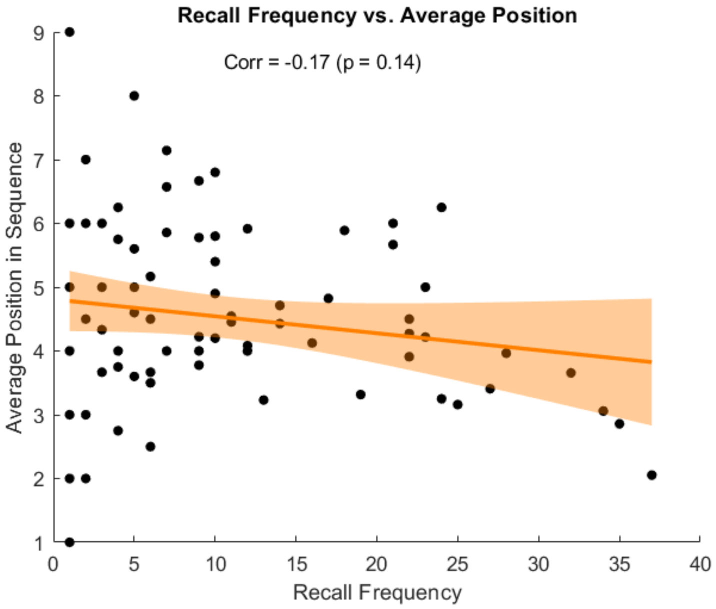


Figure 3.8: Scatter plot showing the relationship between the frequency with which a location was recalled (x-axis) and its average position within participants' recall sequences (y-axis), aggregated across all six starting locations. Each point represents a unique location. A linear regression line with a 95 % confidence band is overlaid.

(measured in pixels), i.e. $d\left(x^{S_j}_{i,l_i^{S_j}}, T_k\right)$ represents the distance of the recalled place from the sequence $X_i^{S_j}$ to the target area T_k and the y-axis representing the recall position in the sequence. The dot color reflects the frequency with which a location was recalled at a given position across participants, transitioning from blue (low frequency) to red (high frequency).

Fig. 3.7 gives an overview of recall patterns by combining data from all starting locations into one figure. This makes it easier to compare trends and see the big picture, while still showing how participants recalled locations. [1]

A linear regression line with a 95 % confidence band is overlaid. The analysis shows a significant positive correlation ($r = 0.32$, $p < 0.001$), suggesting a trend in which closer locations tend to be recalled more often at the beginning of the

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[1] For a detailed breakdown of individual recall patterns, see Appendix Fig. A.4, which presents scatter plots for each starting location–target area pair separately.

recall sequence.

Fig. 3.8 combines data from all six starting location - target area pairs S_j-T_k into a single scatter plot, showing the relationship between the frequency of location recall (x-axis) and their average position within participants' sequences (y-axis). Each dot represents a unique location named by participants. The x-axis shows the total number of times each location was recalled across all participants, while the y-axis indicates the average position of that location across all sequences.[2] A linear regression line with a 95 % confidence band is overlaid. The analysis reveals a weak, non-significant negative correlation (r = –0.17, p = 0.14), suggesting a slight tendency for frequently recalled locations to appear earlier in the sequence. However, this effect does not reach statistical significance and should be interpreted cautiously.

As shown in Fig. 3.8, the scatter plot reveals a distinct pattern: a small number of locations were recalled very frequently, whereas many other locations were mentioned only a few times. Locations with higher recall frequency tended to appear, on average, in the beginning of the recall sequences.

To formally assess this trend, we calculated the *Pearson correlation* between the distance of each recalled location from the starting point and its *position in the recall sequence*, separately for each target area. For *Holzmarkt* and *Neckarbrücke*, the correlations were statistically significant ($r = 0.40$, $p < 10^{-8}$ and $r = 0.53$, $p < 10^{-15}$, respectively), indicating that participants tended to mention *closer locations earlier* in the sequence. For *Marktplatz*, the correlation was very weak positive but not statistically significant ($r = 0.12$, $p = 0.095$). These findings provide quantitative support for the general trend observed in Fig. A.4.

This trend likely reflects a natural tendency for participants to recall common or easily remembered or prominent locations first.

The influence of spatial proximity on recall frequency is further explored in Fig. 3.9, which combines data from all six starting location – target area paris S_j-T_k into a single scatter plot. The figure represents the relationship between the distance of recalled locations from the starting location (x-axis, measured in pixels) and how often these locations were recalled (y-axis). By unifying the data,

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[2] For a detailed breakdown of individual recall patterns, see Appendix Fig. A.5, which presents scatter plots for each starting location-target area pair separately.

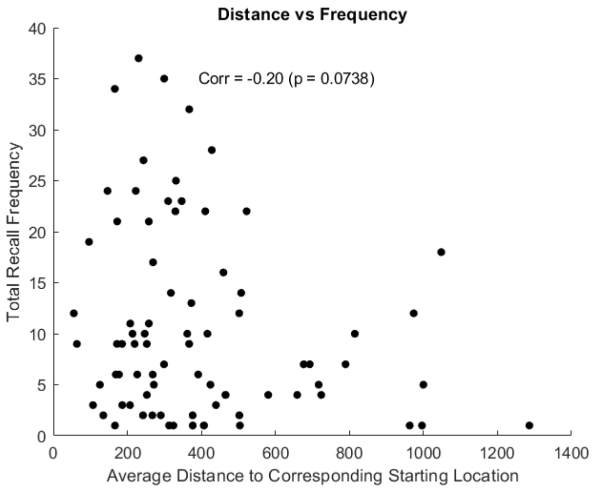

Figure 3.9: Scatter plot showing the relationship between the average distance of each recalled location from the target area (x-axis, in pixels) and the total frequency with which that location was mentioned within the first 50 positions of all recall sequences (y-axis). Each dot represents a unique location. The data combines trials from all six starting locations.

this visualization provides a comprehensive view of recall patterns across all target areas (T_1, T_2, and T_3) and both groups, A and B. [3]

The analysis shows a weak, non-significant negative correlation (r = –0.10, p = 0.40), suggesting a slight trend in which closer locations tend to be recalled more frequently, while those farther away are mentioned less often. This suggests that participants typically recall nearby places first, likely due to their proximity. However, the effect is not statistically significant and may reflect individual variability rather than a consistent recall strategy.

Interestingly, a few locations are mentioned more frequently than expected based on their distance from the target. These may represent well-known or prominent landmarks. For example, certain locations, despite being farther away, were recalled more often than closer ones. This pattern suggests the influence of familiarity on recall frequency.

The scatter plot also reveals clusters of locations at medium distances with relatively high recall frequency. These may correspond to intermediate landmarks

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[3] For a detailed breakdown of recall pattern see Appendix Fig. A.6.

that participants commonly recognized, even if they were not immediately adjacent to the target.

Together, Figs. 3.7 – 3.9 provide a comprehensive visual overview of the key recall patterns observed in the study. Fig. 3.7 highlights the progression of recall sequences, with participants generally recalling closer locations first. Fig. 3.8 reveals how frequently locations were mentioned and their typical positions in recall sequences, emphasizing the tendency for commonly recalled locations to appear earlier. Finally, Fig. 3.9 illustrates the relationship between distance from the target and recall frequency, showing that while proximity plays a major role, certain prominent or familiar landmarks are recalled more often regardless of distance. These visualizations lay the foundation for a deeper mathematical and analytical examination of the data, highlighting the role of spatial proximity, familiarity, and recall patterns.

Analysis of Recall Sequences

For the following analysis, we focus on the sequences $X_i^{S_j} = \left(x_{i,1}^{S_j}, x_{i,2}^{S_j}, \ldots, x_{i,5}^{S_j}\right)$, representing the first five locations named by each participant i from a given starting location S_j. This subset allowed us to compute the lengths of all possible paths for each participant enabling us to model all potential routes composed of the first five locations within each sequence $X_i^{S_j}$.

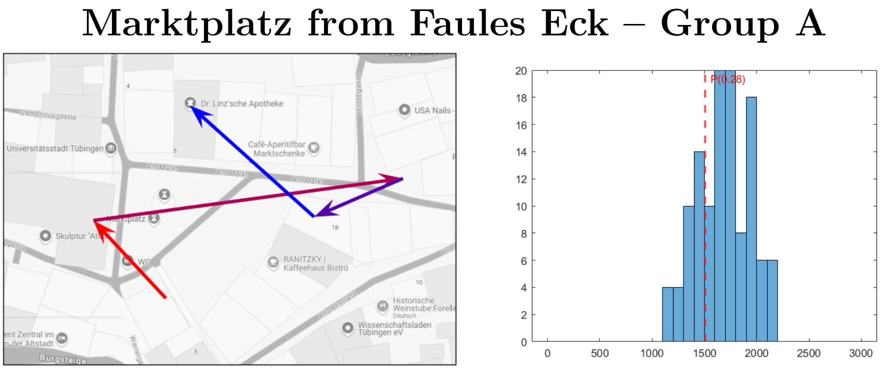
The length $\left|X_i^{S_j}\right|$ of a sequence was computed as:

$$\left|X_i^{S_j}\right| = \sum_{k=1}^{l_i^{S_j}-1} d\left(x_{i,k}^{S_j}, x_{i,k+1}^{S_j}\right) \tag{3.1}$$

where $l_i^{S_j}$ denotes the total number of locations in the sequence (in this case, five), and $d(p,q)$ is the function that measures the Euclidean distance between two consecutive points in pixel coordinates:

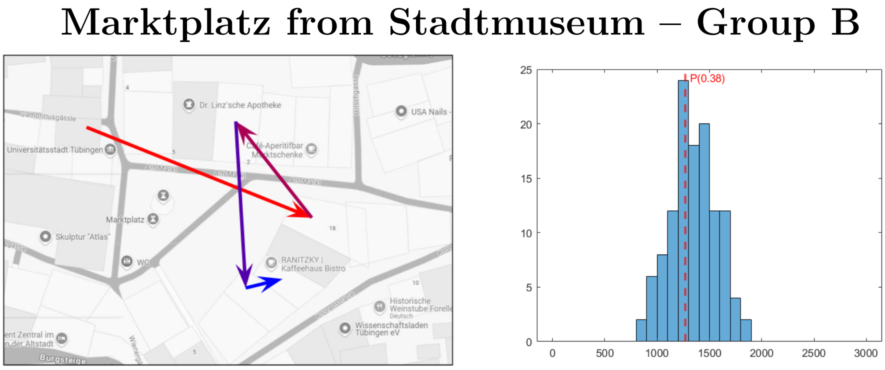
$$d(p,q) = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2} \tag{3.2}$$

The following figures (Figs. 3.10 – 3.15) illustrate the analytical procedure by showing path visualizations from selected participants across different starting location and target areas. In each case, only the first five recalled locations were



Marktplatz from Faules Eck – Group A

Figure 3.10: *Left*: Scaled-down map of the recalled locations for participant 2 from Group A, with target area Marktplatz and starting location Faules Eck. The order of recalled locations is indicated by the arrows. Only the first five recalled locations are shown. Map source: maps.google.com *Right*: Histogram of the path lengths of all path combinations using the five recalled locations of participant 2. Path lengths are given in pixels with respect to the original-sized map. Length of path representing the recalled sequence of the participant marked with dotted red line and corresponding to the 28th percentile.



Marktplatz from Stadtmuseum – Group B

Figure 3.11: *Left*: Scaled-down map of the recalled locations for participant 2 from Group B, with target area Marktplatz and starting location Stadtmuseum. The order of recalled locations is indicated by the arrows. Only the first five recalled locations are shown. Map source: maps.google.com *Right*: Histogram of the path lengths of all path combinations using the five recalled locations of participant 2. Path lengths are given in pixels with respect to the original-sized map. Length of path representing the recalled sequence of the participant marked with dotted red line and corresponding to the 38th percentile.

