THE VIRTUAL EXPERIENCE – EXAMINING VISUAL, AUDITORY AND HAPTIC CAPABILITIES AND ASPECTS OF SPATIAL COGNITION AND USER EXPERIENCE IN VIRTUAL REALITY

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“Lucidity, come back to me,
Put all five senses back to where they’re meant to be**”**

Lucidity by ***Tame Impala (Kevin Parker)***

“Knowing is not enough, we must apply.
Willing is not enough, we must do**”**

Johann Wolfgang von Goethe

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Remarks

The article used for Chapter 3 is a translated and adapted version of the short paper published as “The Art of Orientation – How not to be Lost in 3D” in the Proceedings of the MuC 2021, written by Jendrik Müller, Nils Beese, Jan Spilski, Alexander Jaksties, Jan-Hendrik Sünderkamp, Jan Hendrik Plümer, and Kerstin Müller. For continuity reasons, the citation style was changed to match the APA style of the rest of this dissertation. The software implementation was done by Jendrik Müller, Alexander Jaksties, Jan-Hendrik Sünderkamp and Jan-Hendrik Plümer. Experiment design, data collection and analysis were done by Nils Ove Beese and checked by Jan Spilski.

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Abbreviations

2D	two-dimensional
3D	three-dimensional
AR	Augmented Reality
CAVE	Cave Automatic Virtual Environment
CTJ	Cervicothoracic Junction
FOV	Field of View
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
IPQ	iGroup Presence Questionnaire
KSS	Karolinska Sleepiness Scale
MCD	Multi-user Centered Design
MM	Manual Medicine
MT	Manual Therapy
PUT	Prototype Usability Testing
PPA	Parahippocampal Place Area
RSC	Retrosplenial Cortex
SSQ	Simulator Sickness Questionnaire
SUS	System Usability Scale
TLM	Temporal Luminance Modulation
TLX	NASA Task Load Index
UCD	User-Centered Design
UEQ	User Experience Questionnaire
UX	User Experience
VE	Virtual Environment
VR	Virtual Reality

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Chapter 1: Introduction

The very first concepts of Virtual Reality (VR) can be traced back to the 1960s, when Morton Heilig, considered to be one of the godfathers of VR, filed a patent for the Sensorama Simulator. The Sensorama Simulator was designed to "stimulate the senses of an individual to simulate an actual experience realistically" (p. 9, Heilig, 1961). The chair of the Sensorama could move, the display was color and stereoscopic, the simulator also included odor emitters, fans and a stereo-sound system. The Sensorama simulated a motorcycle ride through the city of New York, triggering the different parts of the system at the appropriate times according to events during the ride. In 1965, Ivan Sutherland wrote an essay entitled "The Ultimate Display", describing what could be considered the basis for VR with the following words: "such a display could literally be the Wonderland into which Alice walked" (p.507). A few years later, Sutherland published an article called "A head-mounted three-dimensional display" (1968) for a conference, stating his idea to "present the user with a perspective image which changes as he moves" (p.757). In this article, he went on to specify what would later become the basis for Head-Mounted Displays (HMD) in VR. Machover and Tice argued in 1994 that "the quality of the experience is crucial" and that the experience needed to be consistent while being realistic was of secondary importance. Nowadays, that statement still has merits (Van Gisbergen et al., 2019), it might also depend on what one wants to accomplish with the experience in VR (Niedermayr et al., 2023).

Investigating some of the different aspects of the experiences in VR with a particular focus on spatial cognition was the basis for this dissertation. Since VR has been used and continues to be used in psychological experiments (e.g. Hoffman, 1998; Kuliga et al., 2015; Riva, 2005), a detailed literature review on the current state of spatial cognition and search paradigms in VR as well as the user experience and usability of VR will be described in Chapter 2. Chapters 3 to 7 describe several studies done in VR. Chapter 3 (study 1) will deal with a pilot study in which several aspects of the experience in a spatial orientation task have been manipulated. Using the insights provided by the pilot study, Chapter 4 and 5 (study 2) takes a closer look at how landmarks can change behavioral and physiological aspects of the experience in a spatial orientation task. Chapter 6 (study 3) then investigates what happens when a search cannot be visual, but instead needs other sensory cues, namely vibrotactile and auditory, to find hidden objects. After diving into other modalities in VR in Chapter 6, Chapter 7 (study 4) will then closely investigate the use of haptic gloves as interaction devices in a haptic heavy manual medicine and therapy setting in VR. Last but not least, Chapter 8 will discuss the findings of these studies in a larger context and paint a picture of what VR and VR research could aspire to become.

Chapter 2: Literature Review

2.1. Spatial Cognition, Orientation and Navigation

Spatial cognition is concerned with the investigation of how spatial knowledge about the surroundings and places as well as the spatial properties of objects are acquired, stored, and retrieved (Montello, 2015). The main aspects of spatial cognition research include spatial navigation and orientation as well as searching for objects. Without the ability of spatial orientation and navigation, we would arguably be walking around aimlessly, not knowing where to go and how to get there.

But how are the different parts of spatial cognition, orientation and navigation represented and what strategies are employed? Ekstrom and Isham (2017) wrote about three forms of representations that also are the basis of the navigation strategies: allocentric, beacon as well as egocentric. The allocentric representation and navigation strategy is using a position that is decoupled from one's own body position as a reference frame (Ekstrom & Isham, 2017), e.g., a cartographic map that uses the relations of distances and directions between stationary landmarks. Egocentric strategies and representations, as the name suggests, are using one's body position as a frame of reference for distances and directions (Ekstrom & Isham, 2017). Using visible locations that are supposed to be near a not-yet-visible target location as a reference for navigation is then defined as beacon navigation, since one uses that visible location as a beacon (Ekstrom & Isham, 2017). Ekstrom and Isham (2017) concluded in their article that the ability to use those representations in a flexible way is one of the trademarks of human spatial cognition.

Another form of representation of spatial cognition are cognitive maps and cognitive graphs which typically represent structural knowledge of a given space (Peer et al., 2021). The concept of cognitive maps was first introduced in 1948 by Edward Tolman. Tolman studied the orientation skills of mice and found out that the mice would still find the way to the goal even if he changed the mice's starting point. He concluded that the rodents would develop a cognitive map of the test environment which would help them with the orientation task. Typically, the information encoded in cognitive maps is bound to Euclidean space (p.10, O'Keefe & Nadel, 1978). A Euclidean space is a two- or three-dimensional space that is defined by two or three axes, respectively, and locations as well as their relationships to each other can be specified by coordinates, distances, and angles in this space (Peer et al., 2021). However, studies also have shown that in some cases the cognitive representations of participants violated the laws of Euclidean spaces (e.g., Byrne, 1979; Moar & Bower, 1983, McNamara et al., 1984). Byrne (1979) described two experiments. In his first experiment, he let participants estimate walking distances between several location pairs, routes being varied by location, number of turns as well as length. For the second experiment, another sample of participants had to estimate angles between road pairs by sketching the road configuration at the junctions. The results of the first experiment showed overestimations of route length if routes were located near the town center, were short, and if they had several big turns. The angles in the second experiment were mostly estimated to be at and around 90°, even though the actual angles were either between 60 and 70 degrees or between 110 and 120 degrees. In a similar series of experiments, Moar and Bower (1983) examined if the spatial information derived from cognitive maps does follow the Euclidean properties. In their first experiment, the participants had to judge six directions between sets of locations from memory. For the second experiment, another sample of participants needed to judge directional information between pairs of American cities bidirectionally. The first experiment found that the derived angles were biased to be around 90 degrees, similar to Byrne (1979). The results of their second experiment showed that, consistently, the directions from the participants were non-reversible. In 1984, McNamara and colleagues investigated the spatial knowledge acquired from maps. Their results indicated as well that distance in cognitive maps does not rely on Euclidean distances, necessarily. All of these findings already gave some credence to the notion that spatial representations might not only be cognitive maps that follow the Euclidean laws back then. Kuipers (1978) and Byrne (1979) suggested that the representation might be more akin to networks than maps, so the term "graph" might be more appropriate. Furthermore, Downs (1981) and Kuipers (1982) both argued that the metaphor behind the term "cognitive map" might be misleading considering research showing those maps not to be exactly map-like. Over the years, this led to the notion of representations being cognitive graphs rather than cognitive maps. Nowadays, arguments are made that there are common aspects of cognitive maps and cognitive graphs, both concepts might be true (Peer et al., 2021, Weisberg and Newcombe, 2018). The kind of representation that is in action might depend on the task and spatial information of a given environment (Peer et al., 2021).

While Kuipers wrote about the structure of spatial knowledge, i.e., cognitive maps versus graphs, in his article in 1978, he also conceptualized a model of acquiring this kind of representations, new spatial information, thus describing one of the first models of spatial knowledge acquisition. This concept, however, did not gain a lot of traction in terms of research interest. Another model that was first conceptualized by Siegel and White in 1975 and refined by Thorndyke and Goldin (1983) is a three-level model of spatial knowledge acquisition, sometimes referred to as the Landmark-Route-Survey model or framework. According to their model, spatial knowledge has three distinctive stages of acquisition and representation. The first element of their model is landmark knowledge. Siegel and White (1975) argue that spatial representations generally start with landmarks. Landmarks can identify both beginnings and ends as well as help to maintain a route. Furthermore, Siegel and White (1975) state that landmarks can be seen as "unique patterns of perceptual events at a specific location". According to Thorndyke and Goldin (1983), landmark knowledge is the foundation to recognize a location and helps orientation in any given environment. The second stage of this model is the acquisition of route knowledge (Siegel & White, 1975), also referred to as procedural knowledge (Thorndyke & Goldin, 1983). Siegel and White (1975) state that "routes are predominantly sensorimotor", i.e., they rely on both sensory and locomotory processing to form knowledge. The formed knowledge is derived from navigating routes (Thorndyke & Goldin, 1983). The knowledge representation of routes is typically a sequence of salient points, i.e., landmarks, along a particular route at which a person needs to act to maintain said route, e.g., turning left, turning right, keep straight ahead (Siegel & White, 1975; Thorndyke & Goldin,1983). The third kind of spatial knowledge acquisition is survey knowledge (Thorndyke & Gordin, 1983), also referred to as configurational knowledge (Siegel & White, 1975). As the name suggests, this part of spatial knowledge acquisition takes the aforementioned parts, i.e., landmarks and routes, and builds an all-encompassing representation of an environment. Representations of survey knowledge are likely the closest to the original idea of cognitive maps that follow Euclidean laws, as they are said to consider the object locations and distances in relation to a fixed coordinate system (Thorndyke & Gordin, 1983). According to Siegel and White (1975), configurations can be of different types: figurative metaphors, perceived outlines of a terrain and graphic skeleton. Figurative metaphors would be describing the map of Italy as a "boot" (Siegel & White, 1975). An example for perceived outlines of some terrain would be any outline of any country on a map (Siegel & White, 1975). Furthermore, examples for graphic skeletons are the schematic routes of underground subway systems found in subway stations that show the different subway lines (Siegel & White, 1975).

There has been some debate whether the spatial knowledge acquisition as described happens in stages or in parallel. Going by the first concept of Siegel and White (1975), it should happen in stages. However, there are studies arguing that the acquisition is at least partially parallel (e.g., Buchner & Jansen-Osmann, 2008; Kim & Bock, 2020; Montello, 1998). Kim and Bock (2020) set out to replicate earlier evidence towards the parallel concept of acquisition, while trying to prevent floor and ceiling effects that were present in earlier research. They ran a series of pilot tests that gradually got more difficult to determine the correct degree of difficulty for the main task which ended up being ten trials. Per each of the ten trials, the participants had to navigate three routes and perform four spatial knowledge tests after navigating the routes. The tests consisted of a recognition test to see how familiar the landmarks seemed to participants after navigating, a sequence test to test if participants could name each landmark of a route in the correct order, a map test to determine the correct sequence of turns along the routes, and a direction test in which the participants had to draw lines to the destinations and starting point of the routes (Kim & Bock, 2020). The results of their study showed a trial-to-trial increase for all three kinds of knowledge as well as a significant increase of correlations from trial to trial (Kim & Bock, 2020). These findings do point towards parallel spatial knowledge acquisition. Kim and Bock (2020) further argue that this might also point towards there being one memory system that stores all of the spatial information.

2.1.1. Spatial Cognition in Virtual Reality

Nowadays, research on spatial representations and spatial cognition in general is often done via VR experiments (Creem-Regehr et al., 2024). Due to the sheer size of environments that participants need to walk or the aspects a study might want to examine, like landmarks' sizes or salience of different landmarks and presence versus absence of landmarks, doing these kinds of spatial experiments in a real environment is often very hard or sometimes even impossible. Therefore, a common way to do spatial cognition experiments has been to examine those aspects of spatial cognition in VR-based experiments, both head-mounted as well as desktop-based VR.

One of first studies of that kind was an experiment study by Regian and colleagues in 1993. They evaluated if VR had the potential to be used as a visual-spatial training tool. The participants had to do two spatial tasks, one in a small-scale space and the other in a large-scale space. The small-scale space task was operating a virtual console. In the small-scale task, the participants were assigned to one of two groups randomly and saw visual task prompts on which knob or button to press next. One group of participants was given meaningful prompts on what the press of said button would do, the other did not get meaningful prompts. The results suggested no difference between instruction types, but they found a practice effect. The large-scale task was navigating through a virtual three-dimensional maze. The same participants of the first experiment did this task. At first, the participants were given three different tours of the maze while being verbally guided by the examiner. Each tour had different start and end rooms. After these tours, the examiner told them that their knowledge of the maze would be tested, and they then had one hour to navigate through the maze and familiarize themselves with it. The participants' objective was to get from start to finish while minimizing the rooms traversed. The results showed a significant learning effect in this task. Based on the results of both experiments, Regian and colleagues (1993) concluded that VR can be a good training tool for visual-spatial tasks.

Since then, VR has become a viable tool to examine different aspects of spatial cognition. Creem-Regehr et al. (2024) argued that VR provides a kind of control over the participants and environment that is not possible in the same way in the real world. The use of VR also leads to having easier access to a bigger population in comparison to experiments reliant on real world locations (Creem-Regehr et al., 2024). Concerning what can be examined with VR, Creem-Regehr and colleagues (2024) stated four overarching topics: Cues for navigation, spatial representations, individual differences, and comparison of spatial navigation in virtual and real worlds.

Navigation cues like landmarks, spatial boundary cues, self-motion cues as well as combinations of those have been studied quite frequently using VR (Creem-Regehr et al., 2024). Teleportation can cause disorientation (Cherep et al., 2020), but nonetheless is often used because more natural locomotion, i.e., walking on a treadmill, usually requires more space that might not be available. Thus, it makes sense to look for ways to minimize this disorientation. Kelly and colleagues (2022) examined how both self-motion cues and boundary cues could minimize disorientation. They found that both boundary cues as well as self-motion cues can reduce disorientation in a virtual environment (VE). Participants had the highest amount of task errors in an open field VE and the lowest in a classroom VE with landmarks and walls (Kelly et al., 2022). While these differences were significant between the VEs in the teleportation setting without self-motion cues, they were not significant in the setting with self-motion cues (Kelly et al., 2022). However, when comparing errors of the two teleportation settings in the corresponding VEs, the setting with self-motion cues had significantly less errors in all but the classroom

VE. This points towards boundary cues being a good remedy to disorientation when using teleportation, especially when the teleportation does not offer self-motion cues. Bruns and Chamberlain (2019) examined the influence of landmarks on cognitive maps. Participants had to walk around in a virtual urban environment that was unknown to them which contained ten landmarks. The route on which they walked through said environment was fixed, as were the positions where a landmark could be. The order of landmarks was randomized in eight out of ten positions to examine the influence the different landmarks might have on recall accuracy. Bruns and Chamberlain (2019) found that the accuracy of the landmark configuration in their study correlated highly with recall of the routes as well as scene recognition, no matter the type of the landmarks in the VE. This suggests that participants that were better at recalling landmarks were also more accurate in navigation and identification of the routes and scenes.

As for spatial representation, VR has already been used to investigate the cognitive graph versus cognitive maps concepts. Warren and colleagues (2017), for instance, let participants walk through a virtual environment that was either Euclidean or non-Euclidean to examine what the spatial representation might be like. The non-Euclidean version contained two “wormholes” that could be used as teleporters between locations. During the experiment run, the wormhole routes were preferred by participants. Furthermore, the results of the experiment showed that the spatial knowledge that was acquired in the wormhole VE violated metric assumptions thus pointing towards cognitive graphs (Warren et al., 2017). Studies using “wormholes” or similar non-Euclidean settings (e.g., Jaksties et al., 2022; Schnapp & Warren, 2007; Warren et al., 2017) would not be possible without the use of VR.

Creem-Regehr and colleagues (2024) also mention individual differences in spatial navigation as something that can be easily examined using VR. The possibly underlying individual differences stated by Creem-Regehr et al. (2024) are route integration and landmarks and other cue usage among others. Regarding route integration strategies, Widdowson and Wang (2022) studied how learning strategies might differ individually in virtual wormholes environments. Their results point toward different strategies that preserve different kinds of information, thus suggesting that non-Euclidean representations might be highly diverse among individuals.

The comparison between real and virtual world spatial navigation is probably the most interesting overarching topic mentioned by Creem-Regehr et al. (2024). As Creem-Regehr and colleagues stated in their article (2024), there have been several studies that compare different elements of spatial perception in virtual and real environments (e.g., Creem-Regehr et al., 2023; Drewes et al., 2021; Kelly, 2022), but a lot of studies did not focus on spatial navigation itself. In 2011, Koenig et al. examined navigation in a real and a corresponding virtual environment of a university building. In their between-subject experiment, the participants needed to find the shortest possible way to a target location without using shortcuts, i.e., taking an elevator or asking for help. Their results showed no significant differences between the VR condition and the real-world condition. Savino and colleagues (2019) also compared VR and real-world regarding differences in navigation performance as well as spatial knowledge acquisition. Participants had to navigate through both a real-world residential district and a VR environment that was built to be as close to the real-world setting as possible. This included using map data of the real-world setting, rebuilding landmarks that are present in the real world as well as having equivalents for maps and smartphone apps used in the real-world setting. Savino et al. (2019) found significant differences in most of their navigation measures, pointing towards VR and real-world setting not being equally well-fitting for spatial navigation research. Nonetheless, they discussed what kinds of issues came to light during their experiment as well as presented guidelines on how to alleviate these issues in future studies. These two studies, while having different outcomes, also highlight how different scales of spaces might be more or less suited for spatial navigation research in VR at the current point in time.

Chapter 3, 4 and 5 will examine how different parts of the experience in VR might influence perceived, behavioral as well as physiological aspects of spatial cognition in an office building with different kinds of landmarks as navigational cues.

2.1.2. Search Tasks in Virtual Reality

Be it searching for a target location during navigation or looking for a target object, searching is an essential part of spatial cognition and orientation and has been examined using VR quite frequently. Visual searches might be the most common kind of searches in cognitive psychology (Chan & Hayward, 2013). Typically, the task is to find a target stimulus that is surrounded by distractor stimuli that differ on one or a combination of features (Chan & Hayward, 2013). This kind of search task has also been done in VR. Olk and colleagues (2018) measured visual search performance in VR and on a computer with a CRT monitor to assess if VR could be used for these kinds of paradigms. For both experiments, the task was to find a target among seven items on a virtual kitchen countertop. The target, a red soda can or yoghurt depending on the scene, was either flanked by a congruent or incongruent distractor and the target would either differ on both color and the kind of item, i.e., high discriminability, or just on the kind of item, i.e., low discriminability. In the VR experiment, participants were slower when discriminability was low, and the flanker items were incongruent. In the computer experiment, the results of the VR setting were replicated, demonstrating that VR can be a feasible way to examine common search paradigms.