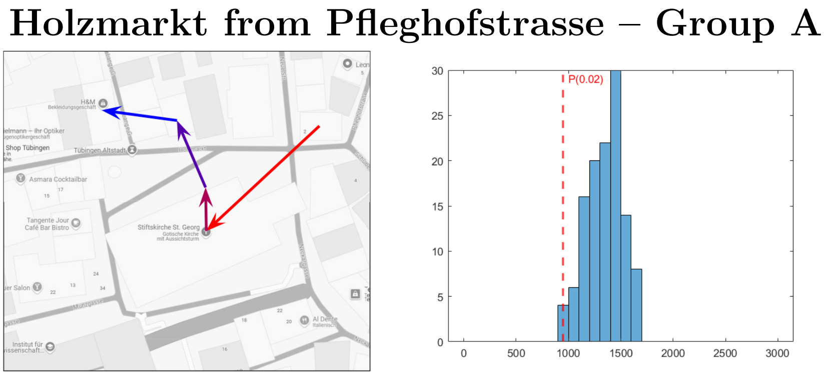


Figure 3.12: *Left*: Scaled-down map of the recalled locations for participant 7 from Group A, with target area Holzmarkt and starting location Pfleghofstrasse. The order of recalled locations is indicated by the arrows. Only the first five recalled locations are shown. Map source: maps.google.com *Right*: Histogram of the path lengths of all path combinations using the five recalled locations of participant 7. Path lengths are given in pixels with respect to the original-sized map. Length of path representing the recalled sequence of the participant marked with dotted red line and corresponding to the 2nd percentile.

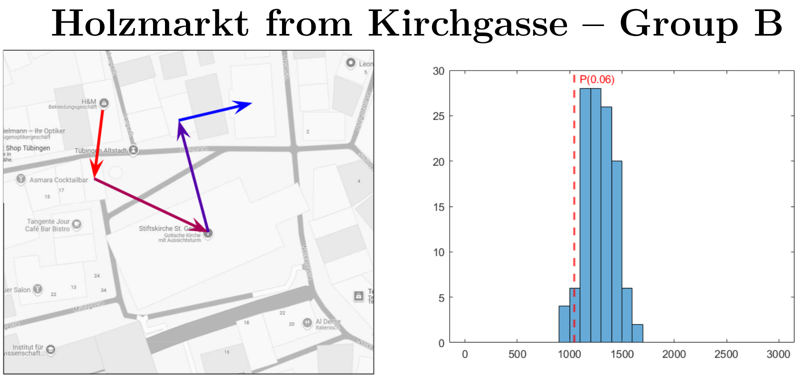


Figure 3.13: *Left*: Scaled-down map of the recalled locations for participant 9 from Group B, with target area Holzmarkt and starting location Kirchgasse. The order of recalled locations is indicated by the arrows. Only the first five recalled locations are shown. Map source: maps.google.com *Right*: Histogram of the path lengths of all path combinations using the five recalled locations of participant 9. Path lengths are given in pixels with respect to the original-sized map. Length of path representing the recalled sequence of the participant marked with dotted red line and corresponding to the 6th percentile.

Neckarbrücke from Neckargasse – Group A

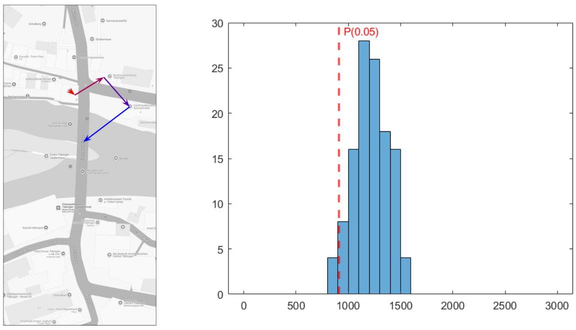


Figure 3.14: *Left*: Scaled-down map of the recalled locations for participant 3 from Group A, with target area Neckerbrücke from Neckergasse. The order of recalled locations is indicated by the arrows. Only the first five recalled locations are shown. Map source: maps.google.com *Right*: Histogram of the path lengths of all path combinations using the five recalled locations of participant 3. Path lengths are given in pixels with respect to the original-sized map. Length of path representing the recalled sequence of the participant marked with dotted red line and corresponding to the 5th percentile.

Neckarbrücke from Wöhrdstrasse – Group B

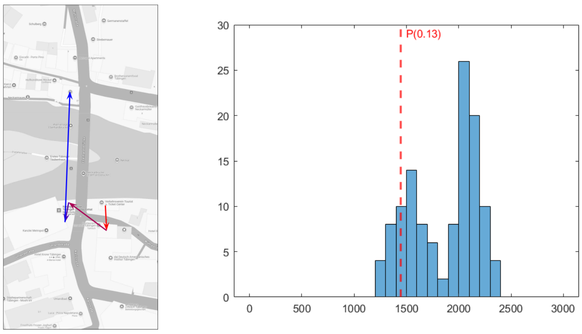


Figure 3.15: *Left*: Scaled-down map of the recalled locations for participant 10 from Group B, with target area Neckerbrücke from Wohrdstrasse. The order of recalled locations is indicated by the arrows. Only the first five recalled locations are shown. Map source: maps.google.com *Right*: Histogram of the path lengths of all path combinations using the five recalled locations of participant 10. Path lengths are given in pixels with respect to the original-sized map. Length of path representing the recalled sequence of the participant marked with dotted red line and corresponding to the 13th percentile.

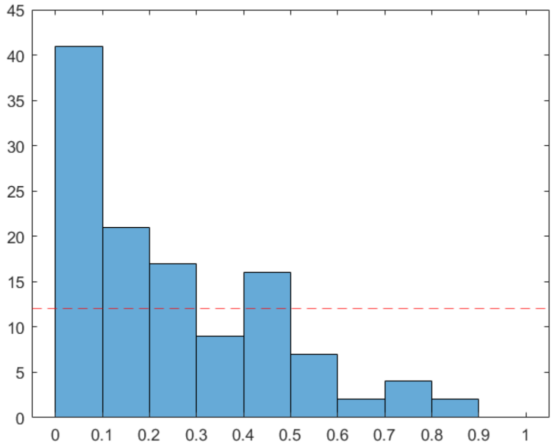


Figure 3.16: **Histogram of fractile values for path lengths chosen by participants in Groups A and B.** For each participant, the length of their recalled path (based on the first five named locations) was compared to the distribution of all possible paths through those same five locations, yielding a fractile score. The histogram is divided into 10 bins, showing how frequently participants' selected paths fall within different portions of the possible distribution. A red horizontal line indicates the expected frequency under a uniform (random) distribution. This histogram suggests that participants consistently selected more efficient (i.e., shorter) paths than would be expected by chance.

used, and all possible permutations of those locations were computed. The resulting path lengths are presented as histograms, where each bin corresponds to a range of path lengths. The length of the participant's actual recalled path is also shown within each histogram together with the percentile it falls into among the lengths of all possible paths. If the recalled path is among the shortest possible, it appears in the first (leftmost) bin; in contrast, a randomly ordered path would more likely fall within the central bins of the distribution.

The following analyses further examine the structure of recall. Given their exploratory nature, we focus on whether patterns are consistent across different target areas and groups, rather than on individual significant results.

Fractile Analysis of the Lengths of Initial Recall Path

To further understand participants' recall patterns, we performed a fractile analysis of their initial recall sequences, focusing on path continuity and the role of spatial proximity in recall order. Path length was used as a measure of how smoothly recall progressed through the target area: shorter paths indicate that consecutively recalled locations were spatially close to one another, whereas longer paths reflect larger spatial jumps between successive recalled locations. If recall order were largely independent of spatial structure, the resulting path lengths would be similar to those obtained from random permutations of the same locations.

Specifically, we examined the sequence length of each participant's first five named locations and compared it to the distribution of path lengths obtained from all possible permutations of those same five locations. This approach allowed us to determine whether participants tended to choose shorter, more typical paths or longer, less common ones compared to other potential routes.

For each subject i, we computed the lengths of the paths for all permutations of the sequence $X_i^{\prime S_j}$ of length 5, resulting in $5! = 120$ possible paths per subject. This resulted in a subject-specific distribution of possible path lengths, from which we determined the fractile value of each participant's recalled sequence $X_i^{\prime S_j}$.

Fig. 3.16 presents a histogram of these fractiles for both experimental groups (A and B), with fractiles binned into deciles. As the figure shows, the majority of participants chose paths that fall into the lower fractiles, with a strong concentration near 0.1. This indicates that participants often selected paths among the shortest possible options, suggesting a preference for efficiency in their mental mapping.

Implications of Path Length Choices for Recall Efficiency

The sharp drop in frequency as the fractiles increase suggests that very few participants chose paths that were longer than average. This pattern supports the idea that spatial proximity is key in recall choices, with only a handful of participants choosing for less direct or less intuitive routes. Overall, this trend indicates a general preference for efficient, shorter paths, while a few participants deviated from this pattern, possibly due to personal familiarity with certain locations or other individual cognitive factors.

Statistical Analysis of Proximity Effects in Landmark Recall

To better describe the structure of participants' recall sequences, we analyzed the fractile values from Groups A and B. The main goal of these analyses was to test whether recall behavior followed a proximity-based strategy.

χ^2 Tests Against a Uniform Distribution For each group, we tested whether the distribution of fractile values deviated from a uniform distribution. Fractile values were binned into ten equal-width intervals. Under the null hypothesis (H_0), fractiles are uniformly distributed, which would be expected if recall order did not systematically favor shorter or longer paths. The alternative hypothesis (H_1) stated that the fractile distribution deviates from uniformity.

For both groups, the χ^2 tests rejected the null hypothesis, $\chi^2(9, 200) = 59.78$, $p < 0.001$ for Group A, and $\chi^2(9, 200) = 47.54$, $p < 0.001$ for Group B. These results demonstrate a strong deviation from a balanced recall strategy. In both groups, participants disproportionately selected recall sequences corresponding to lower fractiles, indicating a systematic preference for shorter paths. This finding support that participants favoured a proximity-driven recall organization.

χ^2 Tests Between Groups To examine whether the fractile distributions differed between Groups A and B, we conducted an additional χ^2 test comparing the two distributions directly. The null hypothesis (H_0) stated that both groups were drawn from the same fractile distribution.

This test yielded a significant result, $\chi^2(9, 200) = 17.80$, $p = 0.0376$, indicating a difference between the fractile distributions of Groups A and B.

Thus, although the two groups differ in their fractile distributions, both show the same overall pattern of proximity-based recall, with a strong bias toward shorter paths. The group difference therefore reflects variation in how this general recall strategy is expressed, rather than indicating a different or group-specific recall mechanism.

Definition of Distance Measures: $d_i^{S_j}$ and $\bar{d}_i^{S_j}$

We calculated two different average distances to better understand the recall patterns for each participant. The first measure, $d_i^{S_j}$, represents the average distance of all named locations at position i in the sequence $X_i^{S_j}$ from the actual starting point in the experiment S_j. This gives us an understanding of how far participants tended to recall places in relation to where they began.

The second measure, $\bar{d}_i^{S_j}$, helps us understand whether participants with different starting points tend to recall similar places, despite having different perspectives. Specifically, it calculates the average distance of all named locations at position i in the sequences $X_i^{S_j}$ from the starting location of the other group, $S_{j'}$, associated with the same target area T_k. Comparing distances from this alternate starting point $\bar{d}_i^{S_j}$ helps us to understand whether recall patterns are influenced by the specific spatial orientation and the starting locations.

Calculation of Distance Measures for Recall Sequences

To calculate the spatial distances for each recalled location, we used an auxiliary function that averages the distances across all sequences starting from the same location. Specifically, for each recall position n, we computed:

$$\hat{d}_{i,n}^{S_j} = \frac{1}{L} \cdot \sum_{i=1}^{L} d\left(S_j, x_{i,n}^{S_j}\right) \tag{3.3}$$

Here, L is the number of sequences for each starting location (in our case, 20), S_j is the starting location, and $d\left(p, q\right)$ is the distance between two points, as defined in Eqn. 3.2.

From these distances, we derived two average measures:

- the average distance from the current starting location $d_n^j = \hat{d}_{i,n}^{S_j}$
- the average distance from the *opposite* starting location $\bar{d}_n^{j'} = \hat{d}_{i,n}^{S_{j'}}$, where

$$j' = \begin{cases} j+1 & \text{if } j \text{ odd} \\ j-1 & \text{if } j \text{ even} \end{cases}$$

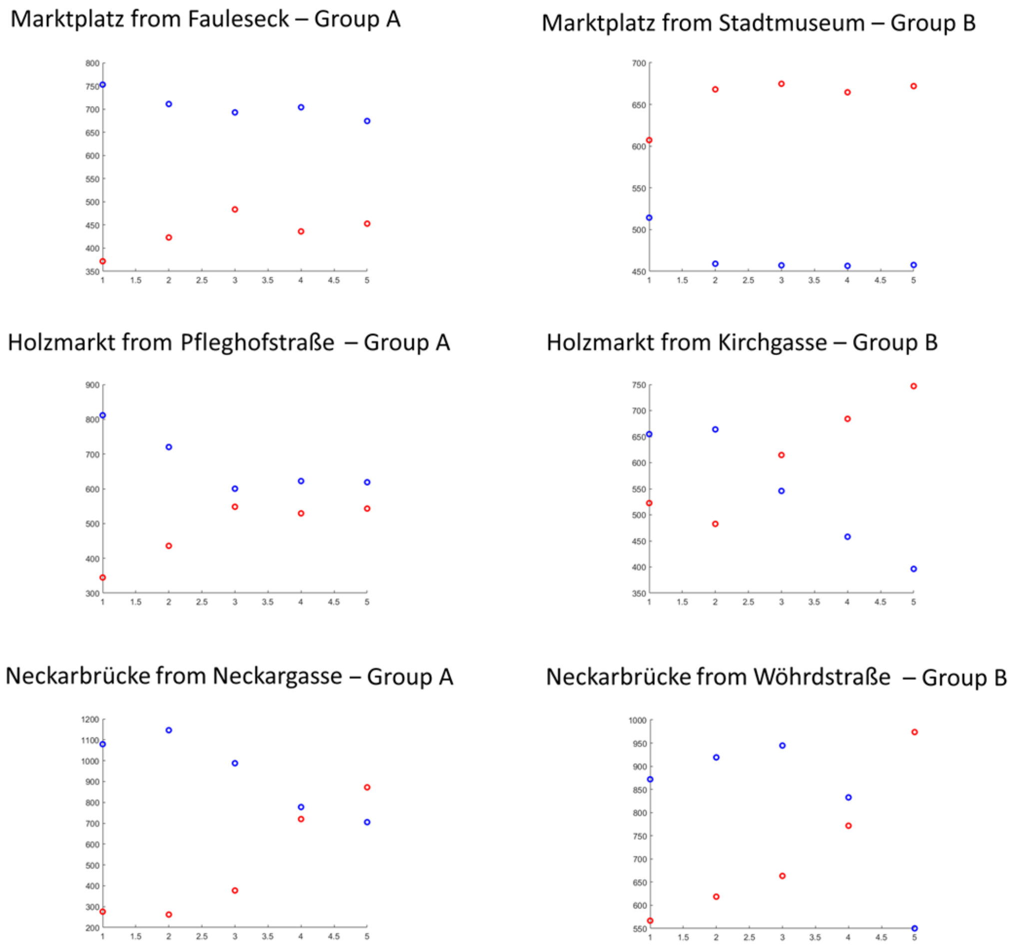


Figure 3.17: **Average Distances of Recalled Locations by Sequence Position for Different Starting Points.** The x-axis represents the position of each recalled location within the recall sequence, while the y-axis indicates the average distance of these locations from the starting location (in pixels). The red markers represent the average distances from the participants' actual starting location to the recalled locations, whereas the blue markers represent the average distances from the alternate starting location used by the other group to the recalled locations.

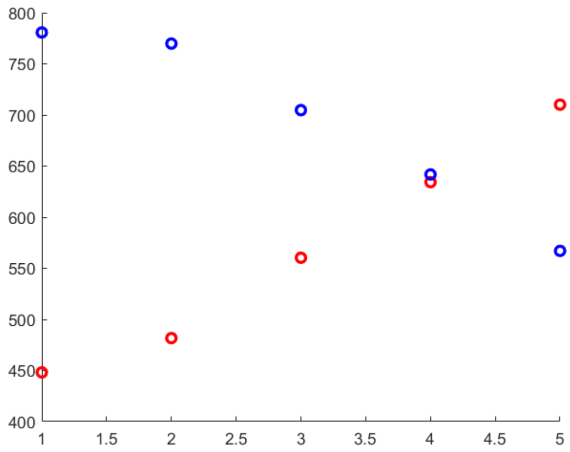


Figure 3.18: **Average Distances of Recalled Locations by Sequence Position Across All Participants.** The x-axis represents the position of each recalled location in the sequence (positions 1 through 5), while the y-axis shows the average distance of these locations from the starting location (in pixels). The red markers represent the average distances from the participants' actual starting location to the recalled locations, while blue markers represent the average distances from the alternate starting location used by the other group.

Recall Pattern Trends by Position in Sequence

To analyze recall patterns, we examined the average distance of recalled locations at each position in the recall sequence, as shown in Fig. 3.17. Here we limit the analysis to the first five recalled locations for each recall sequence. The x-axis represents the position of each recalled location in the sequence (e.g., from 1 to 5), while the y-axis shows the average distance of the recalled locations from the starting location (in pixels). The red dots indicate the average distances from the actual starting locations, while the blue dots represent average distances from the starting points of the alternate groups to the same recalled locations, respectively.

If recall is not spatially organized, the red and blue graphs should look similar. If recall is spatially organized, clear differences or trends between them should appear.

In this figure, we observe a trend where the average distance from the target area (red dots) generally increases as the recall sequence progresses. This suggests that participants tend to recall locations closer to their actual starting point initially and then move on to more distant ones, reflecting an efficient recall strategy guided by spatial proximity.

Similarly, the blue dots show a decreasing trend and appear to mirror the red dots. This pattern also reflects spatial proximity, as the alternate starting locations are positioned on the opposite side of the target. The mirrored trend highlights how the recall of locations is strongly influenced by their relative distances to either starting point, with participants recalling locations progressively closer to the alternate starting point as they move through the sequence.

Position-Based Recall Strategies and Starting Point Influence

Fig. 3.18 shows the average distances d_i and $\bar{d_i}$ of recalled locations based on their position in the recall sequence, averaged across all participants and all starting location - target area pairs S_j -T_k. The x-axis represents the recall position (1 through 5) and the y-axis shows the average distance of the recalled locations from the target area in pixels. The red markers represent distances from the actual starting point, while the blue markers represent distances from the starting point used by the other group. The average distances are computed as follows:

$$d_i = \frac{1}{L} \cdot \sum_{l=1}^{L} d_i^l, \tag{3.4}$$

$$\bar{d_i} = \frac{1}{L} \cdot \sum_{l=1}^{L} \bar{d_i^l} \tag{3.5}$$

with $L = 6$ as we have 6 different starting locations.

As shown in the Fig. 3.18, the average distance d_i of recalled locations tends to increase as their position in the sequence progresses. This suggests that participants typically recall locations that are closer to their starting point first, then gradually move on to more distant locations—indicating an efficient, proximity-based recall strategy. In contrast, the blue markers, which represent average distances $\bar{d_i}$ (from an alternate starting point), show a different trend, forming a decreasing pattern. This inverse trend suggests that recall patterns are influenced by the specific starting position, with participants mentally organizing recalled

Target Area	**Hotelling's T^2**	**F(2, 37)**	**p-value**
Marktplatz	5.9110	2.8777	0.0689
Holzmarkt	8.7002	4.2356	$0.0221 < 0.05$
Neckarbrücke	5.5379	2.6961	0.0807

Figure 3.19: Results of the two-sample Hotelling test comparing progression vectors between Groups A and B for each target area. All differences are statistically significant.

locations in a way that aligns with their initial spatial orientation.

Together, these trends indicate that participants' recall behavior is guided by spatial proximity, with distinct patterns emerging based on the starting location's influence on recall order and distance.

3.4.2 Directional Progression Vectors in Recall Sequences

To further explore directional consistency in participants' recall behavior, we computed progression vectors for each participant based on the gradient of a regression plane fitted to their recalled location sequence. This analysis was used to capture the overall direction of mental movement across the recalled landmarks.

We used the first five (or fewer) recalled locations for each participant. The first recalled location was referenced relative to the starting position while all other landmarks were calculated *relative to the previously mentioned landmark* that is, the second location was referenced with respect to the first recalled location, and third location with respect to the second location and so on.

The gradient for each participant was estimated using a least-squares solution of the overdetermined linear system $Xg = I$, where X is the matrix of relative position differences and I the sequence index vector.

Participants were grouped into Group A and Group B for each target area (Marktplatz, Holzmarkt, and Neckarbrücke), and their resulting direction vectors were visualized. Vectors for Group A are shown in black, and for Group B in green (see Figures 3.20–3.22).

Two-Sample Hotelling Test For further analysis the Hotelling test was applied to the two-dimensional progression vectors derived from participants' recall sequences. The null hypothesis states that the mean progression vectors of Group A and Group B are equal, indicating no systematic difference in directional recall patterns between different starting location. The alternative hypothesis states that the group mean vectors differ, implying that starting location influences the overall direction of mental progression during recall. The results of the two-sample Hotelling test are summarized in Table 3.2. The findings indicate a directional difference between the two participant groups for the target areas, even when progression is assessed solely on the basis of the recalled landmarks. For the target area Holzmarkt, a statistically significant difference was observed, whereas for Marktplatz and Neckarbrücke the results did not reach statistical significance, although clear trends are apparent. Overall, this pattern supports the hypothesis that participants follow non-random, group-consistent paths in their mental recall sequences, independently of their virtual environment orientation.

The progression vector analysis in Figs. 3.20 – 3.22 includes the initial vector from the starting location to the first recalled landmark. This initial step contributes substantially to the observed group-level differences. This methodological difference explains why the recall sequence visualizations show less clear group differences, whereas the progression vector analysis show a stronger effect.

Correlation Analysis: Place Consensus Over All Target Areas

To investigate the degree of overlap in recalled landmarks between participants, we performed a correlation analysis based on binary vectors indicating which locations were named by each subject. Each subject's recall sequence was transformed into a 0/1 vector, with ones marking the presence of a specific named location. This allowed us to compute pairwise correlations between subjects, providing a measure of place consensus – that is, how similarly different individuals recalled the same landmarks.

We first observed that no common landmarks were recalled across the three target areas. In other words, participants mentioned completely distinct sets of places depending on the target area they were assigned. Below is the list of all

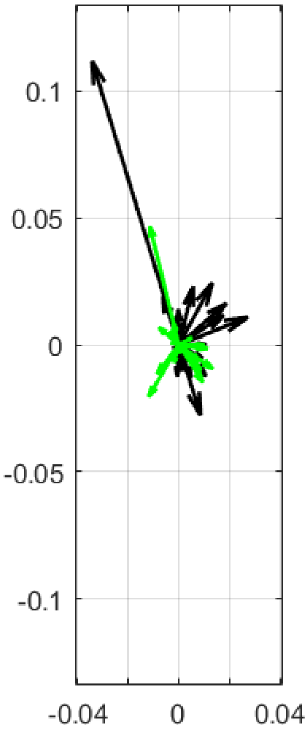


Figure 3.20: Progression vectors for Group A (black) and Group B (green) at target area Marktplatz.

landmarks named across subjects for each target area:

- **Marktplatz:** *Rathaus, Weinhaus Beck, vom Fass, Apotheke, Gemeinde Lamm, Sparkassenautomat, Ernstings Family, Marktschenke, Crepe, FotoMarkt, Volksbank, Ranitzky, Jesus Live, Antiquitäten, Silberburg, Lichtenstein, Whisky, Samarkand, Rewe Chocolatier, WC, Fountain Marktplatz, Covid Testcenter Markt, Chez Michel, Stairs Marktplatz, ProOptik, Marquart, Alte Kunst*
- **Holzmarkt:** *Stiftskirche, Klassische Münzen, Tangente Jour, Confiserie Donum, Bakery, WMF, H&M, Figo, Osiander, Tchibo, Apollo Optik, New Yorker, Vodafone Holzmarkt, Lush, Fountain Holzmarkt, Fruits And Veggie Market, Stairs Holzmarkt, Alte Aula, Balloon Fee, Buchhandlung Antiquariat*

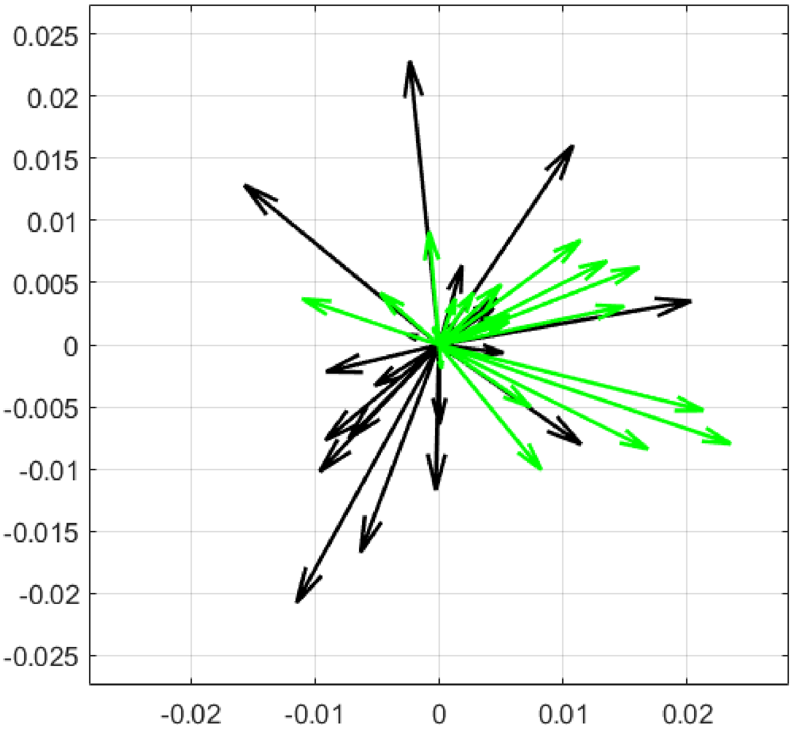


Figure 3.21: Progression vectors for Group A (black) and Group B (green) at target area Holzmarkt.