Hoeg and colleagues (2017) also used the visual search paradigm in VR to examine whether binaural sound could influence the reaction time of the search task. They compared three sound cue conditions in a within-subject experiment with a three-dimensional visual search task. The cue was either stereo, binaural or no sound at all. The binaural sound offered directional information about the location of the target stimulus. Even though their sample size was quite small, the results did point towards binaural cues helping reduce reaction time by providing more information about the location of the target. These as well as similar directional cues have been used rather frequently in VR as well as Augmented Reality (AR) experiments (e.g., Binetti et al., 2021; T. Chen et al., 2018; Cunio et al., 2019; Gröhn et al., 2005; Soret et al., 2019). T. Chen et al. (2018), for instance, compared visual, auditory as well as vibrotactile directional cues in their visual search study.

Besides visual search, another search task that has been gaining momentum in VR is the search for out-of-view or hidden objects (e.g., David & Vo, 2022; Fischer et al., 2011; Grinyer & Teather, 2022). Grinyer and Teather (2022) used a modified visual search paradigm that varied the visibility of the target stimuli. The visibility was modified through two factors: the field of view (FOV) in the task, half or full field of view, and the movement of the target which was either static or dynamic. The full field of view led to faster searches regardless of the movement conditions. Furthermore, the static targets also lead to faster searches whatever the FOV conditions, leading to the combination of full FOV and static targets being the overall fastest searches. David and Vo (2022) examined search behavior for hidden objects in VR. The participants had to find objects in three trial blocks knowing that target objects could be hidden inside another object in the second and third block of trials. Searching for hidden objects did increase search times, but there was no effect on success of the search (David & Vo, 2022).

As Grinyer and Teather (2022) did mention in their study, the current body of research on searching hidden and out-of-sight objects in VR is relatively scarce. VR also does offer the opportunity to construct experiences that are not entirely possible in the real world, e.g., have constantly moving and completely invisible targets. Chapter 6 will therefore combine the insights from T. Chen et al. (2018), Grinyer and Teather (2022) as well as David and Vo (2022) to examine how directional non-visual cues might help finding invisible objects that are either static or dynamic.

2.2. User Experience and Usability of Virtual Reality

Usability and user experience (UX) are concepts from the field of Human-Computer Interaction (HCI). Usability relates to the ergonomics of interfaces of a system, how a system can be designed so users can succeed in using a system with “effectiveness, efficiency and satisfaction in a specified context of use” (Bevan, 2009). UX, as the name suggests, concerns itself with every experiential facet of using a system (Lewis & Sauro, 2021). The UX and usability of a system are vital aspects for a system to be successful and be used (Deng et al., 2010; Portz et al., 2019). Lewis and Sauro (2021) discussed several overarching design aspects and evaluation methods of UX and usability in their book section. The overarching design philosophies are *Iterative Design*, *User-Centered Design* (UCD) and *Service Design* according to Lewis and Sauro (2021). The main idea behind iterative design is to improve the first design idea of a system rapidly through multiple design and evaluation loops in which each loop is informed by the results of the previous loop. The key aspect is the rapid tests and modifications of the design through these iterative loops, as opposed to the typical development and test of hypotheses (Lewis & Sauro, 2021). UCD can be seen as the initial stage of a design process, creating the first product that then can be iterated upon. As the name suggests, this approach does emphasize the involvement of potential users to create a usable first prototype of a system or product. Among the evaluation methods discussed by Lewis and Sauro (2021) were eye tracking, survey, (software) metadata and A/B testing. A/B testing is a blind between-group test that typically test two different iterations or variations of the same product, system, website and the like per each group (Lewis & Sauro, 2021). Metadata of software and the like, referred to as analytics by Lewis and Sauro (2021), can give information about the operating time someone used a system, what a user did at what point in time with that system, as well as where they might have had problems as visible through longer than usual idle times. Surveys are typically constructed out of standardized questionnaires to collect data, both about the users as well as their experience with the product, system, software and the like. Last but not least, the method of eye tracking gathers data about several aspects of the gaze behavior of a user, like time to as well as time of fixation on an area of interest, how often this area has been looked at as well as pupil size which can be used to determine cognitive load during a task (Lewis & Sauro, 2018; Mathôt, 2018; Novák et al., 2023). With recent HMDs, eye tracking technology has found its way into VR and VR research, thus allowing those UX measures in VR as well (Mathôt, 2018; Souchet et al., 2022).

A vital part of the UX in VR is the feeling of presence or immersion. Presence and immersion are concerned with how real the virtual world seems and is presented to a user (Berkman & Akan, 2019). While presence and immersion are often used synonymously, Slater and Wilbur discussed a distinction between those two terms in 1997. According to Slater and Wilbur (1997), immersion is the technological side. Therefore, immersion describes to what extent the used technology, i.e., an HMD or other display systems, can deliver an illusion of the real world that captivates all senses (Slater & Wilbur, 1997). Presence is described as the subjective side. Slater and Wilbur (1997) call it “a state of consciousness, the (psychological) sense of being in the virtual environment” (p. 605). This is often measured via questionnaires like the Igroup Presence Questionnaire (IPQ; Schubert, 2003), in a try to grasp how much a user or participant experienced the virtual world as being as real as the real world.

Concerning VR, UX can be influenced by a plethora of other factors as well: cognitive load (Souchet et al., 2022), transitions (Men et al., 2017), properties of fonts and text (Kojić et al., 2020), input devices and interactions (e.g., Beese et al., 2022; De Paolis & De Luca, 2022; Hufnal et al., 2019), frame rate and motion sickness, sometimes referred to as cybersickness (e.g., Davis et al., 2014; Yu et al., 2018; Wang et al., 2023; Zhang, 2020) as well as multimodality (Martin et al., 2022) among others.

Cognitive load, also referred to as mental load or mental workload, describes the “relative demand imposed by a particular task, in terms of mental resources required” (American Psychological Association, n.d.). As mentioned before, measuring the changes in pupil size responses, also known as pupillometry, is a common method to measure cognitive load and mental effort (Mathôt, 2018). There have been studies that use pupillometry in VR (e.g., Lee et al., 2024; Souchet et al, 2022). The results of Lee and colleagues (2024) did suggest that cognitive load increased with the difficulty of task in VR as well, while there also was a correlation with the self-reported cognitive load via questionnaires.

Cybersickness, sometimes referred to as VR sickness, can be a side effect of any VR experience. It describes a phenomenon caused by various factors that elicit symptoms like nausea or disorientation (Chang et al., 2020). These symptoms are caused mainly by an information mismatch between the visual sensory organs and the vestibular sensory organs (Chang et al., 2020). Chang and colleagues (2020) classified the causes of cybersickness into three main factors: human, hardware and content. Hardware factors can be the display type used like a cave automatic virtual environment (CAVE) or a HMD, display mode, FOV of the hardware, latency, display resolution. Content factors of cybersickness causes can be the task itself, the optical flow, duration of content, graphic realism and the FOV of the content among others. Concerning human factors, Chang et al. (2020) mentioned prior experiences, age as well as interpupillary distance among others. Probably the most well-known measurement instrument for simulator sickness, motion sickness and cybersickness is the Simulator Sickness Questionnaire (SSQ; Kennedy et al, 1993) which is also used throughout the studies found in this dissertation. Although simulator sickness, motion sickness and cybersickness technically differ from one another through minute details, this dissertation will use these terms interchangeably to describe the same phenomenon that is typically caused by the aforementioned symptoms.

Another major factor that influences the UX in VR is interactions and input devices used in the VE (e.g., Beese et al., 2022; De Paolis & De Luca, 2022; Hufnal et al., 2019). Hufnal and colleagues (2019) compared a traditional gamepad against a native VR controller in two games regarding UX in their study. While the two games' UX ratings did not show advantages regarding the native controller, participants' perceived naturalness was higher for the native controller. Beese et al. (2022) examined two different native VR controllers, the Valve Index and HTC Vive Wand controllers, concerning UX as well as performance measures in a number of different tasks. Their findings showed that those two native VR controllers did not differ significantly in performance. UX did only differ in one task where participants noted that a particular part, a small thumbstick, of one of controllers felt more natural than the equivalent part, a touchpad, of the other controller. This finding points towards minute details of interactions being important in the UX of interactions and input devices. De Paolis and De Luca (2022) did a comparative study of the native HTC Vive controllers versus a gesture-based touchless armband. The armband did worse in their study due to the unnatural feeling of the gestures as well as the inaccuracy of gesture detection. Furthermore, participants in this study also felt that they do not need to learn much to be able to use the armband, yet they also needed the support of an expert. This is arguably a markedly contradictory statement. However, McMahan and colleagues (2016) mentioned that semi-natural interactions like this gesture-based armband in VR can lead to a similar situation to the phenomenon known as uncanny valley.

A big part of making interactions and the UX in VR more natural is incorporating all modalities in an equal ratio. As remarked by Hutmacher in 2019, there is a clear bias towards vision research in psychology, with the other modalities being left behind. This is rather unfortunate, especially considering that rather new input devices like the HaptX Gloves G1 (HaptX Inc, n.d.), SenseGlove Nova and SenseGlove Nova 2 (SenseGlove, 2022, 2023) data gloves with haptic feedback are being made available. However, Martin and colleagues (2022) illustrated in their survey report how multimodality can enhance the experience in VR. They argued that multimodality does improve task performance as well as perceived realism. Martin et al. (2022) concluded their report highlighting that creating “compelling user experiences” (p.12) will be of utmost importance for VR to succeed. While revisiting the famous reality virtuality continuum by Milgram and Kishino (1994), Skarbez et al. (2021) even argue that only a “’Matrix-like’ VR” could achieve a complete multimodal experience since the usual immersive VEs are external and can only stimulate the five basic senses but not the interoceptive senses.

Most of these aforementioned UX aspects are examined more closely in the following chapters. While cybersickness and presence are measured via questionnaires in all of the following studies in chapters 3 to 7, the different chapters focus on different aspects. Chapter 3 takes a closer look at visual parts of UX, focusing on differences in visual quality, realism as well as task load during spatial orientation. Chapter 5 examines possible cognitive load changes based on different landmark conditions during spatial navigation. Chapter 6 then compares different modalities in an invisible object search task. Lastly, chapter 7 evaluates the aforementioned SenseGlove Nova (SenseGlove, 2022) in a haptic heavy setting regarding general UX and usability aspects.

Chapter 3: Examining The Influence of Different UX and Task Factors on Spatial Orientation – Study 1

This chapter was the initial idea and precursor to study 2. It was planned as pilot and accepted as a short paper at the Mensch und Computer 2021 and will be referred to as pilot study throughout most of the later chapters.

3.1. Introduction

Spatial orientation is an essential skill in daily life, which is needed for going to work, shopping, or finding one's way in a new city. However, spatial orientation is a complex action and there can be comparatively large differences between individuals (Schinazi et al., 2013). In addition to perceiving and recognizing objects as well as their spatial positions, depth information from texture gradients, for example, or information provided by one's own motion must be processed. This information is dynamic and can foster route and survey knowledge when aligned with previous representations (Thorndyke & Hayes-Roth, 1982; Weisberg et al., 2014). In this study, the focus is on spatial orientation within a virtual environment. Virtual reality (VR) is already being used in a wide variety of research areas, such as astronomy, geology, vocational training and architecture (Hekele et al., 2021; Vasilyeva & Lourenco, 2012). Due to low-cost hardware as well as the high number of choices, the number of VR applications and use of VR continue to increase (PwC Deutschland, 2021). In this context, orientation performance is essential to find one's way in the respective VR application and to solve its tasks. In this experimental study, we investigate orientation performance by sketching one's position on a map after traveling eight previously unknown routes at different levels of complexity, i.e., different layouts as well as length of the shortest possible route to finish. Additionally, the factors *movement form*, the possibility of *landmarks being* *present* and *texture information,* i.e., degree of realism, were manipulated to test their effect on orientation performance.

3.2. Related Work

Teyseyre and Campo (2009) examined the differences in orientation in VR and the real world. In their review regarding 3D applications, Teyseyre and Campo stated that some interactions in three-dimensional virtual environments are more difficult than those same interactions in real or 2D environments. Orientation and navigation are said to be impaired, due to unfamiliar virtual environments. They point out that the abundance of interaction possibilities and the degree of freedom in the 3D applications could overwhelm and disorient users who are not used to it. They concluded that a high degree of immersive measures (gravity, real-world motion shapes, etc.) can counter this problem.

Ruddle et al. (1998) investigated the orientation ability of people within a virtual environment. The navigation task was done on a PC with mouse and keyboard as input methods. In the virtual world, participants had to follow a simple path through rooms and corridors, with the path having one to three changes in direction. In each room, the direction of the starting room had to be determined by the subjects. Paths with three changes in direction had a significantly higher number of errors. In half of the runs, the subjects were given a compass as an aid, but this did not result in significant improvement. In another study, Ruddle et al. (1999) explored whether using a head-mounted display (HMD) instead of a desktop display caused a difference. With an HMD, subjects navigated the environment faster and were better able to estimate direct distances, but there were no significant changes in estimating the direction of the traversed rooms.

To compare different forms of traversing a virtual environment, Ruddle et al. (2011) had participants either physically walking or using a joystick to move in the virtual world. They found that walking improved the creation of a cognitive map in a large, unmanageable environment. Meijer et al. (2009) had participants walk a predetermined route through a virtual supermarket. The participants were divided into two groups: photorealistic vs. non-realistic environment. A subsequent test after walking through the virtual environment showed better spatial memory performance in the group from the photorealistic supermarket. Grzeschik et al. (2020) investigated the effects of landmarks using two different virtual environments. When performing different tasks in the environment with different landmarks, the participants performed better than in the environment with only one type of landmark.

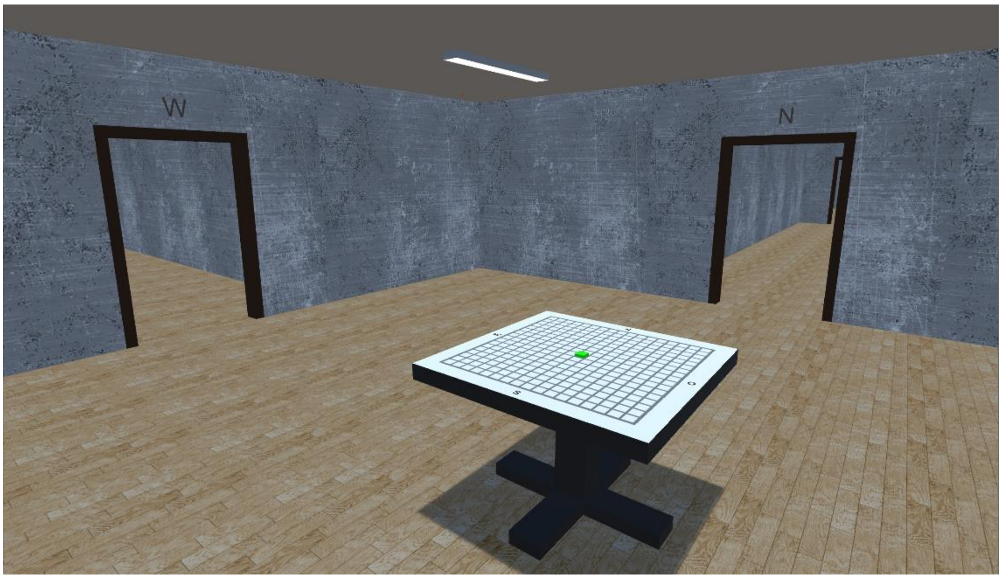
Jaksties et al. (2020) took up the topic of orientation in a virtual building with an HMD and developed a prototype to investigate orientation ability in virtual buildings. In a preliminary study, it was shown that people with better self-assessed orientation ability are also better at orienting themselves in a virtual world. This study is an extension of the work of Jaksties et al. and investigates the extent to which movement form, room design, and virtual building complexity affect orientation ability.

3.3. Methods and Materials

3.3.1. Concept and Prototype

Figure 1

Starting Room in the Virtual Environment.



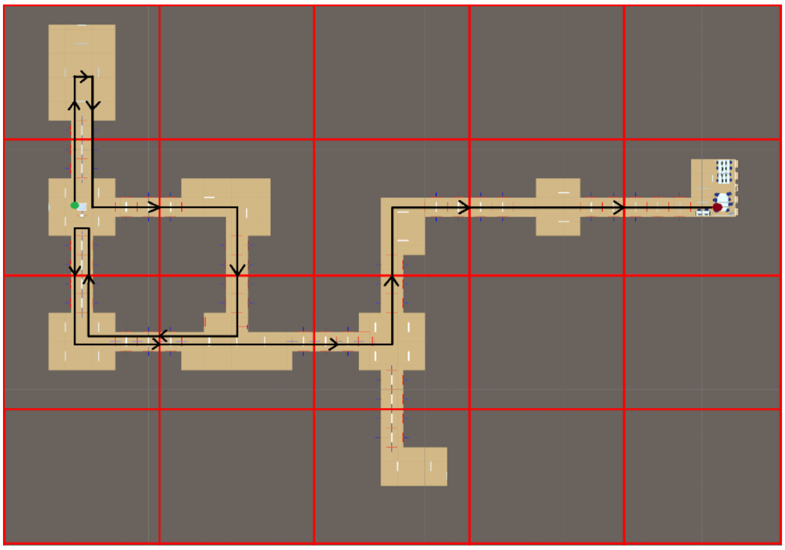
Note: This is a screenshot of the environment with textures used. The other condition uses the same color scheme as shown above, but without textures, i.e., just the colors mapped to floor, walls, and ceiling. [*Figure taken from Müller et al. (2021)].*

To investigate orientation ability in VR, participants were asked to navigate in a virtual building to find the way to a target room. The participants start in VR in a start room in which a 2D map is in the center, aligned according to the cardinal directions (see Figure 1). The map contains a grid, the cardinal directions, and a green-colored marking of the quadrilateral (chunk) in which the start room is located. No other information is included on the map.

The start room has a maximum of four open doors, one in each cardinal direction, i.e., north, south, west and east with a marking N, S, W, E above the door. The cardinal directions were only shown in the start room, in the other rooms no cardinal directions were shown. The rooms in the virtual building were generated with a self-developed dungeon generator. The dungeon generator can set a maximum of one room per chunk in the grid. Rooms in adjacent chunks in north, south, east and west direction can be connected by corridors, these connecting corridors are not counted as rooms. The complexity of a virtual building can be varied by the number of rooms, intersections and turns and loops, i.e., the number of partial paths running in a circle. An example of the arrangement of rooms of a virtual building used for the experiment is shown in Figure 2. The building in Figure 2 consists of 7 rooms that form the shortest path between the start and destination rooms, and 3 additional rooms to form a loop and two dead ends.

Figure 2

Aerial view of a virtual building



[Figure taken from Müller et al. (2021)]

The rooms can be either without textures on walls, floor and ceiling or with textures on the aforementioned elements of the room to investigate their influence on the orientation of the participants according to the conditions while having the same color scheme for both conditions. This assumes that a textured surface provides more information about the room depth than a monochrome surface without structure (Naceri et al., 2011). Furthermore, landmarks can be placed in rooms such as fire extinguishers and pictures to check if an improvement of the cognitive map and thus orientation occurs (Hardwick et al., 1983). To test the influence of the movement form, teleportation and a movement form based on natural locomotion using the *ArmSwinger VR Locomotion System* (*ElectricNightOwl/ArmSwinger*, 2016/2023) were implemented. To perform teleportation, the controller needed to be pointed in the desired direction and the participant pressed the trigger button of the controller. By holding the triggers, the participant gets a preview of the teleportation destination, and after the release of the trigger button, the participant is then teleported to the indicated position. With the movement form *natural locomotion*, the participant mimics walking arm motions on-the-spot. This leads to the arms swinging from front to back, which is detected when the grip buttons of the controllers are pressed and converted into a forward motion in VR. The participant thereby moves in VR, analogous to the natural locomotion in the real world, in the direction of the gaze. As soon as the participant stops arm-swinging and stops pressing the grip buttons, the locomotion is also interrupted. Because of physical locomotion mimicking natural walking, compared to the purely mental perception of teleportation, sensorimotor perception - and thus orientation performance - should be improved (Klatzky et al., 1998).

Figure 3

End room of a VR level

[Figure made by Jendrik Müller, previously unpublished]

Once in the end room, participants had to determine their presumed target location on a target map by specifying the resulting chunk. The deviation in terms of Euclidean distance between the actual final space and the presumed final location was documented. In addition, the time required, and the number of rooms visited or their frequency (e.g., for loops and wrong turns) were stored (see Figure 3).

3.3.2. General Procedure

At the beginning, all participants were comprehensively informed about the experiment and gave their consent to participate. Before the actual VR experiment, general questions were asked about age as well as video game experience and previous VR experience. Fatigue was assessed using the Karolinska Sleepiness Scale (KSS; Shahid et al., 2012) and motion sickness sensation was assessed using the Simulator Sickness Questionnaires (SSQ; Kennedy et al., 1993). Following the survey, the HMD was set up and adapted to each participant. Subsequently, the participants were instructed and went through the exercise trial, a simple room path in a virtual building without branches. This was done once with natural movement and once with teleportation. In the experiment, the participants passed through eight different virtual buildings in succession. After each experimental run, the subjects were asked by the experimenter about the mental, physical, and time demands, as well as performance, effort, and frustration. For this purpose, the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) was used as a measurement tool. The NASA-TLX uses values between 1 ("low") and 20 ("high") to indicate the subjective rating of the above-mentioned scales in relation to stress. After four experimental runs, a 5-minute break was taken without a headset to prevent possible motion sickness symptoms. Subsequently, the remaining four experimental runs were performed. After those remaining four trials, the SSQ and the Igroup Presence Questionnaire (IPQ; Schubert, 2003) were given to the participants to fill out. For each run, the performance values required time, number of rooms traversed, and the deviation of the estimated target location from the reached target location (Euclidean distance) were collected.

3.3.3. Study Design

A total of four factors were experimentally manipulated in a within-subject 2x2x2 design (number of rooms x movement x texture x landmark): The "number of rooms" factor as the number of rooms (7 vs. 11 rooms) that formed the shortest path between the start and finish points; the "movement" factor as natural movement by walking or by teleportation (natural vs. teleportation); the "texture" factor, which was given or not on the floor and walls (texture vs. solid color); and the "landmark" factor, where objects were additionally present or not at turning points (with vs. without landmark). The experimental design was fully counterbalanced to control for carry-over effects statistically.

3.3.4. Sample

Sixteen participants (*M* = 22 years, range 19 - 26) did the experiment. Eleven participants identified as male, five identified as female, no one identified as diverse or non-binary. Eight of 16 subjects reported previous VR experience. The participants had reported only minor fatigue according to the KSS and *none* to *slight* symptoms of simulator sickness according to the pretest version of the SSQ. Two of the 16 participants had to abort the experiment due to motion sickness during the course of the experiment.

3.4. Results

Table 1. Descriptive Statistics for the 7-point Likert scales version of IPQ.

IPQ Subscale	*N*	*M*	*SD*	*Mdn*	*Min.*	*Max.*
General Presence	14	3.43	1.5	4	1	6
Spatial Presence	14	3.99	1.11	3.9	1.4	5.8
Involvement	14	3.32	1.03	3.12	1.25	5.25
Experienced Realism	14	2.46	0.92	2.5	1.25	4.25

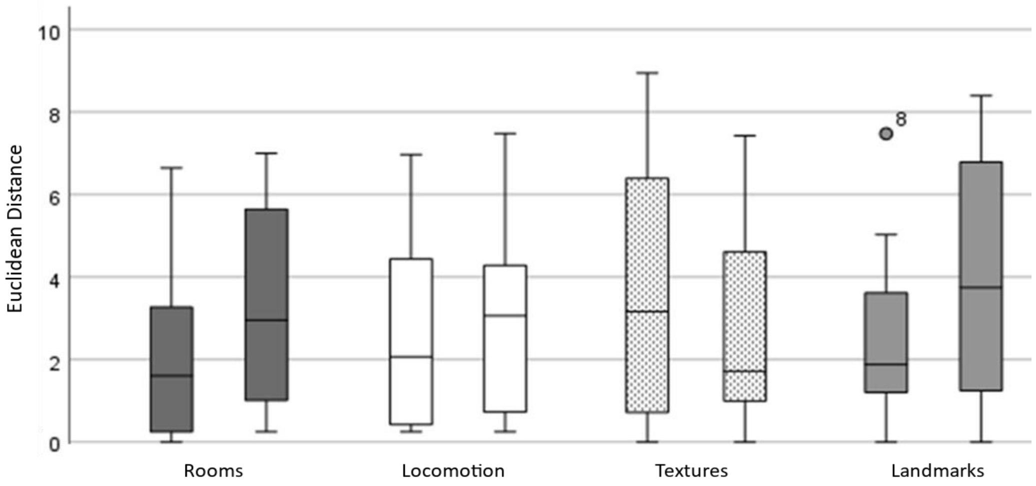
[Adapted from Müller et al. (2021)]

The results of the IPQ can be seen in Table 1. The posttest SSQ did not show any noticeable problems with motion sickness in the remaining sample. Due to the comparatively small sample, only nonparametric statistics were performed. A U-test was used to test whether subjects with VR prior experience differed from subjects without prior experience in performance (Euclidean distance of the estimation result). No significant group differences were found for either the 7-space or 11-space condition U-tests ($Z = -1.053$, $p = .293$ and $Z = -1.231$, $p = .225$, respectively). Next, we examined whether there were any changes in performance over the course of the experiment that might indicate learning or even exhaustion effects. To this end, Friedman tests for performance (Euclidean distance of estimation) were performed for both the 7-space and 11-space conditions. There were no significant changes in the 7-space condition χ^2 (3) = 4.991, $p = .172$, nor in the 11-space condition χ^2 (3) = 1.943, $p = .584$, so there were no statistically significant learning effects or cognitive fatigue. In our study, we operationalized a complex within-subject 2x2x2 design (number of rooms x movement type x texture x landmark). Results are reported below separately for each factor.

Factor 1 (7 rooms vs. 11 rooms): A Wilcoxon test was calculated. For estimation of Euclidean distance, as expected, subjects in the 11-room condition performed significantly worse compared to the 7-room condition, Wilcoxon's $Z = -3.067$, $p = .002$. Due to the small number of cases, medians (*Md*) are reported, and boxplots are shown in the figures. The median Euclidean distance of the reported target room to the actual target room for the 7-room condition was $Md_7 = 1.612$, and for the 11-room condition it was $Md_{11} = 2.958$. The corresponding boxplots can be seen in Figure 4. In addition to performance, subjective assessments of perceived stress were also analyzed. For this purpose, each NASA-TLX scale was tested for differences between the two room conditions. The Wilcoxon tests performed showed no significant differences in perceived strain, $Z = -1.854$, $p = .064$, only for the Physical Demand scale. For all other scales of task load (Mental, Temporal, Performance, Effort, as well as Frustration), significantly higher demands were reported for the 11-room condition, consistent with expectations ($Z = -2.381$ to -3.157, $p = .017$ to $.002$). Figure 5 shows the corresponding boxplots for all six scales comparing the two conditions. Overall, perceived stress was in the middle to lower range.

Figure 4

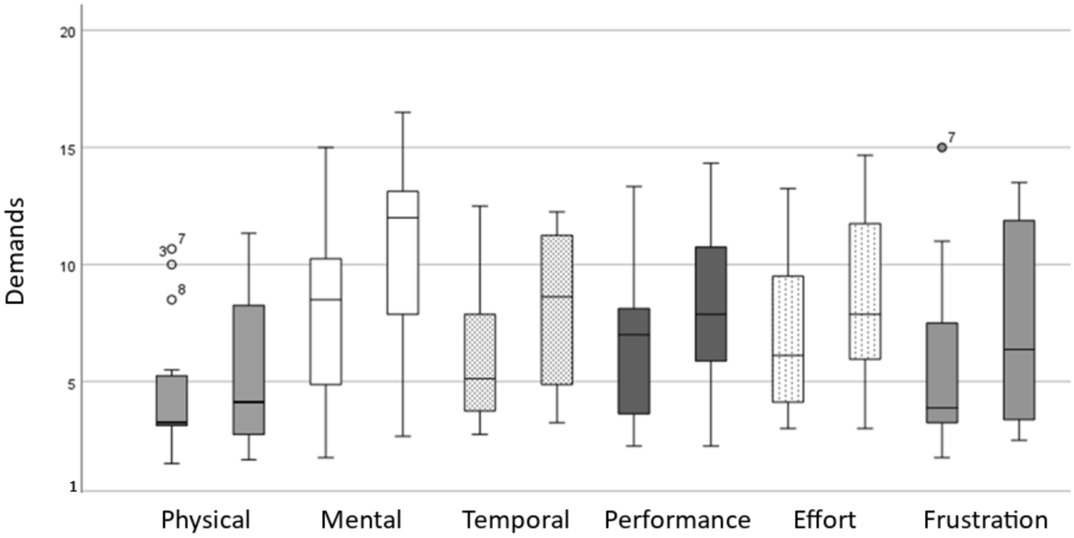
Boxplots of the Euclidean Distance of reported target room to actual target room for the different factors



Note: The two boxplots per factor show the two levels per factor: *Rooms*: 7 (left) vs 11 (right); *Locomotion*: natural (left) vs teleportation (right); *Textures*: with (left) vs without (right); *Landmarks*: with (left) vs without(right). [*Translated from Müller et al. (2021)]*

Figure 5

Boxplots for the self-reported Demands according to the NASA-TLX Scale and its Subscales



Note: The left boxes show the *7 Rooms* condition, the right boxes show the *11 Rooms* condition. [*Translated from Müller et al. (2021)]*

Factor 2 (natural movement vs. teleportation): Statistical testing with a Wilcoxon test showed no significant difference between the two movement types, $Z = -.796$, $p = .426$. No differences could be statistically validated for the movement type factor, although a trend consistent with expectations was evident. In comparison, a smaller Euclidean distance of the estimation results nominally occurred for natural motion ($Md_{natural} = 2.068$ vs. $Md_{teleportation} = 3.062$). Figure 4 shows the corresponding performance.

Factor 3 (texture, with vs. without): A comparison showed no statistical difference, Wilcoxon's $Z = 1.193$, $p = .233$. A descriptive test of the values indicated an unanticipated trend ($Md_{texture} = 3.164$ vs. $Md_{no\ texture} = 1.721$). Accordingly, the estimation results in the environment without texture information were nominally better than with texture. However, the statistical power is not sufficient to statistically validate this effect.

Factor 4 (landmarks, with vs. without): Cue stimuli such as landmarks can help with orientation, which can lead to better performance. Consistent with expectations, better performance was shown when landmarks were given, Wilcoxon $Z = -2.215$, $p = .027$. The variances of the estimation results were smaller with landmarks ($Md_{landmarks} = 1.884$ vs. $Md_{no\ landmarks} = 3.748$).

Due to the small sample size, multivariate statistics were not used to test for interactions e.g., Multivariate Analysis of Variance (MANOVA), yet initial nonparametric tests show interactions between factors consistent with expectations. However, this was shown exclusively for the 11-room condition. Participants did benefit from having the *natural locomotion* and *landmarks present* They showed the best performance in this condition ($Md = 1.207$). In contrast, the worst performance occurred when teleportation had to be used as movement and no landmarks were present in the VR environment ($Md = 2.995$). Thus, facilitative effects were absent in this condition, resulting in significantly worse performance, Wilcoxon test: $Z = -2.197$, $p = .028$, in the scenario without landmarks and with teleportation as movement.

3.5. Discussion

This experiment shows that landmarks can be vital for orientation performance. Furthermore, first tendencies regarding the interaction of the individual factors (number of rooms, movement, landmarks, textures) became apparent. The further performance values of time and number of rooms traversed will be analyzed and examined in more detail in subsequent work.

We were also able to observe that participants benefited more from the investigated factors when the virtual building was more complex. An extension of the test scenarios to more extensive virtual buildings and larger terrain areas is intended, which are also used in games (e.g., adventure or sandbox games). Likewise, during the survey it was seen that some participants tried to visualize their travel path, e.g. by hand movements on the map. Both these observations and the influence of the landmarks could be further investigated using eye tracking. It is also possible to investigate the usability of the movement forms as well as relationships between orientation performance and preference of movement type. Another research possibility is to reuse a landmark type and display it on the map. In addition, the experiment could be conducted over a longer period of time to examine how these factors affect the learning of orientation in VR.

Chapter 4: Spatial Orientation in a Complex Office Environment using Local and Global Landmarks – Study 2

The following chapter builds upon the previous pilot study. The approach was to focus on varying landmarks while keeping the other factors of the pilot study the same throughout this experiment. This was done in an effort to lessen the complexity of the study design and enhance statistical power.

Chapter 4 shines a light on the behavioral aspects of an orientation task in office buildings, while chapter 5 focuses on two physiological aspects, movement and eye pupil size, of the same task.

4.1. Introduction

Orientation is needed in a lot of everyday tasks, such as choosing the fastest way to work, finding your favorite product in the supermarket or navigating through unfamiliar or unknown territory. A basic spatial orientation ability is innate in humans. Furthermore, the sense of orientation can be improved by movement in space and orientation exercises (Taylor et al., 1999; von Stülpnagel & Steffens, 2012).

4.1.1. Spatial Cognition and Orientation

Spatial cognition describes a person’s ability to use spatial information about their surroundings to accomplish goals like identifying objects, using representations of the world like maps, and navigating through the world itself (Landau, 2002). The hippocampus is an important brain area for spatial cognition (Igloi et al., 2010; Schinazi et al., 2013), the right hippocampus being responsible for allocentric spatial representations, the left being responsible for egocentric sequential representations. Epstein and Kanwisher (1998) discovered the parahippocampal place area (PPA). The PPA responds strongly for the layout of places and Epstein and Kanwisher therefore argue that it represents places by encoding the local environment geometry. There is also the retrosplenial cortex (RSC), which integrates local places into the larger spatial environment (Epstein, 2008) and thus plays its part in spatial orientation.

Spatial orientation is one of the most prominent spatial cognition abilities. It refers to perceiving and adjusting the location according to objects in the environment (APA, 2023). The RSC also does play a role in the processing of orientation information (Schinazi & Epstein, 2010). Orientation relies on spatial knowledge acquisition as well as representation.

4.1.2. Orientation and Navigation: Landmark, route and survey knowledge

One of the most established models about spatial knowledge acquisition is the model of landmark, route and survey knowledge used by Siegel and White (1975) and by Thorndyke and Goldin (1983). This model describes spatial knowledge as a theory comprised of three stages. The first stage of acquisition is landmark knowledge. The theory argues that landmarks are extracted first from any given environment due to their salience while also being orientation dependent (Darken & Peterson, 2014). It is presumed that this knowledge takes the form of perceptual images. This kind of knowledge is directly acquired through vision. Recognition of a location and thus orientation in any environment is heavily dependent on landmark knowledge (Thorndyke & Goldin, 1983).

The next stage in the model by Thorndyke and Goldin is route or procedural knowledge. This part of knowledge acquisition is concerned about the actions one must take to follow a route. Route knowledge includes locations where one needs to take a turn, as well as the action itself. It is an integral part of navigation by encoding the spatial relationship between a point A and a point B via the route and actions that connect those two points. It also plays a part in the mental simulation of navigation.

The third stage in the model is survey or configurational knowledge. It represents distances between and locations of objects similar to a standard map. This type of knowledge develops either through repeated navigation or by learning the map of an environment (Siegel & White, 1975).

While Siegel and White (1975) claim that the acquisition happens serially, i.e., landmark knowledge is acquired at the start and needed to acquire route knowledge and so, Montello (1998) argues that the acquisition happens in a parallel fashion. Jansen-Osmann and Fuchs (2006) as well as Kim and Bock (2020) trend towards the view originally shared by Montello. Research on survey knowledge also suggests that an inhibition happens if the main task is simply getting to a finish point (Rossano & Reardon, 1999). In this case, goal specificity interferes with the acquisition of survey knowledge. Taylor et al. (1999), however, found that goal specificity might only interfere with the acquisition if the task itself is not consistent with the kind of knowledge that is to be evaluated, i.e., having a task pertaining to a survey goal will not interfere with the acquisition of survey knowledge. However, a task with a route goal may then affect the acquisition of survey knowledge (Taylor et al., 1999). Also, a major point in spatial knowledge acquisition is movement control (von Stülpnagel & Steffens, 2012). Movement control is said to give an advantage for the acquisition of landmark knowledge as well as route knowledge (Taylor et al., 1999; von Stülpnagel & Steffens, 2012).

4.1.3. Wayfinding

Perhaps the most essential skill in navigation is wayfinding, sometimes also referred to as pathfinding. It describes the basic cognitive process of reaching a destination (Freundschuh, 2001; Passini, 1981). Passini (1981) further conceptualized wayfinding as spatial problem solving and divided it into three different phases: processing of environmental information, decision-making and plan development, and execution of plans. According to Freundschuh (2001), navigation is the combination of locomotion, i.e., moving in an environment, and wayfinding.

There are three different categories of wayfinding tasks according to Allen (1999): Exploratory wayfinding, commute-like wayfinding and wayfinding to novel destinations, also called quest wayfinding by Freundschuh (2001). Exploratory wayfinding describes the process of getting to know an unfamiliar environment. A person begins the task at a known start point, walks around the location to get to know it and comes back to the start point. Commute-like wayfinding is traveling between two known points on a familiar route. Last but not least, the goal of quest wayfinding is reaching an unknown target from a known origin. Moura and Bartram (2014) investigated players' response to different wayfinding cues in 3D games using a wayfinding paradigm. In this study, participants had to play a 3D game in which they needed to escape from an island. They had to face several wayfinding challenges, all of them using one or several different wayfinding cues to help the player. Moura and Bartram found out that the wayfinding cue characteristics need to be adapted to the challenge, e.g., clear cues and landmarks for spaces with difficult visibility like mazes.

To accomplish wayfinding tasks, strategies must be applied. According to Freundschuh (2001) there are several of these strategies, for instance: Piloting, habitual locomotion and the use of internal representations. Piloting relies heavily on landmarks, basically travelling from one landmark to another and exploring the environment. Habitual locomotion typically develops after repeated navigation in an environment. After the repeated exposure to landmarks and their sequence(s), one develops commutes through habitual locomotion. The use of internal representations is the most sophisticated strategy of the three. This strategy, as the name suggests, needs an internal representation of the environment that one needs to traverse. All of these three strategies rely on landmarks and cognitive maps in one way or another.