- **Neckarbrücke:** *Ice Cream Shop, Bakery Neckar, Italian Restaurant, Chinese Restaurant, Telekom, Falafel, El Chico, Neckarmüller, Bus Stop 1, Vodafone Neckarbrücke, Neckarinsel, Bus Stop 2, Osiander Neckar, Sparkassenautomat Neckar, Sparkasse, Bus Stop 3, Traffic Light, Hotel Krone, Cafe Ludwig, Uhlandbad, Cafe L, Commerzbank, Zinser, Cafe Lieb, Rutter, DAI, Istanbul, Shoe Shop, Tourist Info, Primer, Bridge, Asia Food*

The resulting correlation matrix showed a clear pattern. Participants recalling locations related to the same target area had correlations ranging from near zero to moderately positive values, indicating some overlap in the places they recalled. In contrast, correlations between participants from different target areas were consistently negative and close to zero, showing that each target area led to largely unique sets of recalled landmarks.

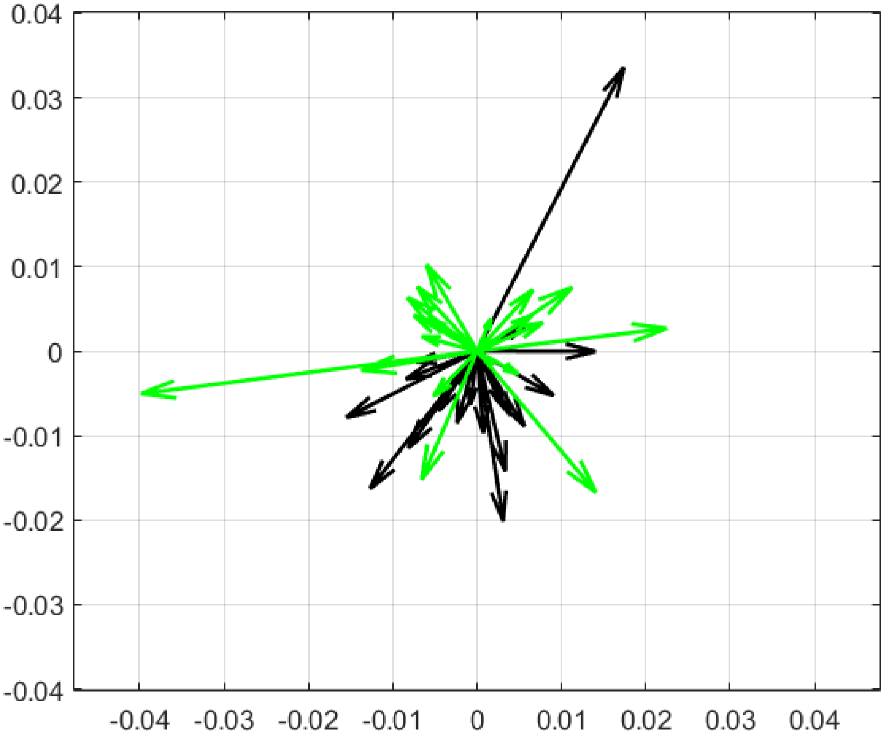


Figure 3.22: Progression vectors for Group A (black) and Group B (green) at target area Neckarbrücke.

To statistically evaluate whether the two starting-location conditions (groups A and B) within each target area differed in the likelihood of recalling specific landmarks, overall χ^2 tests of independence were performed on the place-consensus matrices. None of these tests reached statistical significance, indicating no systematic dependence between starting condition and landmark recall. Specifically, for target area Marktplatz, $\chi^2(1, N = 1080) = 0.00$, $p = 0.945$, $\phi = 0.00$; for target area Holzmarkt, $\chi^2(1, N = 800) = 0.15$, $p = 0.702$, $\phi = 0.01$; and for target area Neckarbrücke, $\chi^2(1, N = 1280) = 2.10$, $p = 0.148$, $\phi = 0.04$.

Because landmark recall frequencies did not depend on starting location, we conclude that participants in both conditions recalled the same imagined target area. In other words, the content of recall—that is, which landmarks were named—was consistent across groups. Differences between groups appeared mainly in the order and spatial progression of recalled locations. This pattern suggests that participants accessed a shared cognitive representation of the target environment, but mentally traversed it along different imagined paths.

3.5 Discussion

Overview and Key Findings

The aim of this study was to examine how participants recalled spatial information when navigating from different starting locations in a virtual environment. The results show a proximity-based recall strategy: participants tended to list nearby landmarks first, and the recall order was influenced by their starting location. However, two effects can be distinguished: while later recalls followed spatial proximity, the first recalled landmark often reflected an imagined arrival viewpoint based on the starting position.

Efficiency in Recall and Proximity-Based Strategy

The fractile analysis shown in Fig. 3.16 supports the influence of starting location on recall efficiency. Most participants chose paths that fell into the lower fractiles, meaning they generally recalled locations in an efficient order — often following the shortest possible routes. This indicates a proximity-based recall strategy, where participants focused on nearby locations first to minimize travel distance. A few participants showed less efficient recall, reflected by higher fractile values, which may be explained by personal familiarity with certain landmarks or individual recall strategies.

The results of the χ^2 tests further support this interpretation. Both groups showed clear deviations from a uniform distribution, confirming that recall was not random but followed an organized pattern based on spatial proximity. The significant difference between Groups A and B in the χ^2 comparison also shows that starting location had a measurable effect on how participants organized their recall, leading to distinct spatial recall patterns across groups.

Role of Proximity in Shaping Recall

Fig. 3.17 and Fig. 3.18 provide further evidence of the effect of proximity on recall. In these figures, the red markers, representing the distances with respect to the actual starting locations, show a clear trend of increasing distance along the recall sequence. This indicates that participants first recalled landmarks close to their starting point and then moved on to more distant ones. In contrast, the blue markers, representing distances with respect to the alternate starting locations, show inconsistent or decreasing trends. This demonstrates that recall was strongly tied to participants' actual spatial orientation, as recalculated distances from alternate starting points did not reflect the outward recall pattern.

Overall, the results show that proximity and starting location played a key role in recall strategy. The order in which participants recalled landmarks was closely linked to their initial viewpoint, highlighting that spatial memory depends not only on recognizing landmarks but also on the spatial viewpoint from which recall begins.

Directional Structure in Recall Sequences

To complement the proximity-based results, we examined the directional consistency of participants' recall behavior by calculating progression vectors from their sequences of recalled locations. Each sequence was expressed in relative steps: the first recalled location was defined in relation to the starting point, and each following location was defined relative to the previous one. This method made it possible to estimate the overall direction of mental movement, independent of the fixed starting position in the virtual environment.

The regression gradient of each sequence was used to compute a progression vector that represents the main direction of spatial change during recall. A two-sample Hotelling's T^2 test was then used to compare the average progression vectors between Groups A and B for each target area.

Although individual sequences showed directional structure, the comparisons between groups did not reveal consistent or strong group-specific differences. This suggests that while recall was spatially organized beyond simple proximity effects, it did not follow distinct directional patterns tied to starting location. The presence of directional trends even when excluding the VR starting point indicates that participants mentally traversed the environment in a structured manner. Overall, these findings further support the conclusion that spatial recall is systematic rather than random, but not governed by stable group-specific directional strategies.

Place Consensus and Landmark Overlap

In addition to the spatial progression structure, we examined whether participants from the same target-location group tended to recall the same landmarks — referred to as *place consensus*. Each participant's recall was converted into a binary vector covering all recalled landmarks, and pairwise correlations between these vectors were calculated to measure recall similarity. The resulting correlation matrix showed moderate to high agreement among participants recalling the same target area, while correlations between different targets were close to zero or slightly negative.

The absence of overlap across different target areas was expected, as the targets were chosen from separate areas of the city and therefore produced distinct sets of recalled landmarks. More importantly, statistical testing confirmed that the consensus *within* each target group was strong. χ^2 tests of independence on the place-consensus matrices showed that the probability of recalling a particular landmark did not differ between the two starting conditions within each target group. This indicates that participants shared a common mental representation of the same target environment. Specifically, for Marktplatz: $\chi^2(1, N = 1080) = 0.00$, $p = 0.945$, $\phi = 0.00$; for Holzmarkt: $\chi^2(1, N = 800) = 0.15$, $p = 0.702$, $\phi = 0.01$; and for Neckarbrücke: $\chi^2(1, N = 1280) = 2.10$, $p = 0.148$, $\phi = 0.04$. Because the choice frequencies did not depend on the starting point, we can conclude that both groups recalled the same imagined target area. This shared recall content reflects a stable, long-term spatial representation of the environment.

At the same time, earlier analyses showed that the sequence and directional progression of recall differed systematically between the two starting-location conditions. This dissociation suggests that spatial recall works on two representational levels: a long-term memory system that stores the stable structure of familiar places (including their spatial and semantic relationships), and a working-memory process that guides the dynamic traversal of this structure during recall. In this view, the place consensus found within target groups reflects access to shared long-term knowledge of the environment, while the different recall sequences result from separate, short-term working-memory paths through that shared representation. This interpretation aligns with the distinction proposed by Röhrich et al. (2014), where long-term representational memory provides the stored map of places, and working memory controls the moment-to-moment direction of recall.

Broader Implications

These findings provide strong evidence that spatial context influences recall patterns, showing that proximity plays a key role in how participants access and organize spatial information in memory. Unlike previous studies such as Hirtle and Jonides (1985), which focused on conceptual clustering, our results highlight the role of physical proximity in shaping recall. Although the first recalled landmark often reflected the imagined starting viewpoint, subsequent recalls tended to follow spatial proximity, indicating that spatial recall is not random but follows an organized, proximity-based structure.

Our findings also extend the understanding of spatial recall beyond pathological cases such as those studied by Bisiach and Luzzatti (1978). While their work showed impaired spatial recall in patients with unilateral neglect, our results demonstrate that even healthy individuals are strongly influenced by spatial context when organizing and recalling spatial information. Using virtual reality, we created a controlled yet realistic environment to observe how starting positions influenced recall strategies in familiar urban settings.

More specifically, the results suggest that consensus and proximity effects likely reflect stable long-term representations of familiar landmarks and their spatial relationships. In contrast, the direction of progression during recall appears to involve a working-memory process that guides movement through this stored structure. In this view, long-term memory provides the overall spatial framework of what can be recalled, while working memory shapes how this framework is accessed and the direction in which recall unfolds. This interpretation aligns with the distinction proposed by Röhrich et al. (2014), where representational memory provides the map-like base and working memory enables its temporary, task-driven reactivation.

This interpretation is also consistent with earlier work of Couclelis, Golledge, Gale, and Tobler (1987) on the anchor-point organization of cognitive maps. According to the anchor-point hypothesis, long-term spatial memory is structured around highly familiar and personally important locations, such as home or work, which serve as reference points anchoring surrounding regions of space. Rather than being stored as a uniform metric representation, spatial knowledge is organized into regions with stronger internal coherence than relations between regions. From this perspective, the proximity-based recall patterns observed here may reflect access to such anchored regions in long-term memory. Recall trajectories may begin within a region centered on a salient reference location and then progress outward or toward other anchored regions, producing orderly sequences that resemble movement through a structured cognitive space.

Additionally, the differences between the actual starting locations and the recalculated distances from alternate starting locations help to clarify how spatial updating may operate during recall. Unlike the work of Loomis, Klatzky, and Giudice (2013), which focuses on the effects of continuous movement in spatial imagery, our findings show that even static starting positions can produce patterns consistent with mental travel. Participants seemed to mentally move through the environment as they recalled each landmark, producing sequences that resemble a continuous journey toward the target. This process is similar to the "mental scanning" phenomenon described in classic imagery research, where spatial distance is mentally represented as temporal scanning time. The presence of these travel-like recall sequences suggests that participants did not simply retrieve individual landmarks from memory but instead engaged in an internally guided navigation through representational space—consistent with theories of mental travel and spatial updating proposed by Loomis et al. (2013). In this sense, spatial recall can be interpreted as a form of simulated navigation, in which long-term spatial knowledge is accessed and dynamically organized through working-memory processes.

Future Directions

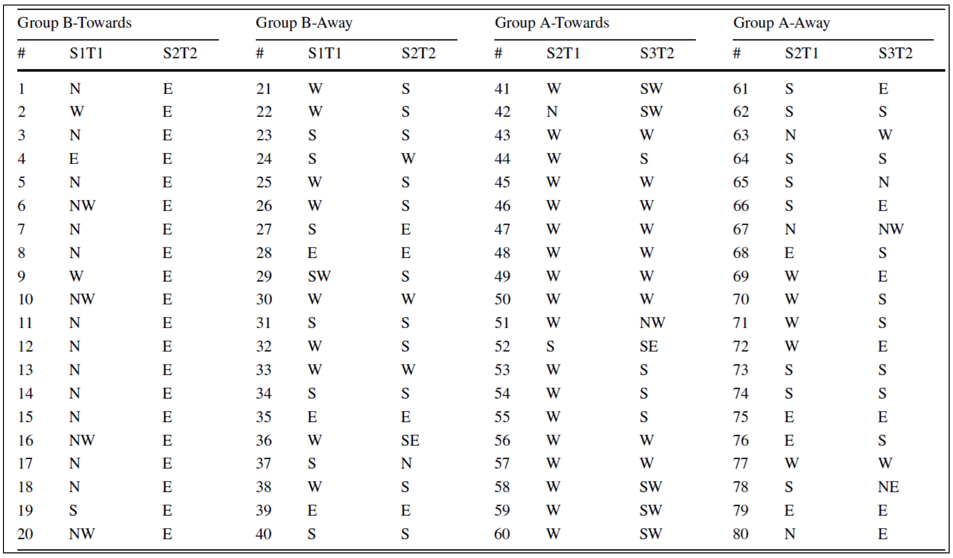
In future studies, we could investigate spatial recall using less familiar locations or entirely new environments. By asking participants to learn an unfamiliar place first, we could observe how the learning process affects recall structure compared to the familiar environment used in this study. Additionally, we could provide participants with tangible recall tools — such as a camera, desk, and a set of cards — while they remain in VR. Participants could use these tools to physically select and arrange locations on paper, representing their recall sequence. This setup would help us understand the priority in which they choose landmarks, offering more detailed insights into the cognitive processes behind spatial recall.

Conclusion

In conclusion, this study shows that starting locations significantly influence how participants recall landmarks in a virtual environment. Recall sequences were strongly shaped by spatial proximity, with participants tending to move from locations near their starting position toward more distant ones. These findings highlight that spatial recall is closely linked to participants' initial spatial orientation and perspective. Overall, the results advance our understanding of spatial cognition by emphasizing the importance of starting context, spatial proximity, and cognitive processes in how individuals organize and recall spatial information.

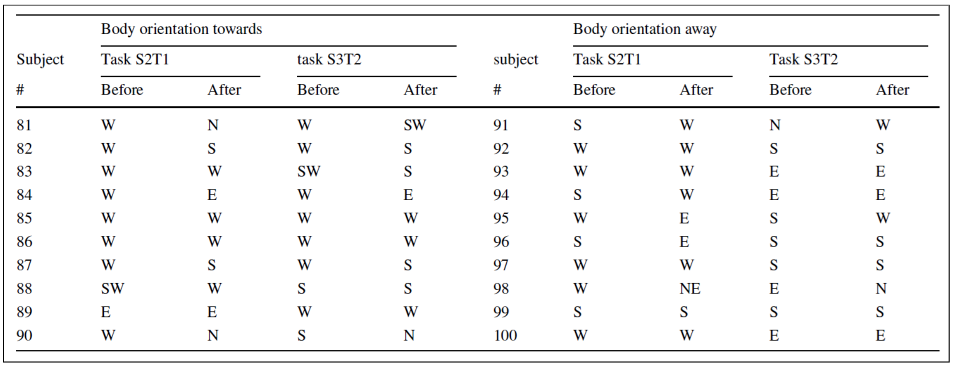
Appendix A

Data from experiments



Group B-Towards			Group B-Away			Group A-Towards			Group A-Away		
#	S1T1	S2T2	#	S1T1	S2T2	#	S2T1	S3T2	#	S2T1	S3T2
1	N	E	21	W	S	41	W	SW	61	S	E
2	W	E	22	W	S	42	N	SW	62	S	S
3	N	E	23	S	S	43	W	W	63	N	W
4	E	E	24	S	W	44	W	S	64	S	S
5	N	E	25	W	S	45	W	W	65	S	N
6	NW	E	26	W	S	46	W	W	66	S	E
7	N	E	27	S	E	47	W	W	67	N	NW
8	N	E	28	E	E	48	W	W	68	E	S
9	W	E	29	SW	S	49	W	W	69	W	E
10	NW	E	30	W	W	50	W	W	70	W	S
11	N	E	31	S	S	51	W	NW	71	W	S
12	N	E	32	W	S	52	S	SE	72	W	E
13	N	E	33	W	W	53	W	S	73	S	S
14	N	E	34	S	S	54	W	S	74	S	S
15	N	E	35	E	E	55	W	S	75	E	E
16	NW	E	36	W	SE	56	W	W	76	E	S
17	N	E	37	S	N	57	W	W	77	W	W
18	N	E	38	W	S	58	W	SW	78	S	NE
19	S	E	39	E	E	59	W	SW	79	E	E
20	NW	E	40	S	S	60	W	SW	80	N	E

Figure A.1: Orientation ratings for all sketched maps from participants in experiment 1.

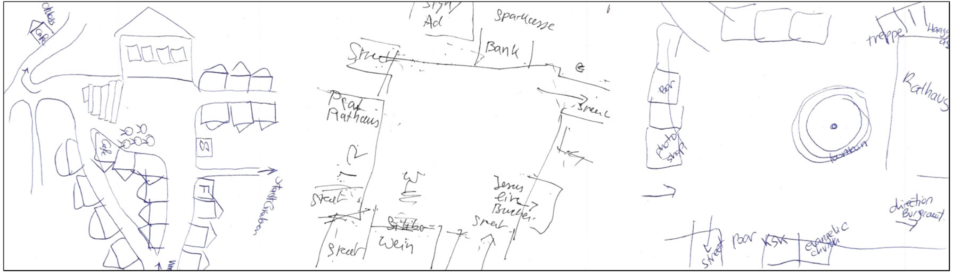


	Body orientation towards					Body orientation away			
Subject	Task S2T1		task S3T2		subject	Task S2T1		Task S3T2	
#	Before	After	Before	After	#	Before	After	Before	After
81	W	N	W	SW	91	S	W	N	W
82	W	S	W	S	92	W	W	S	S
83	W	W	SW	S	93	W	W	E	E
84	W	E	W	E	94	S	W	E	E
85	W	W	W	W	95	W	E	S	W
86	W	W	W	W	96	S	E	S	S
87	W	S	W	S	97	W	W	S	S
88	SW	W	S	S	98	W	NE	E	N
89	E	E	W	W	99	S	S	S	S
90	W	N	S	N	100	W	W	E	E

Figure A.2: Orientation ratings for all sketched maps from participants in experiment 2.

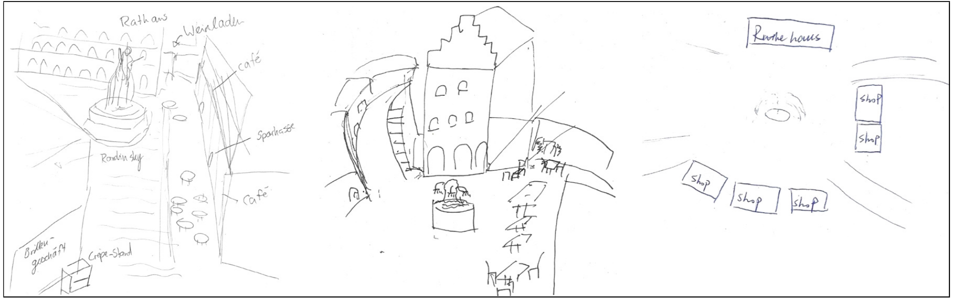
Marktplatz from Kirchgasse, towards

Marktplatz from Kirchgasse, away



Marktplatz from Faules Eck, towards

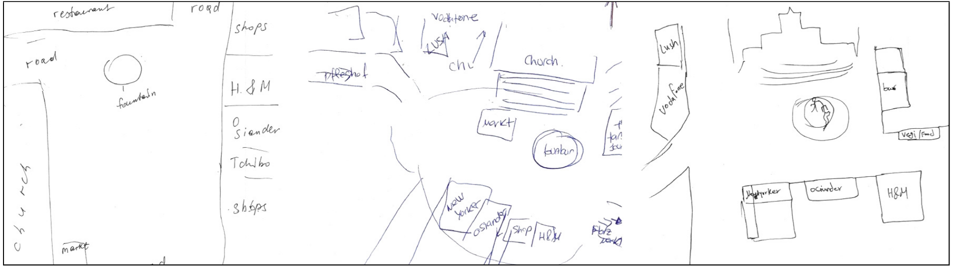
Marktplatz from Faules Eck, away



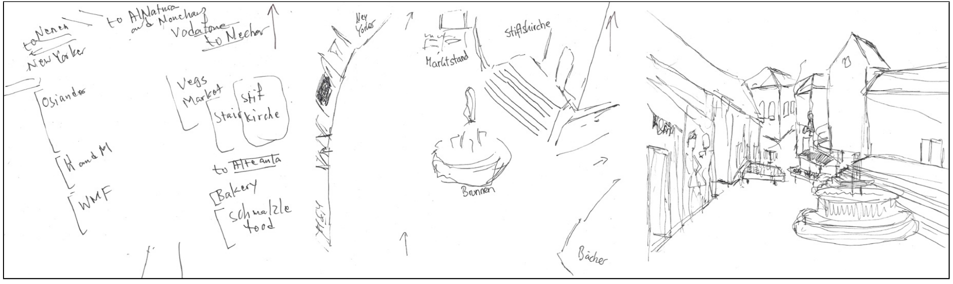
(a) Sketching examples from first sketching task.

Holzmarkt from Pfleghofstraße, towards

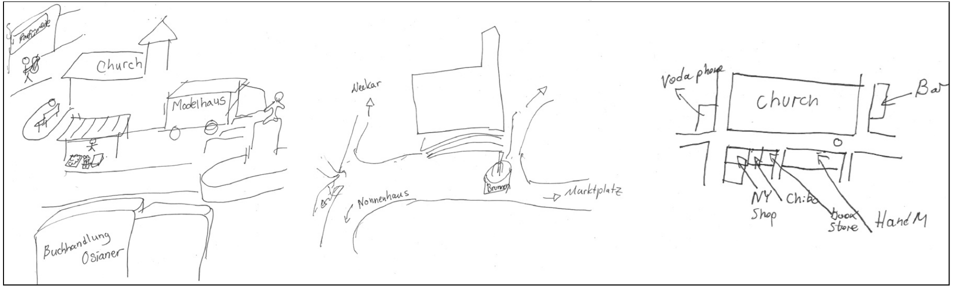
Holzmarkt from Pfleghofstraße, away



Holzmarkt from Kirchgasse, towards

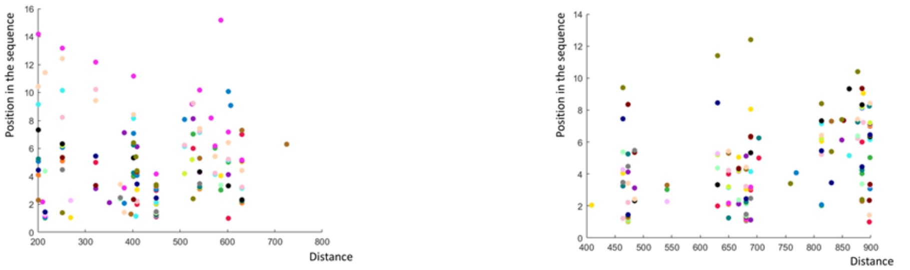


Holzmarkt from Kirchgasse, away



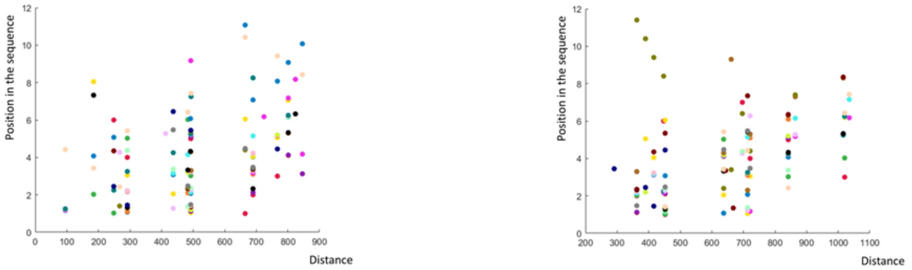
(b) Sketching examples from second sketching task.