4.1.4. Landmarks, Cognitive Maps, Sketch Maps

Landmarks play a vital role in orientation of an unknown environment. The uncertainty of an unknown environment lends itself to looking for landmarks to help orientation (Keller et al., 2020; Miller & Carlson, 2010). Grzeschik and colleagues (2021) showed that if landmarks are placed on intersections, they can support the development of route knowledge. Similarly, Wang et al. (2013) varied between different landmark conditions, i.e., no landmark, one landmark, two identical landmarks or two different landmarks on an intersection and demonstrated that participants could already use landmark knowledge for guidance after only one run in their experiment setting. Schinazi and Epstein (2010) found that the RSC processes the direction information at landmarks. Jansen-Osmann and Fuchs (2006) showed that landmarks can be helpful for orientation, as school children are able to form landmark-location relationships for wayfinding in unknown environments. Von Stülpnagel and Steffens (2012) demonstrated that a combination of using landmarks and navigation maps might also bring a disadvantage in comparison to only using landmarks in route knowledge tasks.

Cognitive maps were introduced by Edward Tolman (1948) as mental representations of a spatial environment. He showed that rats chose the right direction in a maze even after changing their start point. The terminology "map" was criticized by Downs (1981) among others as it suggests a complete spatial representation. A study of Warren et al. (2017) argues that a graph like representation might be a better analogy. Weisberg and Newcombe (2018) suggest that there are common aspects of the two approaches "cognitive map" and "cognitive graph", integrating both views while also highlighting differences in individuals' performances. Peer et al. (2021) further argues for the integration or existence of both cognitive maps and cognitive graphs, depending on the task in the environment and spatial information given by the environment.

A reliable method to measure cognitive maps or graphs in the real world (Blades, 1990) as well as in virtual environments (VE) (Billinghurst &Weghorst, 1995) are sketch maps. Keskin et al. (2018) demonstrated that sketch mapping might also not be influenced by expertise of the drawer, boding well for use in studies with heterogenous participant groups.

4.1.5. Investigating Spatial Cognition in Virtual Environments

VEs have the advantage that they are easy to modify and to control. Additionally, VEs provide a way of investigating the impact of different factors that are more difficult to investigate in the real world like changing the amount of visual realism (Meijer et al., 2009) or the method of movement (Ruddle et al., 2011b). Regarding navigation, Weisberg and colleagues (2014) found that learning patterns from VEs compared to the real-world setting were similar, while accuracy was higher in the real world. Comparing navigation performance using desktop VE versus HMD VE, Ruddle at al. (1999) showed that participants could navigate faster and had a better assessment of the direct distance between two places when using the HMD VE. However, the ability to estimate the direction of different places in relation to the own position was the same in both environments. Using a desktop VE, Jansen-Osmann (2002) showed that landmarks improve orientation when finding a way and that a route with landmarks is memorized faster than a route without landmarks. Grzeschick et al. (2021) showed that landmarks also improved the ability to navigate novel routes. Ruddle et al. (2011a) investigated the impact of local and global landmarks in a virtual marketplace on route knowledge. Participants had to navigate a desktop VE four times: without landmarks, only global landmarks, only local landmarks and with both global and local landmarks. They did expect to find that global and local landmarks would both reduce errors in the first experiment of that study, but that did not happen. In their first experiment, local landmarks could reduce the number of errors participants made while global Landmarks did not. In both of their experiments, local and global landmarks are situated inside the virtual marketplace. Ruddle and colleagues suggest that the recall of the direction at decision points might be influenced by a landmark-action pair rather than the visual cue of the landmark itself. According to Stankiewicz and Kalia (2007), there is also a possible competition for cognitive resources when there are different kinds of landmarks available. Stankiewicz and Kalia set up three experiments to test structural, i.e., the configuration of hallways, and object landmarks and the acquisition of landmark knowledge. For object landmarks, they used pictures that were placed on the wall in the hallways. In their first experiment, they examined how structural and object landmarks might differ in knowledge acquisition if the information content of both is equal. The structural landmarks in this experiment were remembered with higher accuracy than the object landmarks. For their second experiment, Stankiewicz and Kalia (2007) investigated how increased information content of the object landmark might affect the accuracy of remembering. There was no difference between the structural and the object landmark, meaning the increased information did enhance the accuracy of the object landmarks but not to a point where they were better than the structural landmarks. Regarding their third experiment, the object landmarks were arranged in a way that they were identical in adjacent hallways. This meant that both the structural and object landmarks were not independent from each other. Structural landmarks were again remembered more accurately than the object landmarks. The results of experiment 3 suggest that dependence is not reason for the superior memory accuracy of the structural landmarks. Müller et al. (2021) developed a virtual reality (VR) software to explore connection between spatial cognition and different factors like landmarks, complexity of the environment, method of movement and texture. With the developed VR software, a positive impact of local landmarks could be confirmed.

In the present study, the aim was to investigate the spatial orientation ability in a VR office building. The focus lies in the visual aspects of VR and spatial orientation. VR is a useful tool in researching spatial orientation since several aspects can be controlled or changed rather easily, such as the environment in which the participant operates. While it is either cumbersome or nearly impossible to change either the existence or arrangement of landmarks in a real-world setting (Loveland et al., 1995), doing so in VR is almost trivial. Péruch et al. (2000) argued that studies have shown that spatial representation is mostly the same between the real and the virtual world and that there might occur a transfer of spatial information from one to the other. Witmer and colleagues (1996) demonstrated such transfer and therefore argue that virtual environments can be used for learning complex routes. A study by Dong et al. (2021) also revealed similar performance for spatial cognition measures in both the real and the virtual environment.

The present study aims to examine the influences of different kinds of landmarks on spatial knowledge in a quest wayfinding task in a complex office building in VR.

Based on the results by Ruddle et al. (2011a), Stankiewicz and Kalia (2007) and Müller et al. (2021), we hypothesize that the assessment performance in VR should be better in conditions with landmarks compared to conditions without landmarks (**H1**).

Furthermore, the orientation assessment at the end of a wayfinding task should benefit from outdoor landmarks rather than indoor landmarks due to better recall of the more salient outdoor landmarks (**H2**). This hypothesis is based on Stankiewicz and Kalia's findings (2007) on the salience of landmarks and their possible storage in memory.

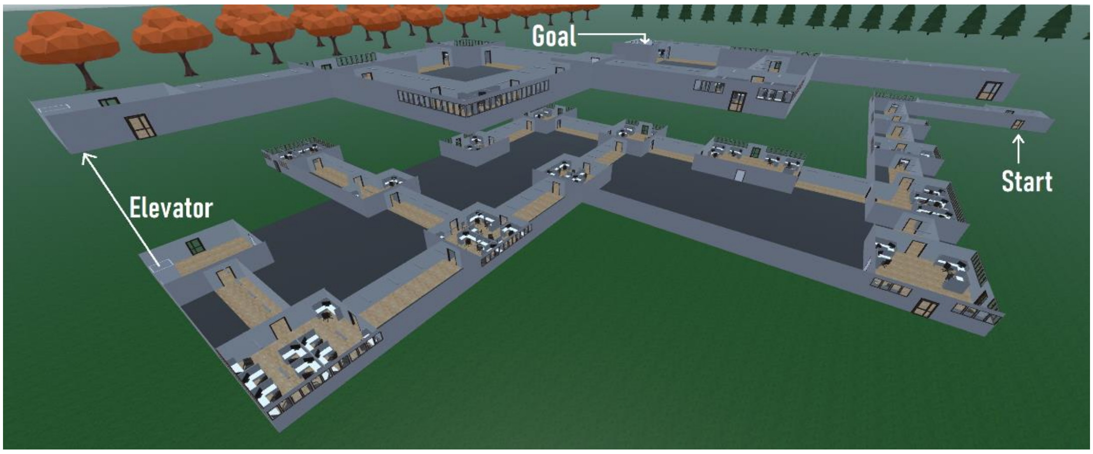
Moreover, we hypothesize that the time for orientation assessment should be better in a outdoor landmark only condition compared to a combined indoor and outdoor landmark condition due to the competition of cognitive resources and a possibly split attention (Sweller et al., 1998; Tarmizi & Sweller, 1988) which should result in longer processing times for participants, as suggested by Stankiewicz and Kalia (2007) (**H3**).

4.2. Methods and Materials

4.2.1. *Prototype of the Virtual Environment*

Figure 6

Exploded View of a generated Two-story Building



[Figure taken from Müller (2022)]

To test our hypotheses, we developed an application using the Unity3D Engine that can generate a building with a randomized room structure (see Figure 6). The building is created in a predefined area which is divided into multiple chunks. First, the entrance room is placed in the chunk at the center of the area. Starting from this room the main path connecting the entrance with the elevator is generated. To build the path randomly selected rooms are placed successively in a chunk next to the last placed room. The rooms are all rectangular and of similar complexity. They are equipped with office furniture (cubicles with chairs, keyboards, monitor, desks) which are distributed in the room either close to the walls, in the middle of the room or both. After the main path of the ground floor is created additional rooms are placed in a random chunk next to a room with an unoccupied exit. Following the creation of the ground floor, the upper floor is generated. The generation of the upper floor follows the same pattern as the generation of the lower floor. The difference is that the main path starts with the elevator and ends with a specific office room representing the target. Additionally, the number of usable chunks is restricted through the ground floor to make sure that both floors are lying on top of each other. After placing all the rooms, their entrances are connected through corridors and if wanted indoor landmarks are placed at junctions (see Figure 11, 12 and 13). At last unused exits are closed with a door. An example of a possible junction with outdoor landmarks and closed doors can be seen in Figure 7. There are several rooms like this. Depending on the generated buildings and rooms as well as their placing inside the buildings, those bigger rooms might have two, three or four open doors and two, one or no closed doors or door-like windows, respectively. Windows and door-like windows, as seen in Figure 7, are present in every building, no matter the landmark condition. Neither closed doors nor door-like windows can be opened while experiencing the prototype.

Figure 7

Example of a big office room with windows on the right side and a closed door on the left.

[Figure from Beese et al. (under review)]

The complexity of the floors can be varied by adjusting the length of the main path, the number of junctions, the number of additional rooms, and by stating if a loop should be created. An example for the ground floor and the upper floor of a generated building is shown in Figures 8 and 9. In the next step walls and ceilings are created that cover the building. Furthermore, windows are placed in rooms that lie next to the exterior wall to make it possible for the player to look outside. Figure 7 gives an insight into a complete building with the ceiling removed and the upper floor lifted. Outside of the building are distinct landscapes in each cardinal direction like two different kinds of trees, a mountain, and historic buildings that serve as outdoor landmarks (see Figure 10). In case outdoor landmarks should not be present, these are made invisible and outside of the building is just a simple green plain.

Figure 8

Plan of ground floor in the generated building

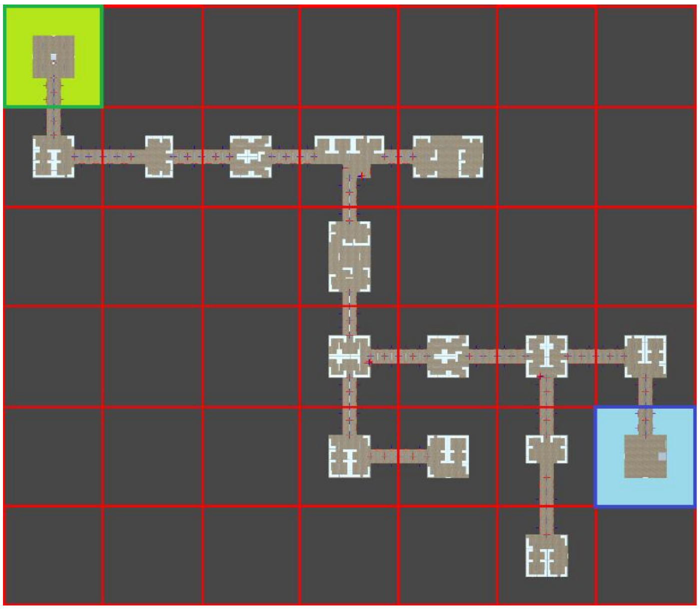
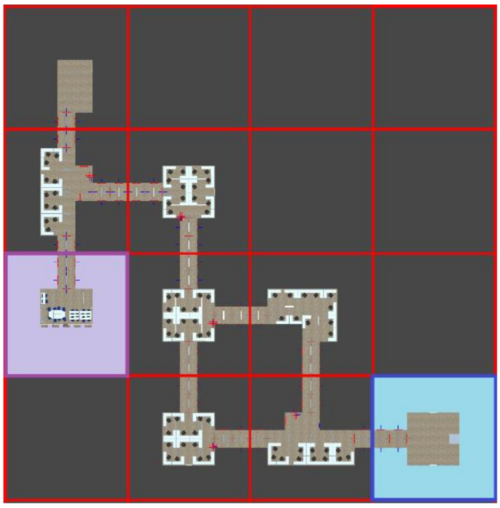


Figure 9

Plan of upper floor in the generated building

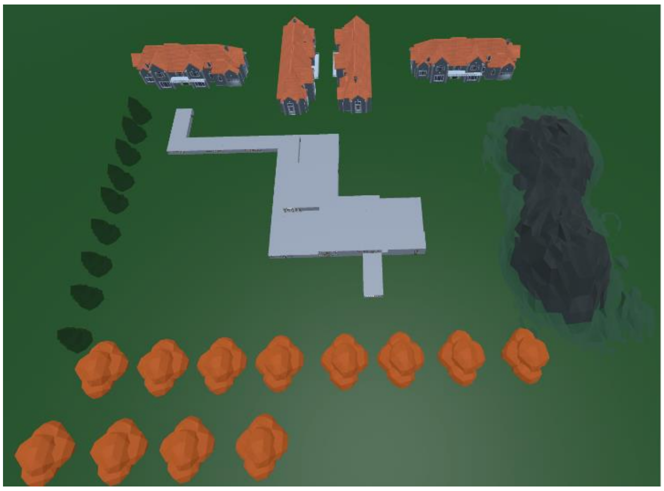


Note: The start room is marked green, the elevator room of the upper floor is marked violet, the end rooms for both floors are marked blue.

[Figures 8 & 9 taken from Müller (2022)]

Figure 10

Aerial view of Outdoor Landmarks



Note: The houses are always located in the north, mountain in the east, pine trees in the west and trees with red-orange leaves in the south.

[Figures 10 to 13 from Beese et al. (under review)]

Figure 11

Fire Extinguisher as Indoor landmark

Figure 12

Couch as a local landmark

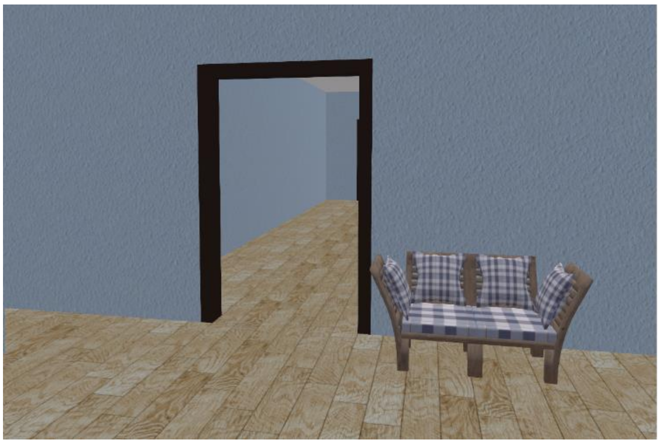


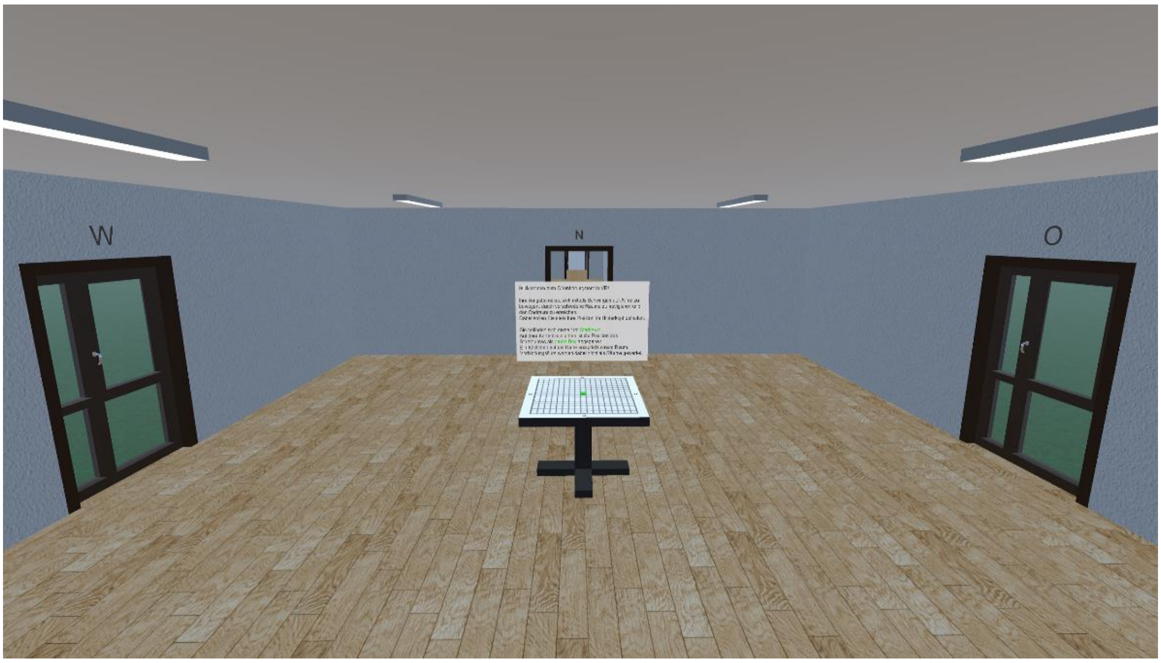
Figure 13

Painting as local landmark in the building

Note: The indoor landmarks are always located at junction decision points. Any instance of indoor landmarks is only available once per level, both floors having their own unique set of indoor landmarks.

Figure 14

Start Room with a Floating Instruction Text, a Map, and Doors and Windows in each of the cardinal directions.



[Figure from Beese et al. (under review)]

To present the virtual building a VR Setup with the HTC Vive Pro Eye and the HTC Vive Wand controllers were used. The HMD has a resolution of 1440 x 1600 Pixel per eye, a 110° FOV, and a refreshment rate of 90 Hz. The player starts at the entrance (see Figure 14) of the building where the cardinal points are indicated through letters over the doors (N, E, S, W) and an empty grid map including the cardinal directions. They were provided with the task of delivering pizza to the conference room (see Figure 15) on the upper floor. To move through the building, the *ArmSwinger VR Locomotion System* was used. Participants have to press the Grip Button of both controllers and swing their arms like they were walking to move through the environment. Upon reaching the end of a floor, they had to sketch the main path of the respective floor. They could archive this through selecting the chunks on a grid map by touching the desired grid with virtual hands. One of these grid maps is placed next to the elevator and the other next to the entrance of the target room which can be seen in Figure 15.

For this study, five buildings were generated. One of these buildings is made for the tutorial and consists of a ground floor with five rooms. This tutorial building was used to familiarize the player with the setting and the controls. Audio files were played at the entrance and upon reaching the elevator, which described the task to the player, so all players had the same starting information. In the subsequent trials, two-story buildings were generated to further investigate orientation performance at different building levels. The ground floor in these buildings consisted of eleven rooms on the main path with three junctions and five additional rooms. Each upper floor had seven rooms on the main path and a loop. Additionally, there was one extra junction that led to a dead end.