Figure A.3: Sketch maps examples of different participants for (a) first and (b) second sketching task from experiment 1, Chap. 2, for each group. Three sketching examples shown per task and group.



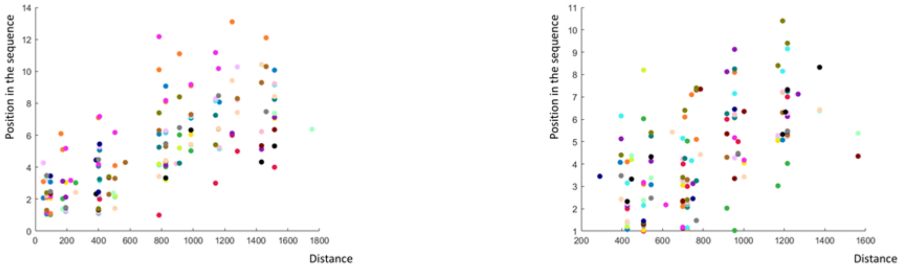
Marktplatz from Fauleseck – Group A

Marktplatz from Stadtmuseum – Group B



Holzmarkt from Pfleghofstraße – Group A

Holzmarkt from Kirchgasse – Group B



Neckarbrücke from Neckargasse – Group A

Neckarbrücke from Wöhrdstraße – Group B

Figure A.4: The scatter plots illustrate the relationship between the distance of each recalled location from the starting location (x-axis) and its position within the recall sequence (y-axis). The x-axis shows the distance measured in pixels, while the y-axis represents the order in which these locations were recalled. Each recall sequence is represented by dots of the same color, with consistent color coding used for each participant within the group. To avoid overlapping points and improve visualization, slight vertical adjustments were made to the positions of the dots for each participant.

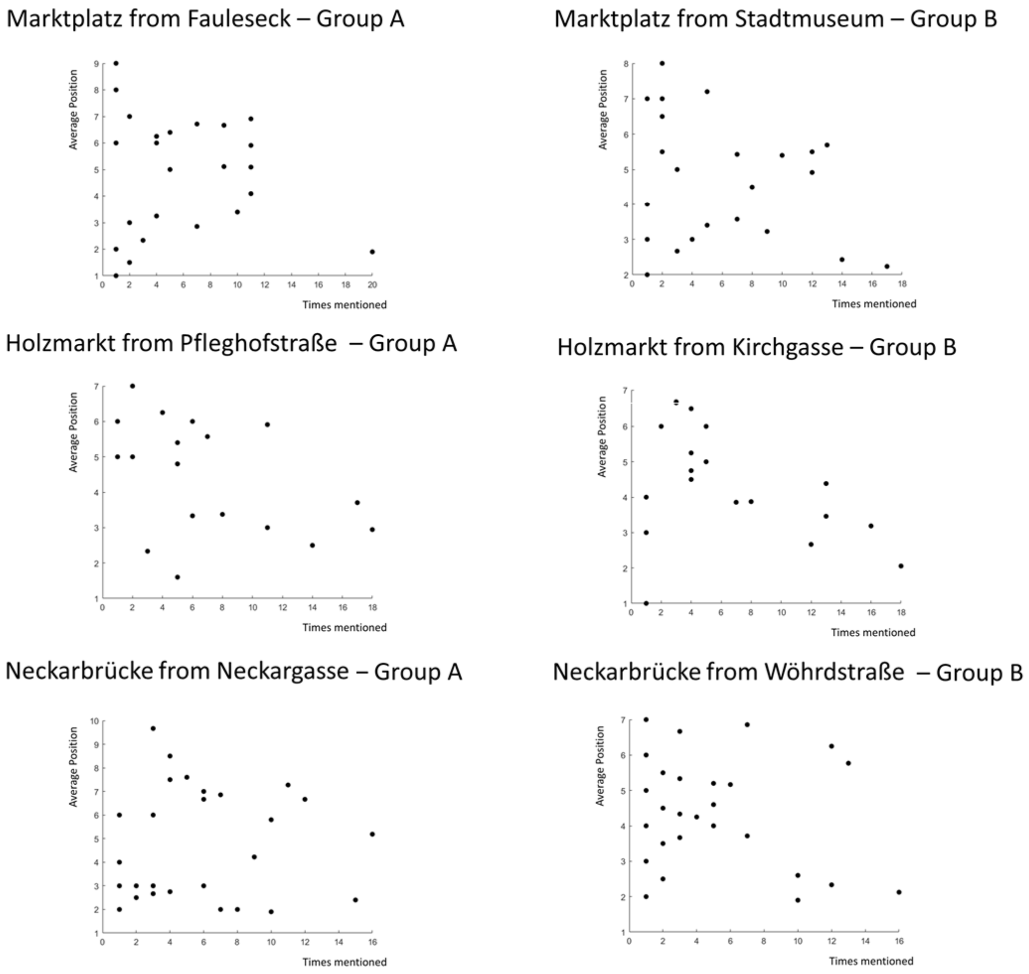


Figure A.5: This scatter plot shows the relationship between the recall frequency the locations and their average position in participants' recall sequences. The x-axis represents the number of times each location was mentioned, while the y-axis indicates the average position of each mentioned location across all sequences.

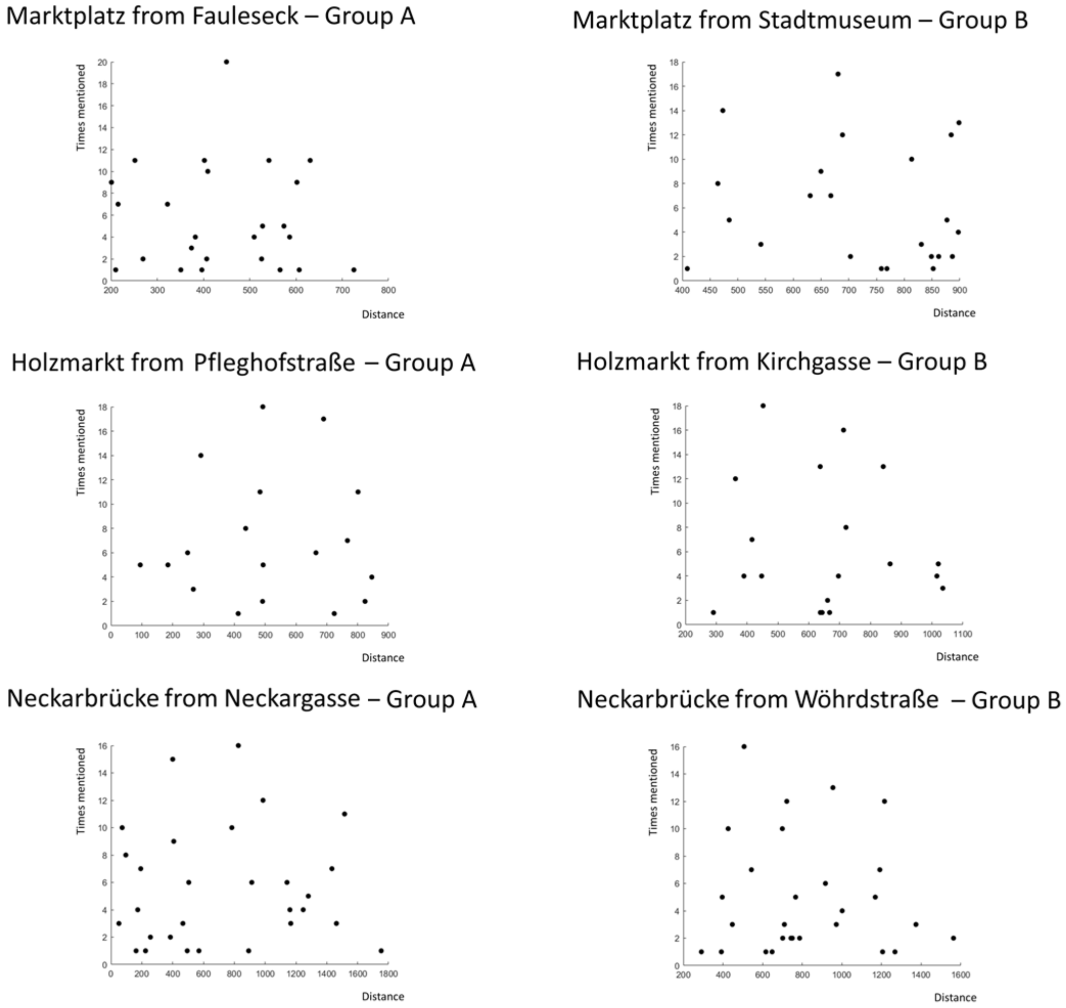


Figure A.6: Scatter plot showing the relationship between distance and recall frequency of named locations. The x-axis represents the distance of each named location from the target area (in pixel), while the y-axis indicates how often each location was mentioned by participants across all sequences. When analyzing recall patterns across different starting locations, variations become apparent. For instance, some starting locations may lead to a wider spread in recall frequencies, while others result in a tighter clustering of frequently mentioned locations near the target. These differences suggest that the starting location influences the sequence and priority of recalled places, likely due to participants' mental maps or familiarity with specific areas.

Seq_{1}^{AMF} = Apotheke; Brunnen Marktplatz; Rathaus; FotoMarkt; Volksbank; Crêpes; Weinhaus Beck
Seq_{2}^{AMF} = Antiquitäten; Rathaus; ProOptik; FotoMarkt; Apotheke; vom Fass; Crêpes
Seq_{3}^{AMF} = Lichtenstein; Rathaus; Brunnen Marktplatz; ProOptik; Weinhaus Beck
Seq_{4}^{AMF} = Antiquitäten; Samarkand; Rathaus; Brunnen Marktplatz; JesusLive; Ranitzky; FotoMarkt; Sparkassenautomat; Marquart; Apotheke
Seq_{5}^{AMF} = Rathaus; Weinhaus Beck; Marktschenke; JesusLive; Ranitzky
Seq_{6}^{AMF} = Rathaus; Whisky; Volksbank; Apotheke; Weinhaus Beck; Brunnen Marktplatz; Samarkand; Crêpes
Seq_{7}^{AMF} = Treppe Marktplatz; Rathaus; Weinhaus Beck; vom Fass; Apotheke; Sparkassenautomat; Marktschenke; FotoMarkt; JesusLive; Ranitzky
Seq_{8}^{AMF} = Antiquitäten; Silberburg; Samarkand; Rathaus; Weinhaus Beck; vom Fass; Apotheke; Gemeinde Lamm; Ernstings Family; Marktschenke; FotoMarkt; Volksbank; Ranitzky; JesusLive; ProOptik
Seq_{9}^{AMF} = Rathaus; Brunnen Marktplatz; Marktschenke; Sparkassenautomat; Ernstings Family; Ranitzky
Seq_{10}^{AMF} = Rathaus; Brunnen Marktplatz; Weinhaus Beck; vom Fass; Apotheke; Sparkassenautomat; Marktschenke; Ranitzky; Crêpes; Volksbank
Seq_{11}^{AMF} = Rathaus; Weinhaus Beck; Marktschenke; FotoMarkt; JesusLive; FotoMarkt
Seq_{12}^{AMF} = Antiquitäten; Lichtenstein; Rathaus; Marktschenke
Seq_{13}^{AMF} = Reve Chocolatier; JesusLive; Rathaus; Brunnen Marktplatz; Marktschenke; Chez Michel; Weinhaus Beck
Seq_{14}^{AMF} = Rathaus; Weinhaus Beck; Apotheke; Marktschenke; FotoMarkt; Ranitzky; JesusLive
Seq_{15}^{AMF} = Rathaus; FotoMarkt; Volksbank; Brunnen Marktplatz; Ranitzky
Seq_{16}^{AMF} = Rathaus; Covid Test-Center Marktplatz; ProOptik; Antiquitäten
Seq_{17}^{AMF} = Ranitzky; Crêpes; Rathaus; Brunnen Marktplatz; Treppe Marktplatz; FotoMarkt
Seq_{18}^{AMF} = Samarkand; Rathaus; Covid Test-Center Marktplatz; Weinhaus Beck; vom Fass; Apotheke; Marktschenke; FotoMarkt; Volksbank; JesusLive; Antiquitäten; Ranitzky
Seq_{19}^{AMF} = Antiquitäten; Rathaus; Brunnen Marktplatz; JesusLive; Volksbank
Seq_{20}^{AMF} = Rathaus; Covid Test-Center Marktplatz; Marktschenke; Ranitzky

Seq_1^{BMS} = Lichtenstein; Ernstings Family; Marktschenke; Brunnen Marktplatz; Covid Test-Center Marktplatz; JesusLive; Ranitzky
Seq_2^{BMS} = Weinhaus Beck; FotoMarkt; Gemeinde Lamm; JesusLive; Ranitzky
Seq_3^{BMS} = Weinhaus Beck; Alte Kunst; Rathaus; Apotheke; Sparkassenautomat; FotoMarkt; Ranitzky; Marktschenke; Silberburg
Seq_4^{BMS} = Rathaus; FotoMarkt; Ranitzky; WC
Seq_5^{BMS} = Rathaus; Brunnen Marktplatz; Marktschenke
Seq_6^{BMS} = Marktschenke; Sparkassenautomat; vom Fass; Weinhaus Beck; Rathaus; Volksbank; Ranitzky; JesusLive
Seq_7^{BMS} = Weinhaus Beck; Rathaus; Brunnen Marktplatz; Marktschenke; Antiquitäten; Ranitzky; FotoMarkt; JesusLive
Seq_8^{BMS} = Rathaus; Brunnen Marktplatz; Marktschenke; Sparkassenautomat
Seq_9^{BMS} = Weinhaus Beck; Rathaus; Brunnen Marktplatz; Sparkassenautomat; Ernstings Family; FotoMarkt; Ranitzky; JesusLive
Seq_{10}^{BMS} = Apotheke; Weinhaus Beck; Rathaus; Brunnen Marktplatz; FotoMarkt; Crêpes; Silberburg
Seq_{11}^{BMS} = Brunnen Marktplatz; Rathaus; Apotheke; JesusLive; Weinhaus Beck; Covid Test-Center Marktplatz; Crêpes; Lichtenstein
Seq_{12}^{BMS} = Weinhaus Beck; Gemeinde Lamm; Ranitzky; Apotheke; Ernstings Family; Marktschenke
Seq_{13}^{BMS} = Weinhaus Beck; JesusLive; Gemeinde Lamm; Rathaus; Brunnen Marktplatz; Marktschenke; Samarkand
Seq_{14}^{BMS} = Rathaus; vom Fass; Ernstings Family; Sparkassenautomat; Marktschenke; Ranitzky; FotoMarkt; JesusLive; Antiquitäten
Seq_{15}^{BMS} = Rathaus; Lichtenstein; Ranitzky; Sparkassenautomat; vom Fass; Marktschenke; Whisky; Weinhaus Beck; JesusLive
Seq_{16}^{BMS} = Rathaus; Sparkassenautomat; JesusLive; Ernstings Family; Apotheke; Crêpes
Seq_{17}^{BMS} = Weinhaus Beck; JesusLive; Reve Chocolatier; Rathaus; Samarkand; Ranitzky; Volksbank; FotoMarkt; Apotheke; Crêpes; Ernstings Family; Marktschenke
Seq_{18}^{BMS} = Lichtenstein; vom Fass; Weinhaus Beck; Rathaus; Brunnen Marktplatz; FotoMarkt; Crêpes; Ranitzky
Seq_{19}^{BMS} = Weinhaus Beck; Rathaus; Samarkand; JesusLive; FotoMarkt; Ranitzky; Apotheke; Ernstings Family
Seq_{20}^{BMS} = Rathaus; Marktschenke; Apotheke; Weinhaus Beck; vom Fass

$\mathrm{Seq}_{1}^{AHP} =$ Brunnen Holzmarkt; H&M; Bäckerei; New Yorker; Stiftskirche; Wochenmarkt
$\mathrm{Seq}_{2}^{AHP} =$ Wochenmarkt; Vodafone Holzmarkt; Stiftskirche; H&M; New Yorker; Figo
$\mathrm{Seq}_{3}^{AHP} =$ Stiftskirche; Treppen Holzmarkt; New Yorker; H&M; Bäckerei; Brunnen Holzmarkt; Tagente Jour; Vodafone Holzmarkt
$\mathrm{Seq}_{4}^{AHP} =$ New Yorker; Stiftskirche; Treppen Holzmarkt; Vodafone Holzmarkt; Wochenmarkt; Osiander; H&M; Bäckerei; Tagente Jour; WMF; Brunnen Holzmarkt
$\mathrm{Seq}_{5}^{AHP} =$ New Yorker; Figo; H&M; Tagente Jour
; $\mathrm{Seq}_{6}^{AHP} =$ Stiftskirche; H&M; WMF; Tagente Jour; Buchhandlung/Antiquariat
$\mathrm{Seq}_{7}^{AHP} =$ Balloon Fee; Stiftskirche; Treppen Holzmarkt; Figo; H&M; Tagente Jour
$\mathrm{Seq}_{8}^{AHP} =$ Balloon Fee; New Yorker; H&M; WMF; Bäckerei; Confiserie Donum; Tagente Jour; Klassische Münzen; Stiftskirche
$\mathrm{Seq}_{9}^{AHP} =$ Stiftskirche; New Yorker; Figo; H&M; Bäckerei; Tagente Jour
$\mathrm{Seq}_{10}^{AHP} =$ Balloon Fee; New Yorker; Stiftskirche; H&M; Buchhandlung/Antiquariat; Tagente Jour
$\mathrm{Seq}_{11}^{AHP} =$ Balloon Fee; Wochenmarkt; New Yorker; Treppen Holzmarkt; Stiftskirche; Tagente Jour; Buchhandlung/Antiquariat; H&M
$\mathrm{Seq}_{12}^{AHP} =$ Treppen Holzmarkt; Stiftskirche; H&M; Lush; Apollo Optik
$\mathrm{Seq}_{13}^{AHP} =$ New Yorker; Figo; Buchhandlung/Antiquariat; Stiftskirche; Tagente Jour
$\mathrm{Seq}_{14}^{AHP} =$ New Yorker; H&M; Figo; Osiander; Tagente Jour; Klassische Münzen; Vodafone Holzmarkt
$\mathrm{Seq}_{15}^{AHP} =$ Stiftskirche; Figo; H&M; Wochenmarkt
$\mathrm{Seq}_{16}^{AHP} =$ Figo; Stiftskirche; Treppen Holzmarkt; New Yorker
$\mathrm{Seq}_{17}^{AHP} =$ Lush; Figo; H&M; Brunnen Holzmarkt; Stiftskirche
$\mathrm{Seq}_{18}^{AHP} =$ Stiftskirche; Lush; Vodafone Holzmarkt; Balloon Fee; New Yorker; Figo; Buchhandlung/Antiquariat; WMF; Bäckerei; Brunnen Holzmarkt
$\mathrm{Seq}_{19}^{AHP} =$ New Yorker; Wochenmarkt; H&M; Bäckerei; Stiftskirche; Treppen Holzmarkt
$\mathrm{Seq}_{20}^{AHP} =$ Stiftskirche; Figo; H&M; Brunnen Holzmarkt; Treppen Holzmarkt

Seq_{1}^{BHK} = H&M; Tagente Jour; Vodafone Holzmarkt; Apollo Optik; New Yorker; Brunnen Holzmarkt; Treppen Holzmarkt

Seq_{2}^{BHK} = H&M; Tagente Jour; New Yorker; Vodafone Holzmarkt; Figo

Seq_{3}^{BHK} = Stiftskirche; Figo; Apollo Optik; Bäckerei; Confiserie Donum; H&M

Seq_{4}^{BHK} = Figo; Stiftskirche; H&M; New Yorker

Seq_{5}^{BHK} = Tagente Jour; H&M; Stiftskirche; Figo; Apollo Optik; New Yorker

Seq_{6}^{BHK} = Tagente Jour; H&M; Bäckerei; Figo; New Yorker

Seq_{7}^{BHK} = H&M; Tagente Jour; Bäckerei; Figo; Stiftskirche; Wochenmarkt; Lush

Seq_{8}^{BHK} = Apollo Optik; Brunnen Holzmarkt; Stiftskirche; Figo; Wochenmarkt; Lush

Seq_{9}^{BHK} = H&M; Confiserie Donum; Stiftskirche; Figo; New Yorker; Vodafone Holzmarkt

Seq_{10}^{BHK} = Stiftskirche; Tagente Jour; Bäckerei; New Yorker

Seq_{11}^{BHK} = H&M; Brunnen Holzmarkt; Stiftskirche; New Yorker; Balloon Fee; Vodafone Holzmarkt

Seq_{12}^{BHK} = Stiftskirche; H&M; Tagente Jour; Treppen Holzmarkt; Wochenmarkt; Apollo Optik

Seq_{13}^{BHK} = H&M; Stiftskirche; Tagente Jour; Figo; Apollo Optik; New Yorker; Wochenmarkt; Balloon Fee; Tchibo

Seq_{14}^{BHK} = H&M; Tagente Jour; Figo; New Yorker; Balloon Fee

Seq_{15}^{BHK} = Alte Aula; Tagente Jour; Osiander; Bäckerei; H&M; New Yorker; Stiftskirche; Balloon Fee

Seq_{16}^{BHK} = Stiftskirche; H&M; New Yorker; Treppen Holzmarkt

Seq_{17}^{BHK} = H&M; Figo; Tchibo; Apollo Optik; Stiftskirche; Treppen Holzmarkt; Wochenmarkt; Brunnen Holzmarkt; Bäckerei; Confiserie Donum; Tagente Jour

Seq_{18}^{BHK} = H&M; New Yorker; Figo; Stiftskirche; Figo; Vodafone Holzmarkt; Lush

Seq_{19}^{BHK} = Bäckerei; Confiserie Donum; WMF; H&M; Stiftskirche

Seq_{20}^{BHK} = Tagente Jour; H&M; Apollo Optik; Buchhandlung/Antiquariat; Stiftskirche

Seq_1^{ANN} = Osiander Neckarbrücke; Neckarbrücke; DAI; Zinser; Cafe Lieb; Cafe Ludwig

Seq_2^{ANN} = Telekom; Asia Food; Bushaltestelle 1; Touristeninformation; Istanbul; Sparkasse

Seq_3^{ANN} = Chinesisches Restaurant; Telekom; Falafel; Neckermüller; Neckarbrücke; Istanbul; Zinser

Seq_4^{ANN} = Chinesisches Restaurant; Italienisches Restaurant; Telekom; Neckermüller; Neckarbrücke; Osiander Neckarbrücke; Istanbul; Hotel Krone; Touristeninformation; Zinser

Seq_5^{ANN} = Telekom; Chinesisches Restaurant; Italienisches Restaurant; El Chico; Asia Food; Primer; Neckermüller; Touristeninformation; Istanbul; Osiander Neckarbrücke; Sparkasse; Cafe L; Cafe Ludwig

Seq_6^{ANN} = Neckermüller; Falafel; Asia Food; Touristeninformation; Ulandbad; Cafe Ludwig; Zinser

Seq_7^{ANN} = Neckermüller; El Chico; Neckarbrücke; Osiander Neckarbrücke; Hotel Krone; Touristeninformation; Istanbul; DAI; Zinser

Seq_8^{ANN} = Chinesisches Restaurant; Telekom; Vodafone Neckarbrücke; Neckermüller; Falafel; El Chico; Neckarbrücke; Touristeninformation; Istanbul; Rutter; DAI; Osiander Neckarbrücke

Seq_9^{ANN} = Neckermüller; El Chico; Touristeninformation; Osiander Neckarbrücke; Sparkasse

Seq_{10}^{ANN} = Neckermüller; Chinesisches Restaurant; Neckarbrücke; Sparkassenautomat Neckarbrücke; Hotel Krone; Ulandbad; Istanbul; Cafe Lieb; Zinser

Seq_{11}^{ANN} = Falafel; Neckermüller; Neckarbrücke; Sparkasse; Osiander Neckarbrücke; Touristeninformation; DAI; Zinser

Seq_{12}^{ANN} = Falafel; Neckermüller; Chinesisches Restaurant; Italienisches Restaurant; Neckarbrücke; Touristeninformation; Istanbul; DAI; Ulandbad; Cafe Lieb