Figure 15

End Room with Sketch Map, Office Furniture and Windows showing the outside.

[Figure from Beese et al. (under review)]

4.2.2. Questionnaires

The participants had to fill out a pretest and a posttest questionnaire. The pretest questionnaire consisted of a questionnaire pertaining to general aspects, i.e., age, sex and socioeconomical status, and previous experience with video games in general and VR in particular as well as the Karolinska Sleepiness Scale (KSS; Shahid et al., 2012) and the pretest version of the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993). The posttest questionnaire consisted of the Igroup Presence Questionnaire (IPQ; Schubert, 2003), the posttest version of the SSQ and the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988).

The Karolinska Sleepiness Scale (KSS; Shahid et al., 2012) comprises a single item, rated on a 9-point response scale, which prompts the participant to rate different levels of their own current sleepiness ranging from 1 (*extremely alert*) to 9 (*extremely sleepy, fighting sleep*).

The Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) is a 16-item questionnaire, each item referencing a symptom typically associated with Simulator Sickness and typically given both pre and posttest. For each possible symptom, participants indicate how strongly it currently affects them on a 4-point scale (*none*, *slight*, *moderate,* or *severe*).

The Igroup Presence Questionnaire (IPQ; Schubert, 2003) is a 14-item questionnaire to assess the feeling of presence in virtual reality. It is constructed out of three subscales pertaining to spatial presence, involvement, and experienced realism as well as another item pertaining to the general feeling of presence. The participant answers on a 7-point Likert scale, from 0 (*strongly disagree*) to 6 (*strongly agree*), on how much they agree or disagree with the given statements.

The short version of the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) is designed to assess six different workload factors. The participant is asked to rate the workload of a given task on a scale from 0 (*very low*) to 20 (*very high*). The six different factors are *Mental Demand*, *Physical Demand*, *Temporal Demand*, *Performance*, *Effort* and *Frustration.*

4.2.3. General Procedure

The experiment was in compliance with the APA Code of Ethics (2017), the WMA Declaration of Helsinki (2013) including all their respective amendments at the time of experiment and has been approved by the ethics committee of the social sciences department of the University of Kaiserslautern-Landau. At the beginning, the participants received information about the procedure of the whole experiment and gave their informed written consent. Then they had to fill out the pretest questionnaires. After this, the VR part began with fitting the HMD to the participants and explaining the controls. After these two steps, the participant had to calibrate the eye tracking of the HMD via the SRanipal SDK's point fixation calibration. The participants had to navigate through five different buildings, one for practice, the other four as actual trials. The four trial buildings were generated beforehand according to the Prototype section. These four buildings were the same and in the same order for every participant. In the end room of each floor, the participants should sketch the shortest possible way from start to finish on a 2-D map and press a button when they are done. After the button press, the map showed the actual position of the end room and participants were instructed to either step into the elevator or a voiceover said "Thank you for the pizza" depending on whether it was the first or second floor of the building. Task instruction was given auditorily before practice trials started and also when reaching and completing the final rooms in the actual trials. First, the participants navigated through the tutorial building as a practice trial, where landmarks at junctions and the outdoor landmarks were present. After that, the participants navigated the other four buildings where the presence of landmarks at junctions and outdoor landmarks was varied. The order of the landmark conditions in Buildings 1 to 4 were counterbalanced among the participants. For instance, the first participant would have no landmarks in the first building, outdoor landmarks in the second, indoor landmarks in the third and both in the final building, while next participant would have the same conditions but in a different order. Other than the possible landmarks as well as the cardinal directions (see 9), there were no other signs or any other way to guide the participants along their way to the end room. In between building 2 and 3, there was a mandatory pause in which the participants had to take of the HMD to combat possible symptoms of cyber sickness. After Building 4, they had to fill out the posttest questionnaires and were debriefed. The VR part took about 75 to 90 minutes including the break and the questionnaires did take about 15 minutes to complete.

4.2.4. Analysis of Orientation Assessment

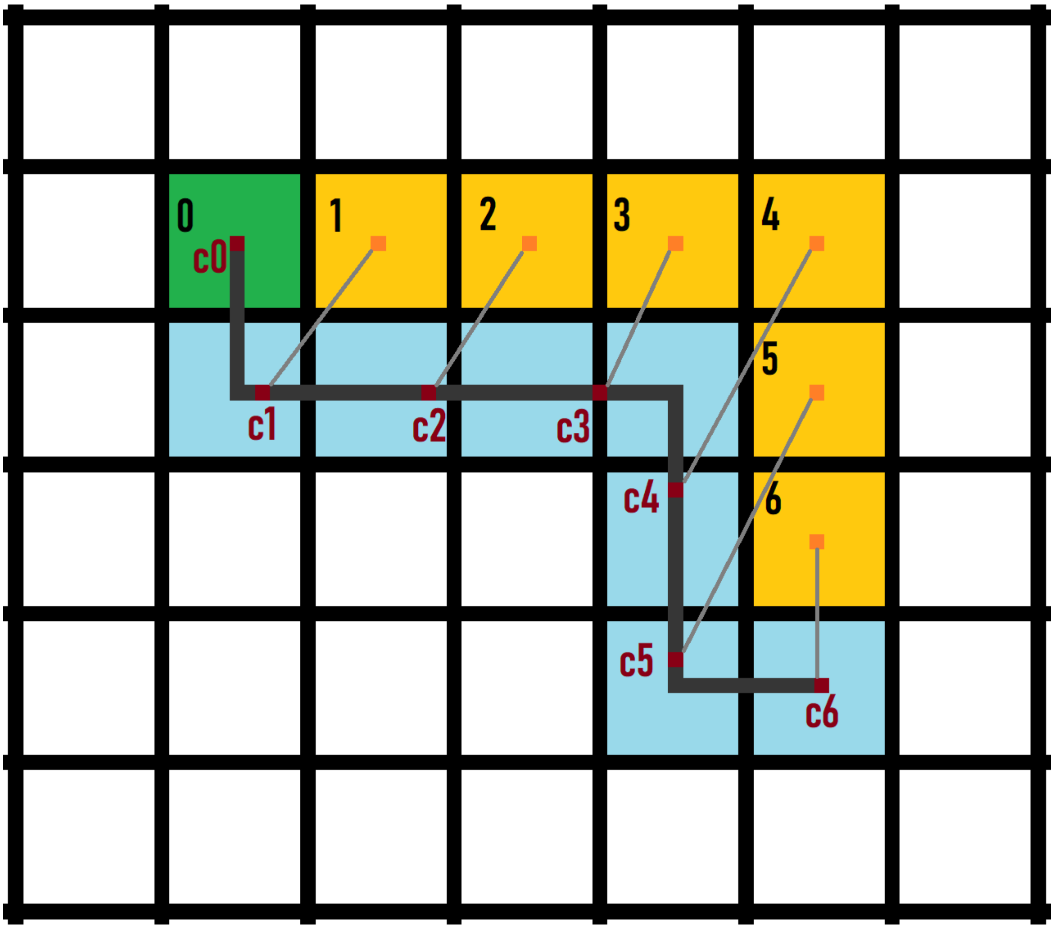
To evaluate the orientation assessment of the participants, the difference between their sketched maps and the shortest way possible as well as the time taken to sketch was calculated. The difference in accuracy of the map was calculated by adding up the Euclidean distances of each room of the shortest way possible to the corresponding part of the sketch map. To determine the corresponding part of the sketch map the following formula was used:

$$c_i = \frac{g}{r} * i$$

With c_i being the corresponding part for room number i on the shortest path, g being the number of marked chunks, and r being the number of rooms on the shortest path. For example, a participant marks seven chunks as the direct way on the upper floor, which consists of only six rooms not counting the start room. The corresponding part for the first room, the one adjacent to the staring room is at $\frac{1}{6}$ between the center of the first and the second marked chunk. Additionally, for the evaluation of the orientation action itself the time to reach the end of each floor, and the number of rooms traversed were recorded. A visualization of this example can be seen in Figure 16.

Figure 16

Visualization of a Sketch Map



Note: The start is marked green, the shortest way possible is yellow-orange and the user input is marked blue. For each room 1-6 the corresponding point c1-c6 on the sketched path is calculated. To evaluate the sketched path, the Euclidean distances between the center of each correct chunk and the corresponding point were calculated. [*Figure taken from Müller (2022)]*

4.2.5. Sample

Twenty-five individuals (18 male, 7 female, 0 non-binary) ranging from 18 - 31 years (*M* = 24.28, *SD* = 3.868) participated in the user study. Three people had to cancel due to severe symptoms of simulator sickness after the first building, therefore only data of the remaining 22 participants were analyzed. All participants were recruited via the university email newsletter, and they received either financial compensation or study credits for their participation. All participants reported normal or corrected to normal vision and hearing. According to the KSS, the participants were mostly *rather alert* (*Md* = 3, *IQR* = 1). Participants reported that *none* or only *mild* symptoms of simulator sickness were present in the pretest SSQ, while reporting *none* or *mild* to *moderate* symptoms in the posttest SSQ.

4.3. Results

The results regarding feeling of presence and task load factors can be seen in Table 2 and Table 3. Of the 22 participants that completed the study, twelve reported previous VR experience. In order to exclude possible biases between participants with and without VR prior experience for the main analyses (hypothesis testing), U-test was carried out. Possible differences were tested for the dependent variables (1) "time to reach the goal", (2) "number of rooms traversed", (3) "time for orientation" and (4) "inaccuracy of orientation". The dependent variable "time for orientation" represents the time participants needed to draw their sketch map in the end room. The dependent variable "inaccuracy of orientation" represents the deviation of their own sketch map drawing from the shortest way possible, meaning the higher the deviation from the shortest way possible the more inaccurate the orientation. There were no statistically significant differences between individuals with and without VR experience for any of the four dependent variables (all *p*'s > .260). Therefore, further statistical analyses were conducted for the whole sample of *N* = 22 without distinguishing between individuals with and without prior VR experience. Table 4 reports the descriptive statistics for all four experimental conditions and the four dependent variables (performance measures).

For all four dependent variables, the assumption of normal distribution was given (Kolmogorov-Smirnov *p* > .20).

Table 2. Descriptive Statistics for Task Load (NASA-TLX).

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration
Mdn	15.50	7	7	15	13.50	11
IQR	2.50	4.50	7.50	6	4.25	5.50

Note: *N* = 22; *Mdn* = Median, *IQR* = Interquartile Range; [*Table from Beese et al. (under review)]*

Table 3. Descriptive Statistics for Presence (IPQ).

IPQ Subscale	*N*	*M*	*SD*	*Mdn*	*Min.*	*Max.*
General Presence	22	3.09	1.82	4	0	6
Spatial Presence	22	3.48	0.88	3.5	2	5.2
Involvement	22	2.65	0.81	2.5	1.5	4.5
Experienced Realism	22	2.42	0.68	2.25	1.75	4

[Adapted from Beese et al. (under review)]

Table 4. Descriptive Statistics for the four Experimental Conditions and four Dependent Variables.

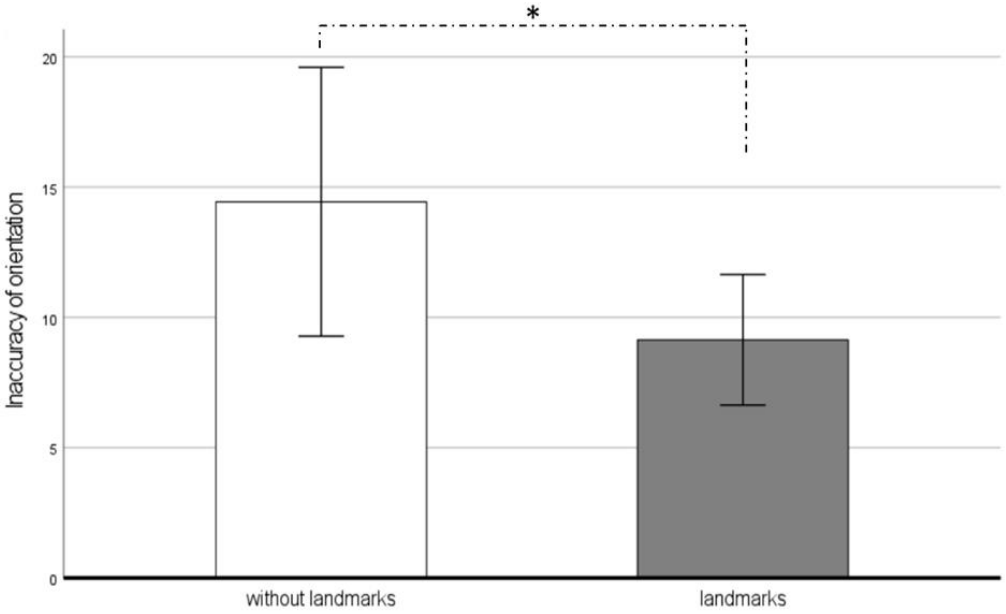
	Without landmark		Landmark outdoor		Landmark indoor		Indoor and outdoor	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Time to reach goal	191.77	80.60	179.18	79.40	156.05	48.49	191.00	96.69
Rooms Traversed	10.27	4.84	9.27	3.45	8.73	2.64	9.73	4.07
Time for orientation	42.33	21.30	32.68	22.57	43.82	28.79	43.00	29.88
Inaccuracy of orientation	14.44	11.63	8.54	9.39	10.51	10.30	8.38	9.05

Note: *N* = 22; *M* = Mean, *SD* = Standard Deviation; [*Table from Beese et al. (under review)]*

For statistical analyses, contrasts (a priori assumptions) were tested with a repeated measure Analysis of Variance (ANOVAs). The necessary condition of the sphericity was achieved for all four dependent variables (Mauchly tests all *p*'s > .252). To test the hypothesis that landmarks lead to better orientation performance compared to no landmarks, a contrast (no landmark condition vs. all three landmark conditions together) was tested. There was a statistically significant difference in the inaccuracy of orientation between the without landmark condition (*M* = 14.44, *SD* = 11.63) and the landmark conditions (*M* = 9.14, *SD* = 5.64), *F*(1, 21) = 4.585, *p* = .044 (see also Figure 17). This is a large effect, η_p^2 = 0.179 (Cohen, 2013), which could already be statistically confirmed with a small sample. The result shows that no landmarks lead to higher inaccuracy of orientation than using landmarks (see Figure 17), therefore hypothesis 1 can be maintained.

Figure 17

Results Hypothesis 1 – Inaccuracy of Orientation – No Landmarks vs Landmarks



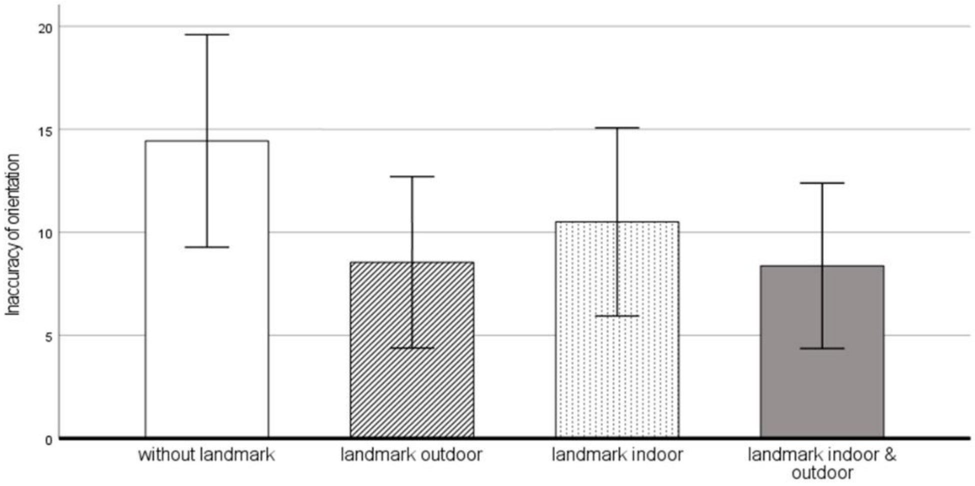
Note: Inaccuracy of orientation is measured as Euclidean distance between sketched map and shortest possible way in the virtual building as mentioned in the *Methods* section. Thus, the best possible score would be *0,* sketching the exact same shortest way as it is situated in the virtual building. * = p < .05. [*Figure from Beese et al. (under review)*]

Hypothesis 2 postulated that participants should benefit more from outdoor landmarks, as they offer higher salience and more information than indoor landmarks. Therefore, it was tested whether there are advantages of the outdoor landmarks condition compared to indoor landmarks. We tested this assumption for both the inaccuracy of orientation and the time for orientation. In line with the hypothesis, participants performed better in the outdoor landmark condition compared to the indoor landmark condition (see Figure 18).

Furthermore, the participants needed less time for orientation when the landmarks were outdoors (see Figure 19). They were therefore faster in performing the orientation task and also better when landmarks were outdoor than indoor.

Figure 18

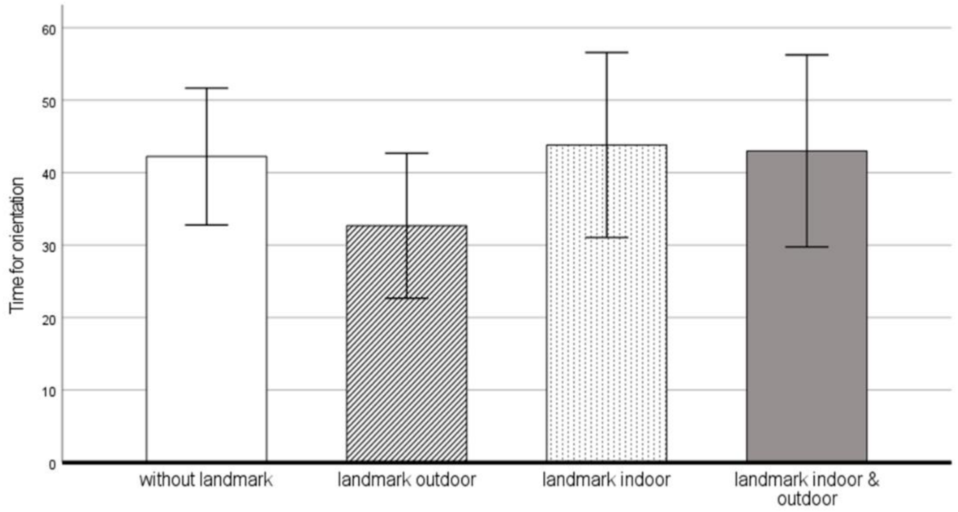
Results Hypothesis 2 – Inaccuracy of Orientation – Different Conditions



Note: Inaccuracy of orientation is measured as Euclidean distance between sketched map and shortest possible way in the virtual building as mentioned before. [*Figure from Beese et al. (under review)]*

Figure 19

Results Hypothesis 2 – Time Needed for Orientation – Different Conditions



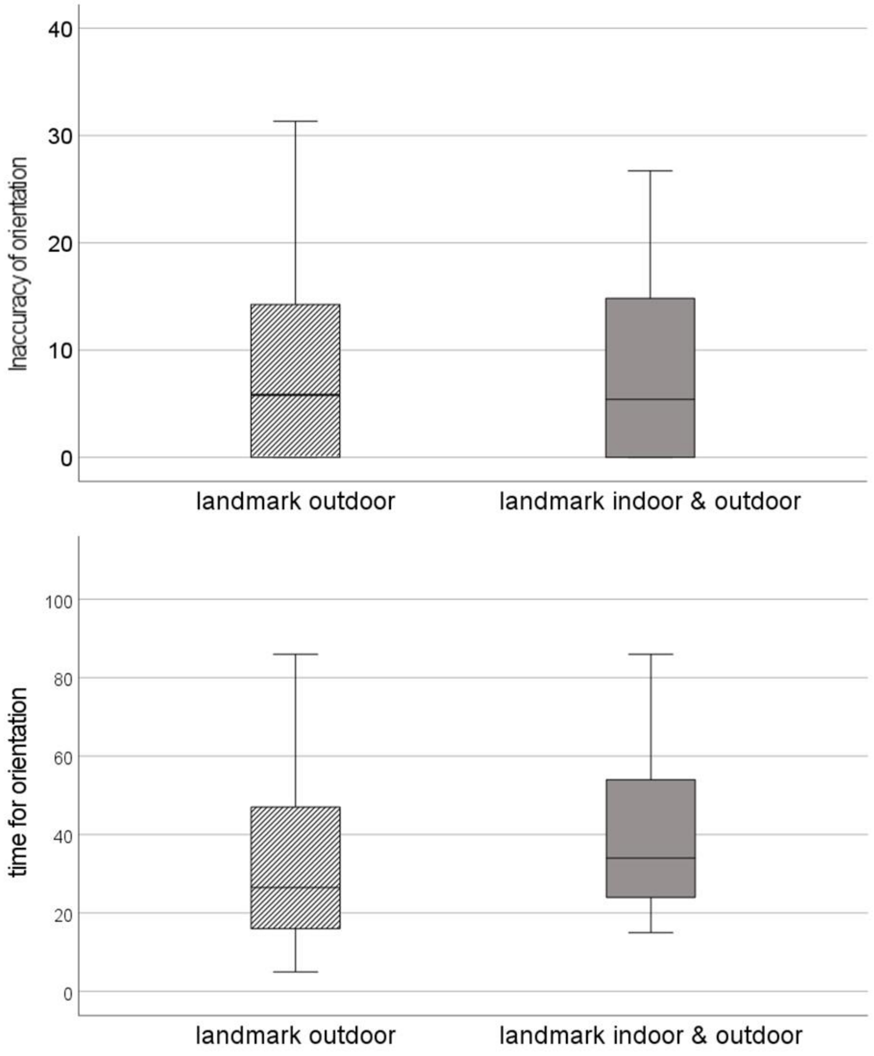
Note: Time taken for the sketch mapping in seconds. [*Figure from Beese et al. (under review].*

However, although there is a tendency for differences, these could not be statistically confirmed by the tested contrasts. There was no statistically significant difference in inaccuracy of orientation, between the outdoor landmark condition (*M* = 8.54, *SD* = 9.39) and the indoor landmark condition (*M* = 10.51, *SD* = 10.30) of -1.96 (*SE* = 3.24), *p* = .551, η_p^2 = 0.017. There were also no statistically significant differences in the time for orientation between the landmark outdoor condition (*M* = 32.68, *SD* = 22.57) and the landmark indoor condition (*M* = 43.82, *SD* = 28.79) of 11.14 (*SE* = 6.90), *p* = .122, η_p^2 = 0.11. There was a small effect (η_p^2 = 0.02) in inaccuracy of orientation and a medium effect (η_p^2 = 0.11) in the time for orientation. The necessary statistical test power was not achieved with the given sample size. For this reason, the hypothesis cannot currently be sustained.

As a third hypothesis, it was assumed that participants in the "indoor & outdoor landmark" condition, in contrast to the "outdoor only" condition, would need more time for the orientation assessment. This should occur because the representations of the indoor landmarks interfere with the particularly helpful representations of the outdoor landmarks during evaluation. For this reason, less cognitive resources should be available for the assessment task of orientation, thus increasing the processing time.

Figure 20

Results Hypothesis 3



[Figure from Beese et al. (under review)]

In contrast to the time for orientation, however, the inaccuracy of orientation in the assessment task should not differ since the helpful outdoor landmarks were also given in the indoor & outdoor landmark condition. In line with the hypothesis, participants showed no differences in inaccuracy of orientation concerning Euclidean Distance, however in the time for orientation (see Figure 20). There was no statistically significant difference in the inaccuracy of orientation, between the “indoor & outdoor” landmark condition ($M = 8.38$, $SD = 9.05$) and "outdoor" landmark condition ($M = 8.54$, $SD = 9.39$) of -0.17 ($SE = 2.44$, $p = .465$, $\eta_p^2 = 0.0002$. As hypothesized, participants in the "indoor & outdoor" landmark condition needed more time for the orientation assessment compared to the "outdoor" landmark condition. However, we were unable to statistically confirm differences in time required between the "indoor & outdoor" condition ($M = 43.00$, $SD = 29.88$) and the "outdoor" condition ($M = 32.68$, $SD = 22.57$), difference of 10.32 ($SE = 8.09$), $p = .216$, $\eta_p^2 = 0.072$. Although the non-existent difference in inaccuracy of orientation was consistent with the hypothesis (zero effect, $\eta_p^2 = 0.0002$), the hypothesized effect for time required for the orientation assessments could not be statistically confirmed. The sample size was not sufficient to statistically confirm the medium effect ($\eta_p^2 = 0.072$). For this reason, the hypothesis cannot be sustained at the moment.

4.4. Discussion and Conclusion

This study implemented a VR prototype of generated two-story buildings in which the participants needed to find the target room and sketch the shortest possible way to this room on a map at the end.

According to hypothesis 1, it was predicted that participants perform better in the sketch mapping, if they have landmarks available for orientation. The results show a significant difference in accuracy of the maps between the runs with landmarks and those without landmarks, in favor of the landmarks being present (see Figure 19). This confirms the assumption of the hypothesis that landmarks are an important orientation factor. According to hypothesis 2, it was predicted that participants perform better in the part of assessment, if outdoor landmarks are present instead of indoor landmarks. While the hypothesis could not be confirmed due to the statistical power, there might still be an argument to be made towards better assessment performance when only outdoor landmarks are available when looking at the data. This could be due to an aforementioned competition between the two kinds of landmarks, similarly to the competition between structural and object landmarks noted by Stankiewicz and Kalia (2007). According to hypothesis 3, it was predicted that the time to sketch the map should be shorter when outdoor landmarks are present compared to the indoor and outdoor landmark conditions while the accuracy of the map should not be different. While this hypothesis could also not be confirmed at the moment, the medium effect size and data of this sample seems to suggest an argument for the hypothesis. Those trends towards the aforementioned effects without being statistically significant can be attributed to the sample size of this study. There might also be possible training effects in the presented study. Contrary to von Stülpnagel and Steffens (2012) previous VR gaming experience did not seem to affect performance. Since we also recorded the number of rooms traversed as well as the time needed to reach the goal, besides the already discussed measures, therein might lie an explanation. Building on previous work (Müller et al., 2021; Ruddle et al.,2011a), indoor or locally arranged landmarks might be a good reference guide to navigate without a lot of errors. Also building on the previous work of Ruddle et al. (2011a) and Ruddle and Lessels (2009), outdoor or globally arranged landmarks might not introduce or reduce errors in the navigation but seem to make the retrieval more accurate.

Furthermore, the existence of both landmark types simultaneously might make the retrieval of orientation information harder. It is possible that one kind of landmark might be more useful in the retrieval of orientation while the other kind of landmark might help in the task of navigation and orientation itself. A reason for this might be higher cognitive load (Sweller et al., 1998) due to both types of landmarks causing higher extraneous cognitive load. Another reason could be split attention (Tarmizi & Sweller, 1988) while both types of landmarks are present. This needs to be addressed in future research as the data of our sample suggests this while not being statistically significant, so it could neither be denied nor accepted.

While this study tried to make each building progressively more complex, similarly to Kim and Bock (2020), to avoid training effects, it did not necessarily add more decision points in the later buildings as the shortest number of rooms needed to remain the same. This study, however, did add a loop into each upper floor to make it more complex since the upper floor had fewer rooms than the lower floor.

Nonetheless, the differences in performance that can be attributed to the presence of the different kinds of landmarks are worth investigating further, especially how those different kinds of landmarks might help one to traverse on higher-than-ground floors. There might also be a case of different kinds of landmarks helping in different parts of knowledge acquisition. Using VR helps to implement these kinds of experiments rather easily regarding the environment as well as making it possible to control confounding variables. Doing so in the real world is either cumbersome or impossible, as mentioned by Loveland and colleagues (1995). While this study used a prototype to randomily generate several buildings a priori which were then used across all participants, a next step can be to randomily generate buildings during the actual experiment. This could be done based on several factors that are established a priori or in an adaptive way to progressively make each trial of the experiment more complex. As Péruch et al.

(2000) as well as Dong and colleagues (2021) argue that performance and spatial representation are very similar between the real world and virtual environments, the results of this study and further work in this area using VR does have implications for the real world as well. The use of salient landmarks as in this study and in the study of Ruddle et al. (2011a), especially when placed at possible decision points, can help to navigate complex buildings. This could be helpful in the design of emergency exit routes or guidance systems in a building with public businesses. A guidance system for navigating in such complex buildings needs to be designed in a way that is salient enough to help find the room or exit one might be looking for without needing prior training or understanding of the building's layout.

Chapter 5: Visualization of Rooms Traversed and Pupillometry Data During Spatial Orientation in a Complex Building with Local and Global Landmarks in Virtual Reality – Study 2

During the experiment of the previous chapter, both rudimentary eye-tracking data as well as rudimentary movement tracking data have been collected. After looking at the accuracy and time of the different behavioral aspects in the previous part, this part will focus on the movement tracking data and eye-tracking data. This is done in a more exploratory manner, comparing the different buildings visually per condition and trial number for both the eye-tracking data and the movement data of the different conditions. Since it is based on data collected during the same experiment as described in chapter 4, some parts refer to the specific parts in the previous chapter for a broader explanation.

5.1. Introduction

Using the same experiment, sample and procedure as for chapter 4, this chapter takes a closer look into two physiological aspects of orientation: Locomotion and Pupillometry.

Locomotion can be defined as “the motor act that allows animals or humans to move through the environment” (Kiehn & Dougherty, 2013, p.1210). There are many ways of movement which can be classified as locomotion, like running, walking, swimming and flying (Kiehn and Dougherty, 2013). This part of the experiment analysis focusses on walking and walking-like movement. In Virtual Reality, enabling natural walking is a non-trivial challenge (Nilsson et al., 2018). This is due to possible physical constraints, i.e., the virtual environment (VE) might be a lot bigger than the real environment in which the VE is entered (Multon & Olivier, 2013; Nilsson et al., 2018; Wilson et al., 2016). There is also the need to replicate the multisensory feedback, e.g., the sound of steps, that walking entails (Nordahl et al., 2011). While physical constraints could be remedied by designing levels and games in VR to use a small area of play or using teleportation to move, in some cases this might not be desirable. To cope with these cases, there are different ways of implementing locomotion and walking in VR. According to Nilsson and colleagues (2018), these implementations typically can be categorized into *proxy gestures*, *redirected walking* and *repositioning systems*. Proxy gestures, as the name suggests, are motions performed by the user that serve as a proxy for actually walking (Nilsson et al., 2018). Examples for this technique include walking-in-place as well as arm-swinging. The technique of redirected walking entails actual physical walking that is redirected through either manipulating the VE or the perspective in the VE. Repositioning systems are typically mechanical setups like linear or omnidirectional treadmills that actively cancel out the user's movement through counter movements and friction-free platforms which prevent movements of the user passively (Nilsson et al., 2018).

Pupillometry is concerned with measuring the changes of eye pupil size (Mathôt, 2018). A change in pupil size can happen due to light or brightness, when looking at a nearby stimuli or object and as a response to mental effort and arousal (Mathôt, 2018). The latter is also called psychosensory pupil response (PPR) by Mathôt (2018), since that term shows that that kind of response is driven by psychological as well as sensory stimuli. Typically, PPRs can either happen as an orienting response, such as sudden sounds or movements (Sokolov, 1963), or, as stated above, as a sign for arousal and mental effort. This has been shown as early as the 1960s in several studies by Kahneman and Beatty (1966) as well as Hess and Polt (1960, 1964). Nowadays, studies on cognitive load and mental effort using pupillometry have also been done in VR (e.g., Lee et al., 2024; Souchet et al, 2022). Eye tracking in VR can be done through different technological approaches

(Adhanom et al., 2023). The most common method in VR HMDs is video oculography, as used in the Tobii eye-tracker equipped HTC Vive Pro Eye (Vive Pro Eye Specs, n.d.), for instance (Adhanom et al., 2023). In video oculography, cameras are mounted inside the HMD, recording the eyes and their movement, the eye orientation is then inferred through analysis of the recorded frames of the eye movement (Adhanom et al., 2023). Souchet et al. (2022) reviewed several scientific papers on measuring cognitive load via eye-tracking in VR. Their findings indicated that pupil size can be used to measure cognitive load in VR, but blinks possibly caused by visual fatigue might make the processing and interpretating of the measures challenging. Lee and colleagues (2024) examined cognitive load in VR training using observation tasks of two different degrees of difficulty. The aim of their study was to find out if the pupillary response evoked by the observation task correlates with performance as well as cognitive load ratings by the participants. While their sample size was rather small, their results did show that cognitive load increased with the difficulty of task and also correlated with the subjective ratings of the participants (Lee et al., 2024).

There have also been efforts in examining how locomotion in VR might affect eye movements (Drewes et al., 2021; Gao et al., 2022). Drewes and colleagues (2021) compared how gaze might change when comparing locomotion in a virtual reality environment and a real-world setting. To achieve a meaningful comparison, they reconstructed one of the real-world campus buildings in VR and let participants navigate through both versions. They found that gaze behavior during locomotion in both settings relied on terrain type, suggesting that their high-fidelity reconstruction of the real-world setting did also capture the constraints of the real world. Gao et al. (2022) examined how different forms of locomotion in VR affect different aspects of eye movements. They compared arm swinging, teleportation as well as three other controller-based input techniques as locomotion methods. The results of their experiment suggest that differences in cognitive responses were affected by the different locomotion techniques. Furthermore, their blink rate results also suggest higher cognitive load when using arm swinging as locomotion method.

5.2. Materials and Methods

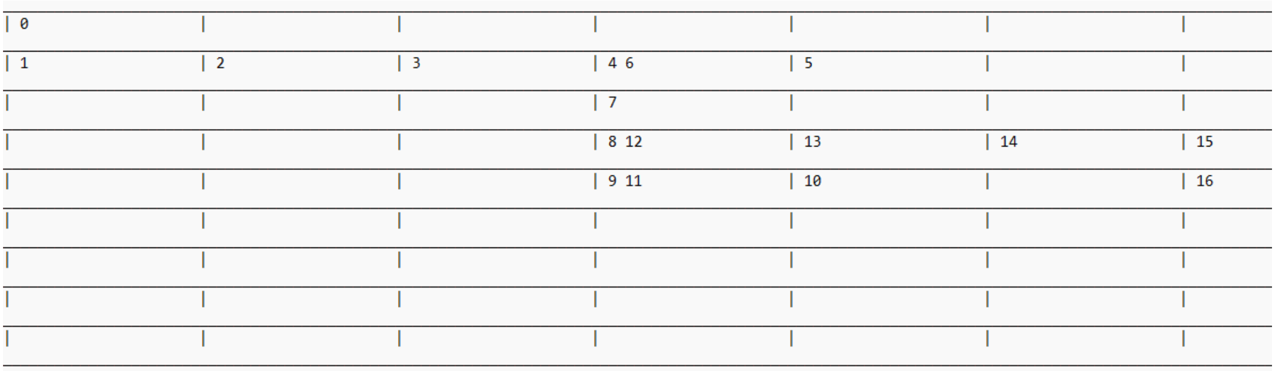
5.2.1. Hardware and Implementation

Using the same application and the same generated buildings with the same conditions and the same sample as in chapter 4, we recorded the movement and the pupil diameter using the VR Headset Vive Pro Eye. The HMD has a resolution of 1440 x 1600 Pixel per eye, a 110° field of view, and a refresh rate of 90 Hz. The eye tracking sensor can measure up to 120hz due to an updated version of the driver at the time of writing. Since we had to use an older version of the driver at the time of data collection, we could only collect pupil diameter data at 30hz.

The movement was recorded via the head tracking built into the VR HMD, i.e. the position was based on where the headset was located in the virtual building. The movement was translated into a two-dimensional 17x17 map showing the order in which the room chunks were entered. The start room is noted as “0” and every room entered adds one onto the number till the task is done. An example of a two-dimensional map can be seen in Figure 21. For every trial, i.e., tutorial as well as ground floors and upper floors for every level, one such map is saved into a file.

Figure 21

Example of Raw Map Data



0						
1	2	3	4 6	5		
			7			
			8 12	13	14	15
			9 11	10		16

Note: This example map was cut to fit the page, actual size is a 17x17 matrix.

5.2.2. Preprocessing, Analysis and Visualization of Movement Data in VR

The movement data was implemented in a way that the maps (see Figure 21) only consist of x and y coordinates as well as a numbered order in which the rooms have been walked through. Those maps were converted into data tables with those coordinates, order of rooms, participant ID and which landmark condition was present in the participant trial that generated this map.

The data makes it possible to follow the paths of the participants and reconstruct how often each room has been traversed by any participant in any trial. However, due to the rudimentary implementation, there is no information on time spent in each room, movement speed of the participant or similar metrics to derive movement speed from, as well as no information on direction changes inside a room.