Seq_{13}^{ANN} = Chinesisches Restaurant; Neckarinsel; El Chico; Bushaltestelle 2; Touristeninformation; Osiander Neckarbrücke; Istanbul; Cafe Lieb; Ulandbad; Cafe L

Seq_{14}^{ANN} = Neckermüller; Eisdiele; Touristeninformation; Ulandbad; Zinser; Istanbul

Seq_{15}^{ANN} = Neckermüller; Telekom; Neckarinsel; Touristeninformation; Ulandbad; Zinser

Seq_{16}^{ANN} = Asia Food; Bäckerei Neckarbrücke; Chinesisches Restaurant; Touristeninformation; Istanbul; Commerzbank; Zinser

Seq_{17}^{ANN} = Neckermüller; Chinesisches Restaurant; Neckarinsel; Touristeninformation; DAI; Rutter; Osiander Neckarbrücke; Sparkasse

Seq_{18}^{ANN} = El Chico; Bushaltestelle 1; Osiander Neckarbrücke; Touristeninformation; Istanbul; Rutter; Cafe Lieb; Zinser; Cafe Ludwig; Ulandbad

Seq_{19}^{ANN} = Falafel; Neckermüller; Telekom; Eisdiele; Neckarbrücke

Seq_{20}^{ANN} = Falafel; Telekom; Chinesisches Restaurant; Neckermüller; Touristeninformation; Sparkasse; Cafe L; Rutter

Seq_1^{BNW} = Touristeninformation; Istanbul; Osiander Neckarbrücke; Sparkassenautomat Neckarbrücke; Neckarinsel; El Chico; Chinesisches Restaurant

Seq_2^{BNW} = Neckermüller; El Chico; Telekom; Chinesisches Restaurant; Osiander Neckarbrücke; Touristeninformation

Seq_3^{BNW} = Touristeninformation; Osiander Neckarbrücke; Sparkasse; Bushaltestelle 1; Telekom; Neckermüller

Seq_4^{BNW} = Istanbul; Osiander Neckarbrücke; Zinser; DAI; Falafel; Neckermüller

Seq_5^{BNW} = Osiander Neckarbrücke; Sparkasse; Touristeninformation; Istanbul; Ulandbad; Cafe Ludwig; Cafe L; Neckermüller

Seq_6^{BNW} = Sparkasse; Istanbul; Hotel Krone; Zinser; Cafe Lieb; Chinesisches Restaurant; Italienisches Restaurant; El Chico; Neckermüller

Seq_7^{BNW} = Osiander Neckarbrücke; Touristeninformation; Istanbul; Cafe L; Sparkasse; Cafe Lieb; Neckermüller; Falafel; Chinesisches Restaurant

Seq_8^{BNW} = Sparkasse; Ampel; Touristeninformation; Bushaltestelle 1; Neckermüller

Seq_9^{BNW} = Istanbul; Osiander Neckarbrücke; Sparkassenautomat Neckarbrücke; Rutter; Telekom; Neckermüller; Falafel; Touristeninformation

Seq_{10}^{BNW} = Touristeninformation; Istanbul; Osiander Neckarbrücke; Sparkasse; Chinesisches Restaurant; Neckermüller; Falafel

Seq_{11}^{BNW} = Touristeninformation; Osiander Neckarbrücke; Ulandbad; Cafe Ludwig; Zinser; El Chico; Chinesisches Restaurant; Neckermüller

Seq_{12}^{BNW} = Touristeninformation; Osiander Neckarbrücke; Sparkasse; Neckermüller; Telekom; Chinesisches Restaurant

Seq_{13}^{BNW} = Touristeninformation; Sparkasse; Osiander Neckarbrücke; El Chico; Chinesisches Restaurant; Falafel; Ulandbad

Seq_{14}^{BNW} = Touristeninformation; Istanbul; Rutter; Zinser; Falafel; Primer; Chinesisches Restaurant; Vodafone Neckarbrücke

Seq_{15}^{BNW} = Touristeninformation; Sparkasse; Neckermüller; Eisdiele; El Chico; Bushaltestelle 1; Bushaltestelle 2

Seq_{16}^{BNW} = Istanbul; Touristeninformation; Zinser; Rutter; Eisdiele; Vodafone Neckarbrücke

Seq_{17}^{BNW} = Touristeninformation; Osiander Neckarbrücke; Sparkasse; Cafe Lieb; Zinser; Cafe Ludwig; Ulandbad; Telekom; Chinesisches Restaurant; Falafel

Seq_{18}^{BNW} = Istanbul; Cafe Lieb; Bushaltestelle 1; Bushaltestelle 2; Bushaltestelle 3; Vodafone Neckarbrücke

Seq_{19}^{BNW} = Touristeninformation; Hotel Krone; Schuhgeschäft; Neckarinsel; Chinesisches Restaurant; Neckermüller

Seq_{20}^{BNW} = Ulandbad; Zinser; Cafe Lieb; Neckarinsel; Chinesisches Restaurant

Bibliography

Avraamides, M. N., & Kelly, J. W. (2008). Multiple systems of spatial memory and action. *Cognitive processing*, *9*(2), 93–106.

Basten, K., Meilinger, T., & Mallot, H. A. (2012). Mental travel primes place orientation in spatial recall. In *International conference on spatial cognition* (pp. 378–385).

Batschelet, E. (1981). Circular statistics in biology. *(No Title).*

Berens, P. (2009). Circstat: a matlab toolbox for circular statistics. *Journal of statistical software*, *31*(1), 1–21.

Bicanski, A., & Burgess, N. (2020). Neuronal vector coding in spatial cognition. *Nature Reviews Neuroscience*, *21*(8), 453–470. doi: 10.1038/s41583-020-0328-7

Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex*, *14*(1), 129–133.

Bülthoff, H. H., Edelman, S., & Tarr, M. J. (1995). How are three-dimensional objects represented in the brain? *Cerebral Cortex*, *5*(3), 247–260.

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and psychological measurement*, *20*(1), 37–46.

Couclelis, H., Golledge, R. G., Gale, N., & Tobler, W. (1987). Exploring the anchor-point hypothesis of spatial cognition. *Journal of Environmental Psychology*, *7*, 99–122.

Golledge, R. G. (1992). Place recognition and wayfinding: Making sense of space. *Geoforum*, *23*(2), 199–214. Retrieved from `https://www.sciencedirect.com/science/article/pii/001671859290017X` doi: 10.1016/0016-7185(92)90017-X

Guariglia, C., Palermo, L., Piccardi, L., Iaria, G., & Incoccia, C. (2013). Neglecting the left side of a city square but not the left side of its clock: Prevalence and characteristics of representational neglect. *PLoS ONE*, *8*(7), e67390. doi: 10.1371/journal.pone.0067390

Hirtle, S. C., & Jonides, J. (1985). Evidence of hierarchies in cognitive maps. *Memory & Cognition*, *13*(3), 208–217. Retrieved from `https://link.springer.com/article/10.3758/BF03197683` doi: 10.3758/BF03197683

Julian, J. B., Keinath, A. T., Marchette, S. A., & Epstein, R. A. (2018). The neurocognitive basis of spatial reorientation. *Current Biology*, *28*(17), R1059–R1073.

Kelly, J. W., Avraamides, M. N., & Loomis, J. M. (2007). Sensorimotor alignment effects in the learning environment and in novel environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(6), 1092.

Kelly, J. W., Cherep, L. A., Klesel, B., Siegel, Z. D., & George, S. (2018). Comparison of two methods for improving distance perception in virtual reality. *ACM Transactions on Applied Perception*, *15*, 1092–1107.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (pp. 1–17). Springer.

Lessels, S., & Ruddle, R. A. (2005). Movement around real and virtual cluttered environments. *Presence: Teleoperators & Virtual Environments*, *14*(5), 580–596.

Le Vinh, L., Meert, A., & Mallot, H. A. (2020). The influence of position on spatial representation in working memory. *Lecture Notes in Artificial Intelligence*, *12162*, 50–58.

Loomis, J. M., Klatzky, R. L., & Giudice, N. A. (2013). Representing 3d space in working memory: Spatial images from vision, hearing, touch, and language. *Multisensory imagery*, 131–155.

Mallot, H. A. (2024). *From geometry to behavior: An introduction to spatial cognition.* MIT Press.

Mallot, H. A., Ecke, G. A., & Baumann, T. (2020). Dual population coding for path planning in graphs with overlapping place representations. In *Spatial cognition xii: 12th international conference, spatial cognition 2020, riga,* *latvia, august 26–28, 2020, proceedings 12* (pp. 3–17).

Marchette, S. A., Vass, L. K., Ryan, J., & Epstein, R. A. (2014). Anchoring the neural compass: coding of local spatial reference frames in human medial parietal lobe. *Nature neuroscience*, *17*(11), 1598–1606.

Marchette, S. A., Yerramsetti, A., Burns, T. J., & Shelton, A. L. (2011). Spatial memory in the real world: Long-term representations of everyday environments. *Memory & Cognition*, *39*(8), 1401–1408. Retrieved from `https://link.springer.com/article/10.3758/s13421-011-0108-x` doi: 10.3758/s13421-011-0108-x

May, M. (2004). Imaginal perspective switches in remembered environments: Transformation versus interference accounts. *Cognitive psychology*, *48*(2), 163–206.

McNamara, T. P. (1988). Mental representations of spatial relations. *Cognitive Psychology*, *20*(2), 149–197. doi: 10.1016/0010-0285(88)90016-2

Meilinger, T. (2008). The network of reference frames theory: A synthesis of graphs and cognitive maps. In *International conference on spatial cognition* (pp. 344–360).

Meilinger, T., Frankenstein, J., Simon, N., Bülthoff, H. H., & Bresciani, J.-P. (2016). Not all memories are the same: Situational context influences spatial recall within one's city of residency. *Psychonomic bulletin & review*, *23*(1), 246–252.

Meilinger, T., & Vosgerau, G. (2010). Putting egocentric and allocentric into perspective. In *International conference on spatial cognition* (pp. 207–221).

Montello, D. R. (1991). Spatial orientation and the angularity of urban routes: A field study. *Environment and Behavior*, *23*(1), 47–69.

Montello, D. R. (1993). Scale and multiple psychologies of space. In A. U. Frank & I. Campari (Eds.), *Spatial information theory a theoretical basis for gis (cosit 1993)* (Vol. 716, pp. 312–321). Springer. doi: 10.1007/3-540-57207-4_20

Montello, D. R. (1999). A new framework for understanding the acquisition of spatial knowledge in large-scale environments. *Spatial Cognition and Computation*, *1*(1), 31–65. doi: 10.1023/A:1010069907467

Mou, W., & McNamara, T. P. (2002). Intrinsic frames of reference in spatial memory. *Journal of experimental psychology: learning, memory, and cognition*, *28*(1), 162.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map.* Oxford University Press.

Riecke, B. E., & McNamara, T. P. (2017). Where you are affects what you can easily imagine: Environmental geometry elicits sensorimotor interference in remote perspective taking. *Cognition*, *169*, 1–14.

Röhrich, W. G., Hardiess, G., & Mallot, H. A. (2014). View-based organization and interplay of spatial working and long-term memories. *PloS one*, *9*(11), e112793.

Ruddle, R. A., & Jones, D. M. (2001). Movement in cluttered virtual environments. *Presence: Teleoperators & Virtual Environments*, *10*(5), 511–524.

Sanchez-Vives, M. V., & Slater, M. (2005). From presence to consciousness through virtual reality. *Nature Reviews Neuroscience*, *6*, 332–339.

Schölkopf, B., & Mallot, H. A. (1995). View-based cognitive mapping and path planning. *Adaptive Behavior*, *3*(3), 311–348.

Shelton, A. L., & McNamara, T. P. (2001). Systems of spatial reference in human memory. *Cognitive psychology*, *43*(4), 274–310.

Slater, M., Lotto, B., Arnold, M. M., & Sanchez-Vives, M. V. (2009). How we experience immersive virtual environments: The concept of presence and measurement. *Anuario de Psicologia*, *40*, 193–210.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*(4), 189–208.

Tversky, B. (1993). Cognitive maps, cognitive collages, and spatial mental models. In A. U. Frank & I. Campari (Eds.), *Spatial information theory a theoretical basis for gis (cosit 1993)* (Vol. 716, pp. 14–24). Springer. Retrieved from `https://link.springer.com/chapter/10.1007/3-540-57207-4_2` doi: 10.1007/3-540-57207-4_2

Wang, R. F., & Brockmole, J. R. (2003). Human navigation in nested environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 398–404.

Werner, S., & Schmidt, K. (1999). Environmental reference systems for large-scale spaces. *Spatial cognition and computation*, *1*(4), 447–473.