Figure 22

Screenshot of the Ground Floor of the First Building

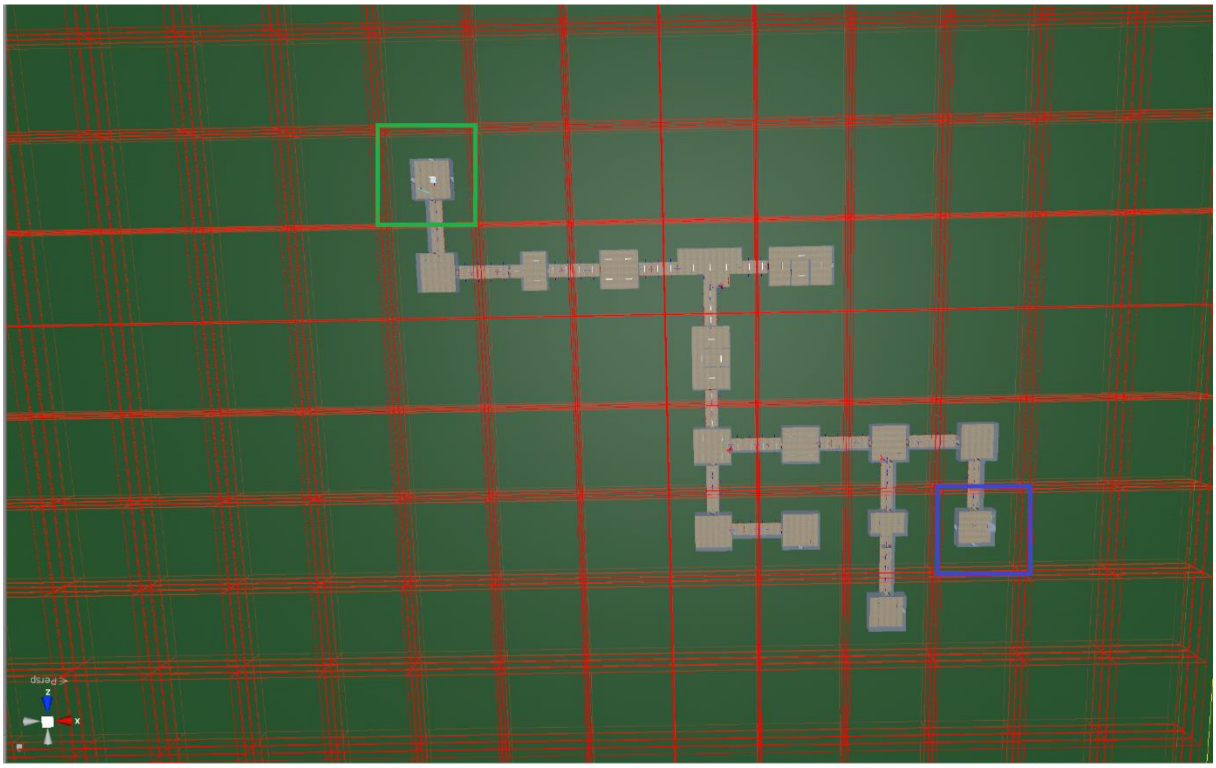
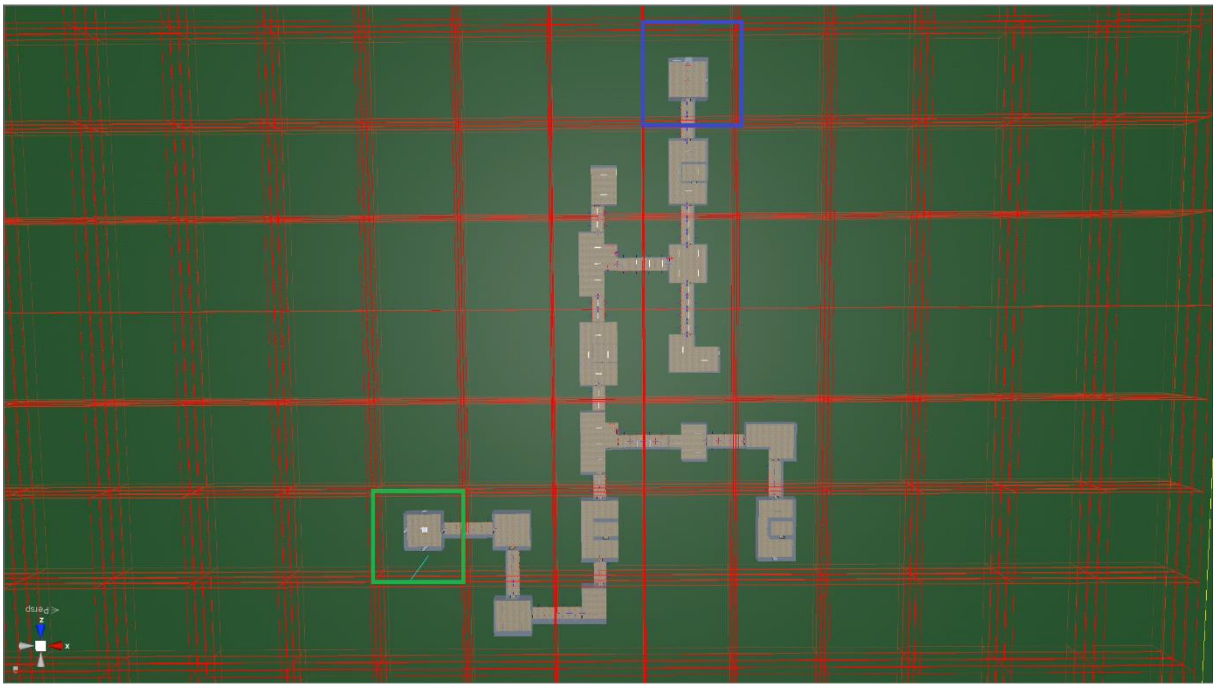


Figure 23

Screenshot of the Ground Floor of the Second Building



Note: The starting room is highlighted by the green square, the target room (elevator room) is highlighted by the blue square. [*Figures made by Jendrik Müller, previously unpublished]*

Figure 24

Screenshot of the Ground Floor of the Third Building (made/taken by Jendrik Müller)

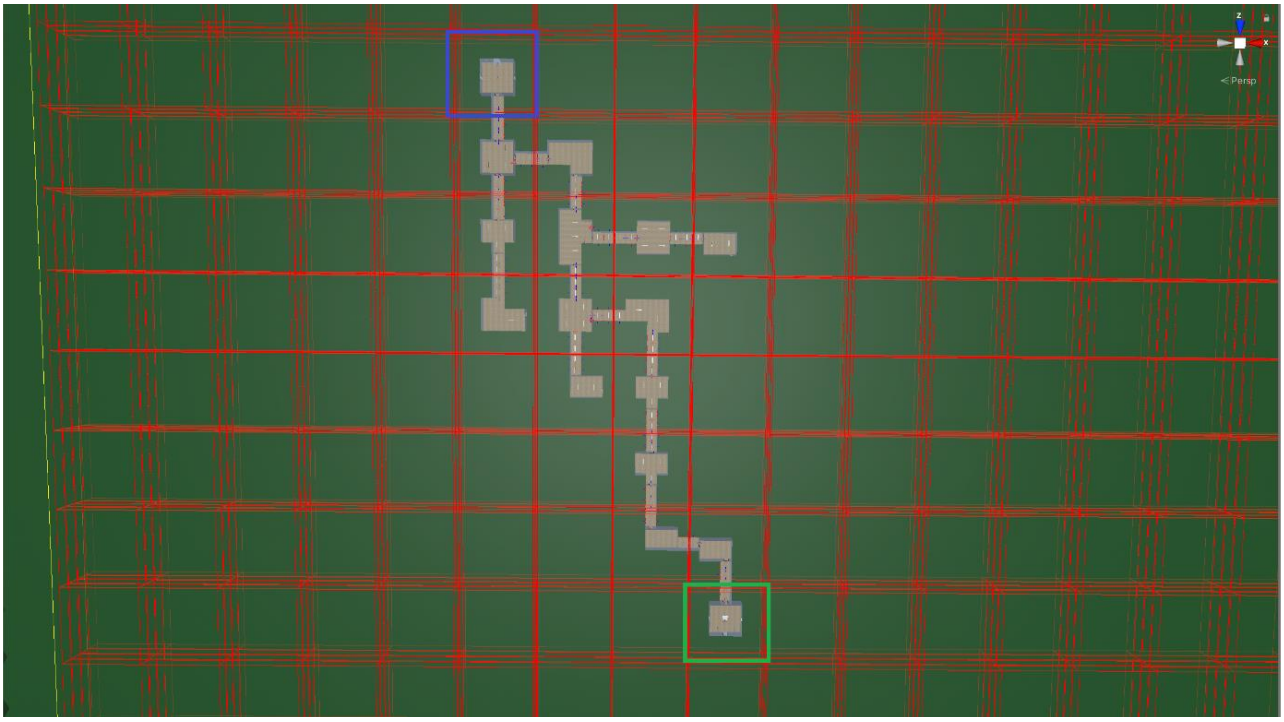
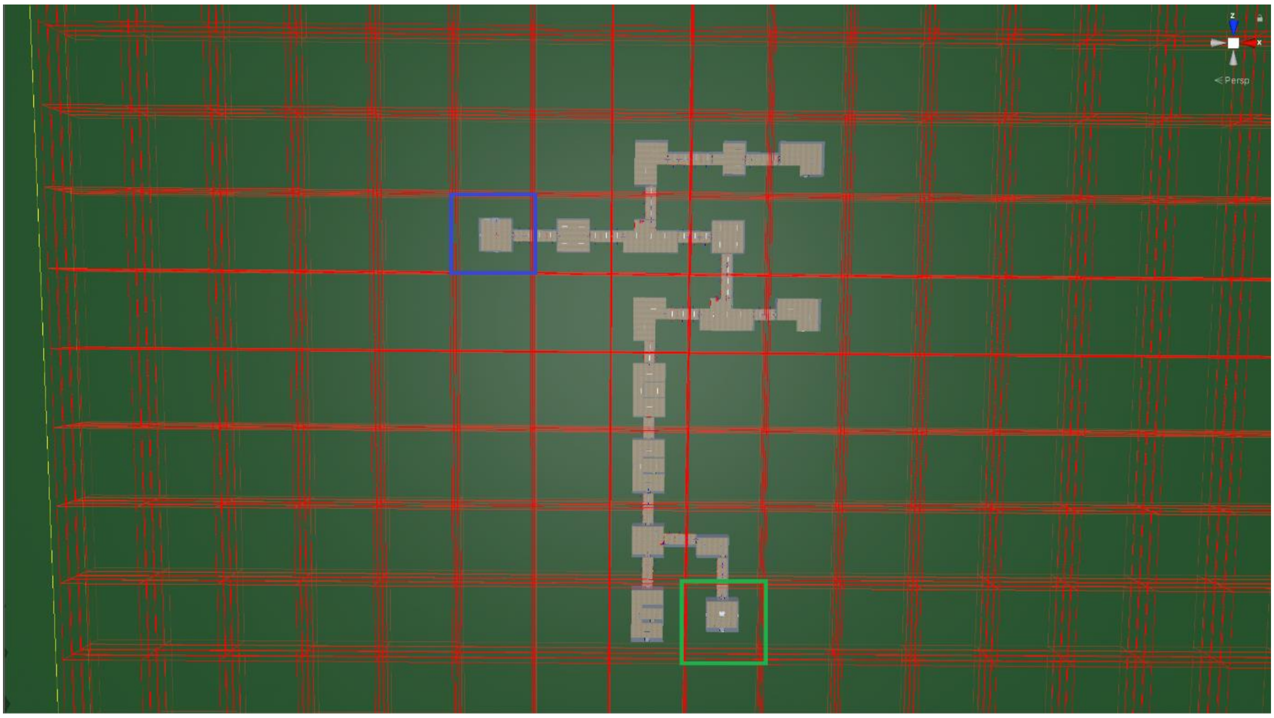


Figure 25

Screenshot of the Ground Floor of the Fourth Building (made/taken by Jendrik Müller)



Note: The starting room is highlighted by the green square, the target room (elevator room) is highlighted by the blue square. [*Figures made by Jendrik Müller, previously unpublished]*

Figures 22, 23, 24 and 25 are screenshots of the ground floor of the four trial buildings to showcase the structure of every building generated for the experiment in chapter 4 and, thus, also used for the analysis in this chapter. Since the pilot study (chapter 3) showed that the 11-room condition was reportedly harder, the visualizations will focus on the 11-room ground floors of the levels. Furthermore, only the first trial will be discussed in this chapter, the visualizations of the other three trials can be found in the Appendix (Figure APX1 to APX12). The visualizations use heatmaps to show how often the rooms in those buildings have been traversed on average.

5.2.3. Preprocessing, Analysis and Visualization of Pupillometry

The eye tracking data was implemented in a very basic way using the Tobii VR SRanipal SDK, Version 1.1.0.1 (*SRanipal SDK*, n.d.). The implementation resulted in a data file that consisted of the pupil size for both right and left pupil as well as their accompanying timestamps.

As a first step, the data of the eye pupil size was regressed as described by Jackson and Sirois (2009) using the PupillometryR package for R 4.3.1. This also handles missing data of one pupil by using the other pupil to interpolate a fitting value as well as calculating linear interpolation for three samples before and after a completely missing value pair, i.e. both eyes having no value for a given timestamp. The next step is then averaging the pupil size of both left and right eye to create a mean pupil size per timestamp as well as filtering the data using the median filter of PupillometryR. After this, the data is then also divided into several time windows to compare possible differences between them.

5.3. Results

5.3.1. Movement

The sample sizes of the movement data per condition and trial are rather small – $n_0 = 6$, $n_1 = 5$, $n_2 = 6$ and $n_3 = 5$, respectively – thus they will only be compared visually and in an exploratory manner, without further statistical analysis.

The heatmaps for the four conditions in the first trial can be seen in Figure 26 (no landmarks), 27 (only outdoor landmarks), 28 (only indoor landmarks) and 29 (both outdoor and indoor landmarks). The lines inside the heatmaps highlight the structure of the buildings, the connections between the rooms, junction points as well as dead ends, thus also highlighting the possible paths that can be taken. In all of these heatmaps, the rooms with junctions are frequented more often on average, the dead ends are frequented less often on average. There seems to be no differences between the different conditions based on the visualizations.

Figure 26

Heatmap of Mean of Rooms Traversed in the First Building with No Landmarks, n = 6

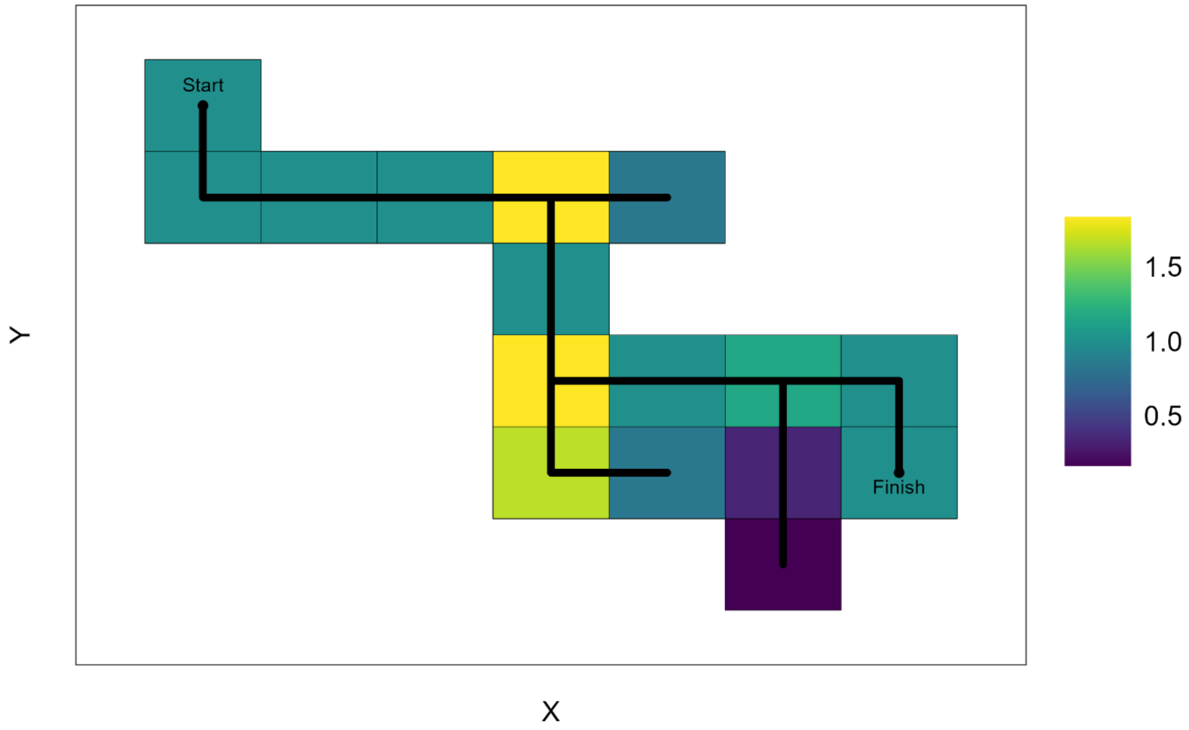


Figure 27

Heatmap of Mean of Rooms Traversed in the First Building with Outdoor Landmarks, n = 5

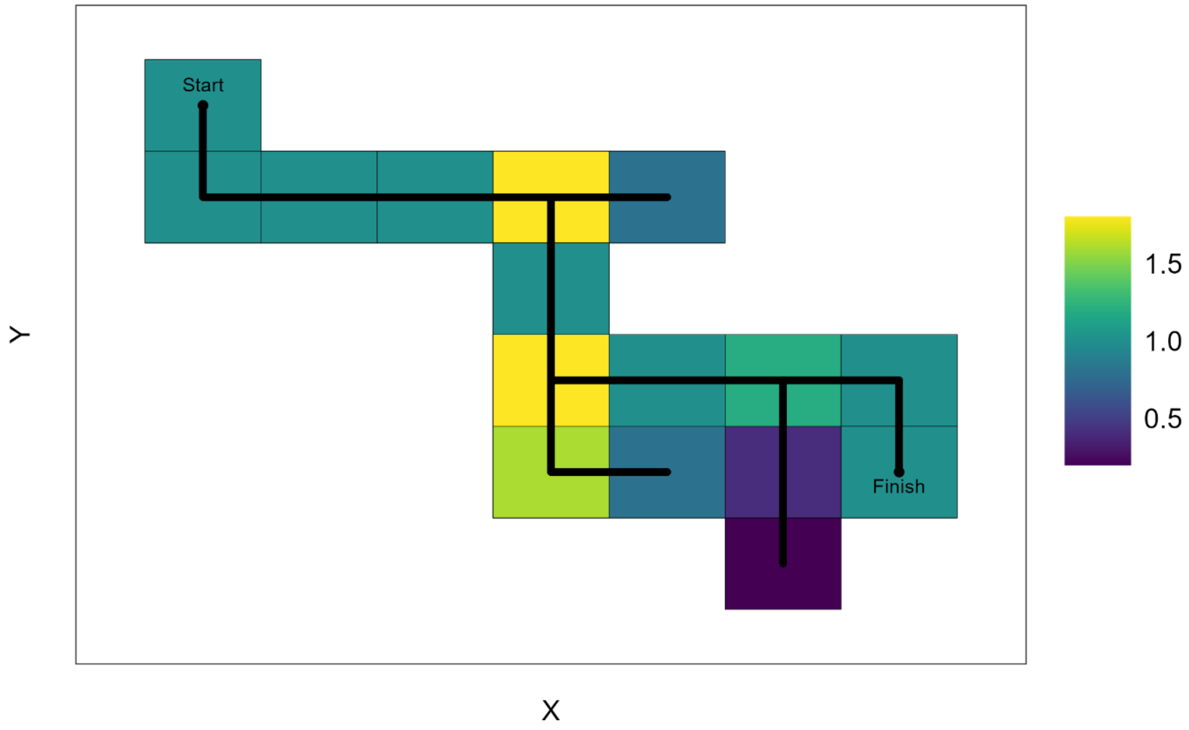


Figure 28

Heatmap of Mean of Rooms Traversed in the First Building with Indoor Landmarks, n = 6

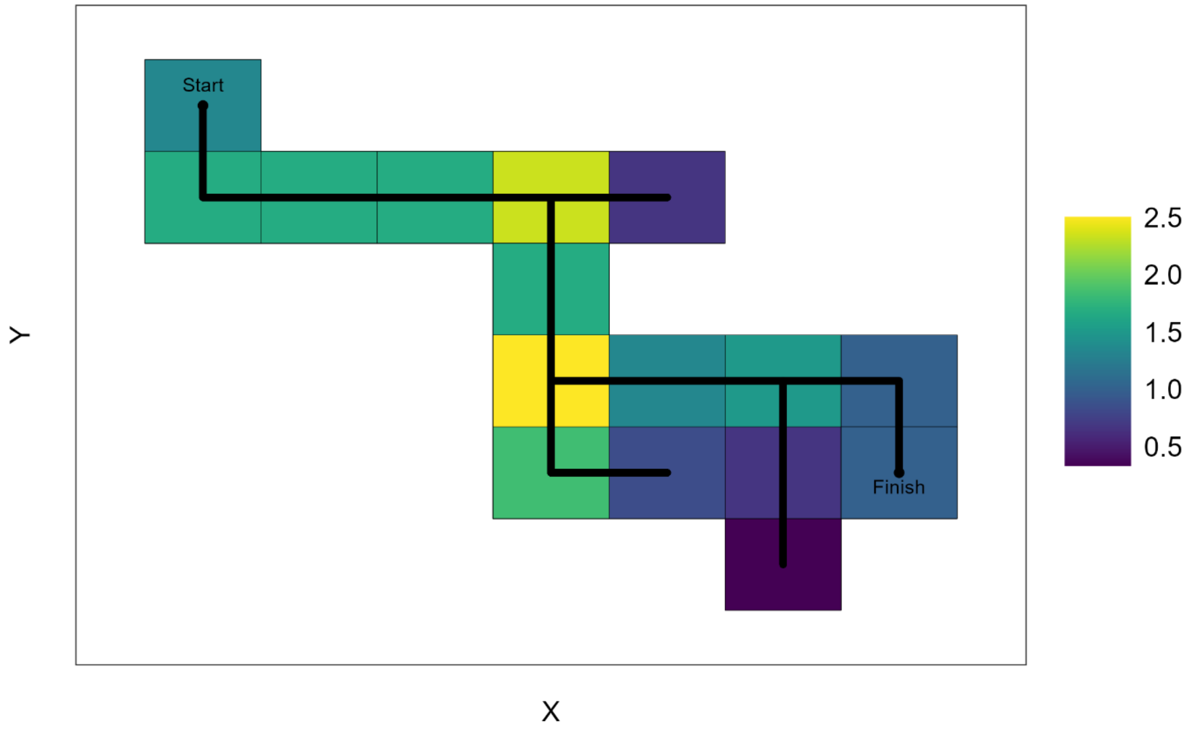
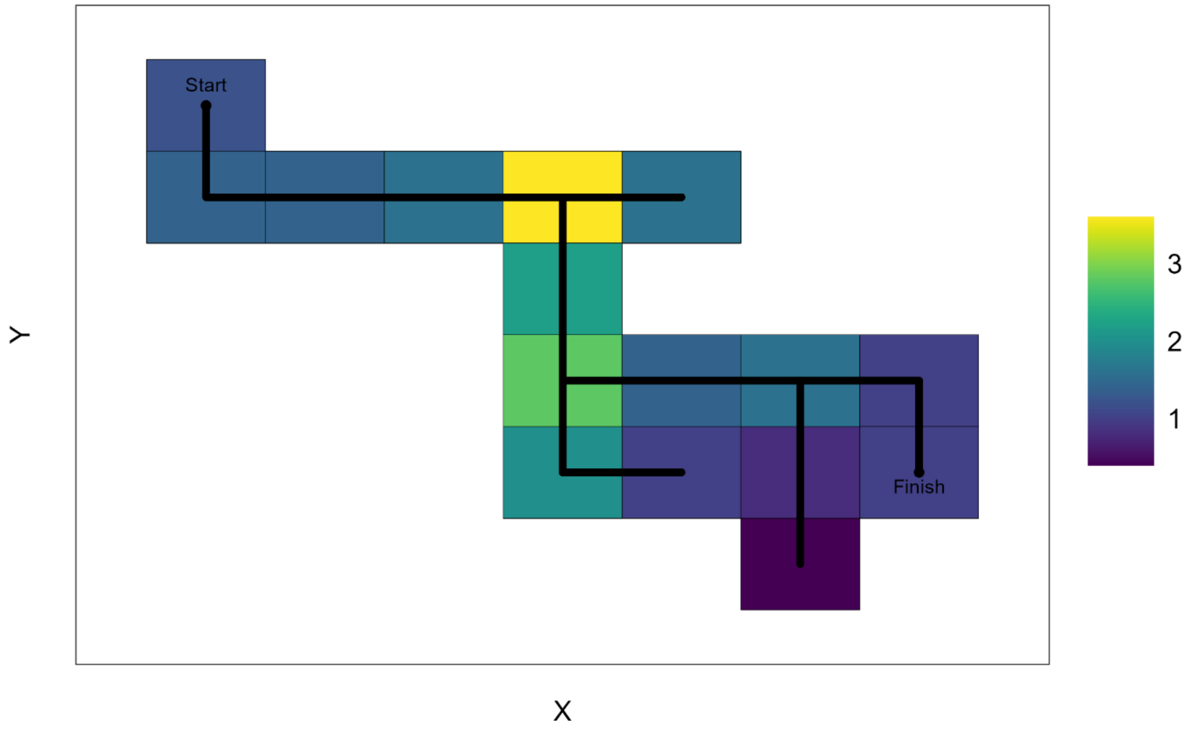


Figure 29

Heatmap of Mean of Rooms Traversed in the First Building with Outdoor and Indoor Landmarks, n = 5



5.3.2. Pupillometry Data

Figure 30 shows the filtered pupil size diameter data of all participants (n = 22) for the trial duration, grouped by subject. The filtered data per subject does indicate a small change over time. When visualizing the filtered data per condition over the trial duration (see Figure 31), there does not appear to be a big difference based on the different conditions.

Figure 30

Filtered Data per Subject over Trial Duration

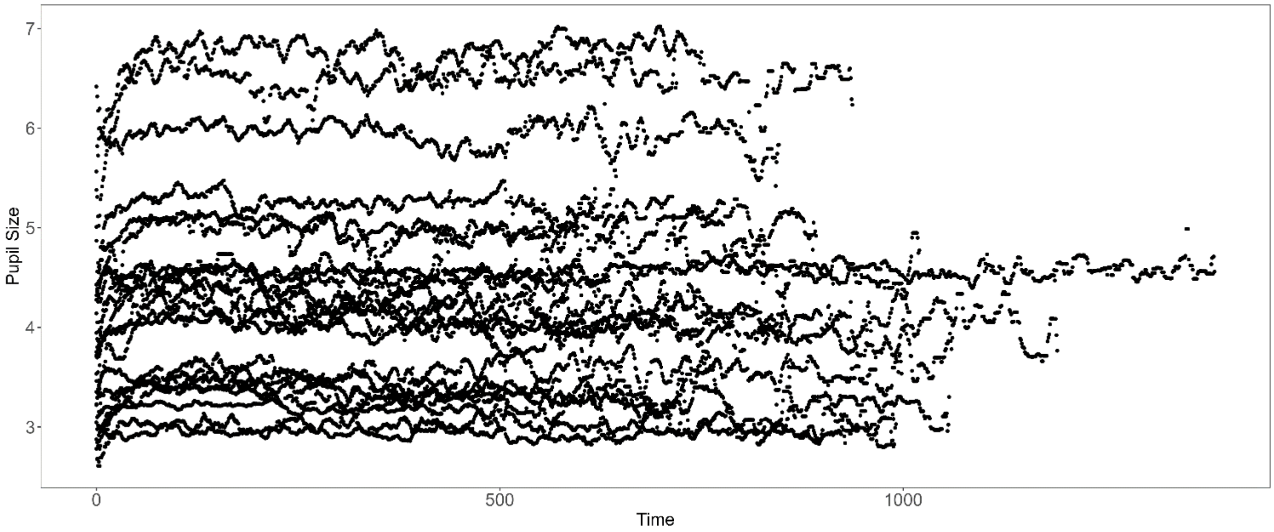


Figure 31

Filtered Data per Condition over Trial Duration

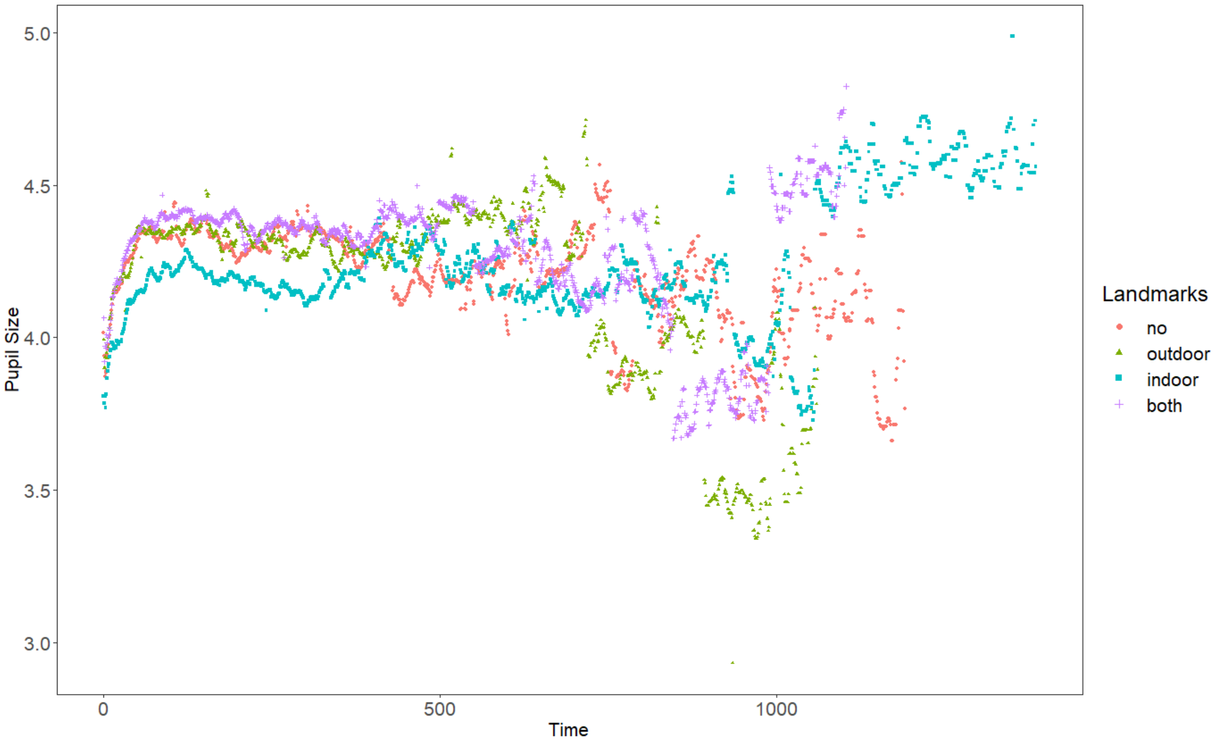


Figure 32

Raincloud Plots for the Change in Pupil Size per Condition, 1^{st} to 3^{rd} Minute

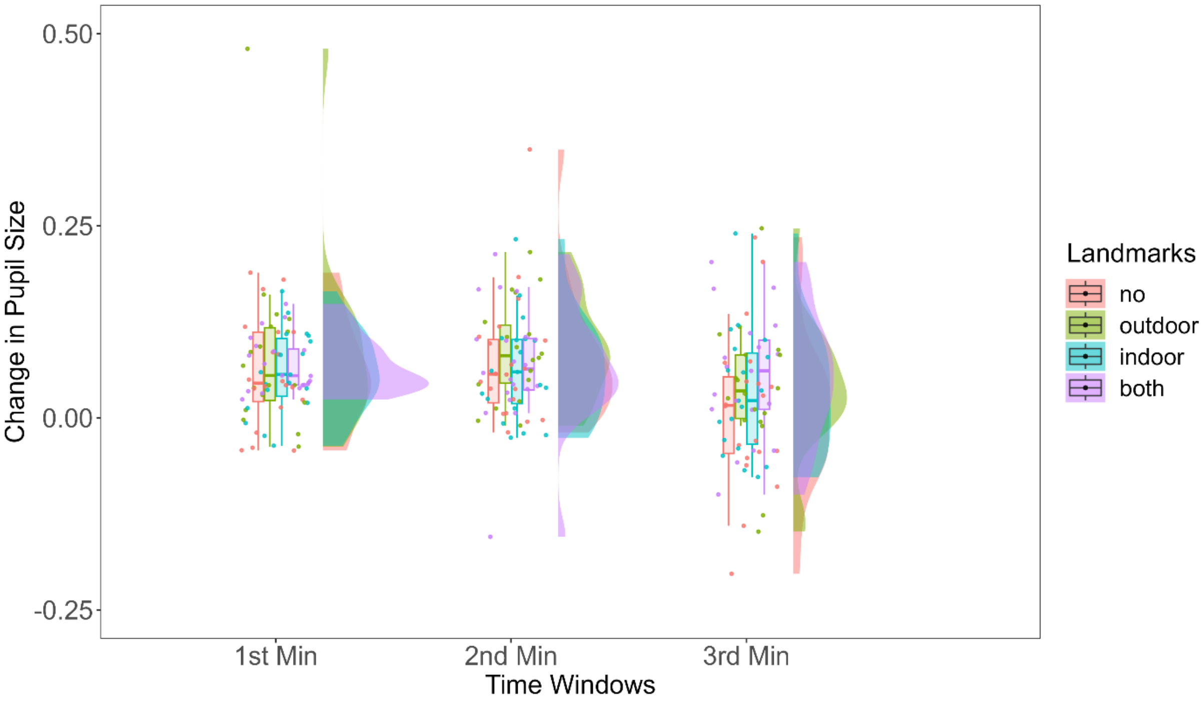
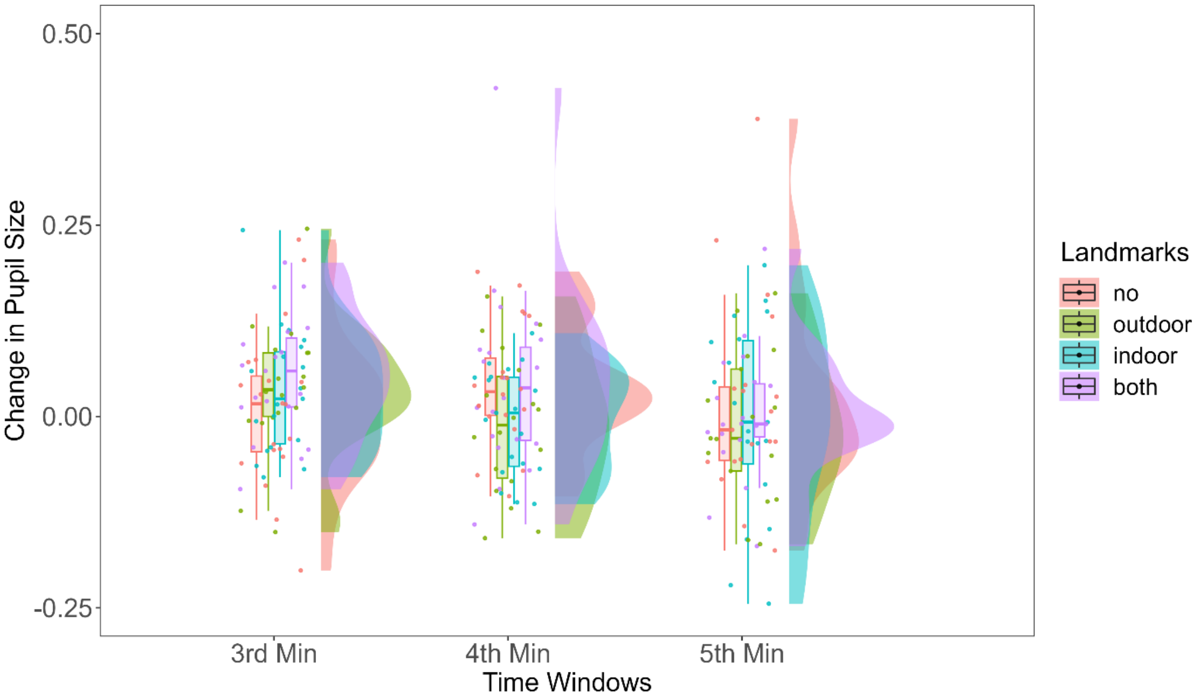


Figure 33

Raincloud Plots for the Change in Pupil Size per Condition, 3rd to 5th Minute



Note: The time windows are set up as follows: 1st: 0s till 60s, 2nd: 61s till 120s, 3rd: 121s till 180s, 4th: 181s till 240s and 5th: 241s till 300s

Comparing the different conditions in five different time windows (see Figure 32 & 33) does again reveal no considerable difference in change of pupil size. This and the visualization in Figure 31 suggest that there might not be any effect of the conditions on pupil size change in this data.

5.4. Discussion

This chapter dealt with the visualization of the movement and eye-tracking data collected during the experiment of chapter 4. There does not seem to be any effect of the landmark conditions on both movement and pupil size.

However, the data of both was implemented in a very basic way which might probably be the main reason why there seems to be no effect. For instance, there is a lack of connection between events and changes in movement as well as changes in pupil size in the actual data files, i.e., there could be events and timestamps marked in the data which correspond to eye fixation on landmarks which is not present in the current implementation of the data collection. Similarly, with a more thorough movement tracking implementation, there could have been information on eye fixation of landmarks and small changes in body movement.

The very basic implementation does hamper any meaningful further analysis and interpretation of these two tracking data aspects. It does, however, show that experiments in VR can relatively seamlessly collect additional data thanks to sensors built into the VR HMD like head tracking or eye tracking, dependent on the implementation in those experiments and the VR systems. And with the easy availability of other sensors, e.g., heart rate monitors or body trackers that are either built into newer VR hardware or can be acquired additionally this can be enhanced even more (HP Inc., n.d.; HTC Inc., n.d.; Tundra Labs, n.d.).

5.5. Interim Summary

Study 1 investigated how the absence or presence of certain room features can alter the performance as well as the user experience of orientation in a closed building. Building on those insights gained in study 1, study 2 simplified most of the experiment design to highlight differences in performance measures depending on the availability of different kinds of landmarks.

Discussing the limitations and shortcomings of those studies and integrating them into a broader, updated body of research will be part of the General Discussion in chapter 8.

Chapter 6: Vibrotactile and Auditory Feedback Cues in an Invisible Object Search Task in Virtual Reality – Study 3

In the previous two chapters, the focus was on the visual cues for orientation and navigation. Unlike before, the play area in VR also was the same size as in the real world to be able to move naturally and use the controllers just for the hand interactions present in this chapter. This chapter will examine what happens if visual cues are absent in a non-visual search task and how both vibrotactile and auditory feedback can help in such situations.

6.1. Introduction

Virtual reality (VR) is predominantly a visual medium, but the auditory and tactile sensory systems also play a part in the experience. Vision is also the most researched of the senses, the auditory sense being the follow-up, while the rest of the senses are trailing regarding number of research studies (Gallace & Spence, 2009; Hutmacher, 2019). Hutmacher (2019) argues that this is due to an inherent bias, such notion being first mentioned in a monograph by Katz (1925). In that monograph, Katz discussed that the then-apparent hierarchy - vision and auditory being on a higher level than the other senses does not exist. In 2021, Tabrik and colleagues found that the tactile sensory system shares features with the visual system during objection recognition and both can substitute for each other if one modality is absent. Similarly, auditory stimuli that do not contain spatial information can still help in a spatial visual search according to van der Burg et al. (2008).

Regarding the visual sense and its perception, visual search tasks are a well-defined and examined paradigm (e.g., Brungart et al., 2019; Burg et al., 2008; Chan & Hayward, 2013; Eckstein, 2011; Hopkins et al., 2016; Lehtinen et al., 2012;

Wolfe, 2018; Wolfe, 2021). Visual search tasks are typically tasks that involve a target stimulus and a response from a participant when the target is found (Eckstein, 2011; Wolfe, 2018). In a classical setting, the target stimulus is surrounded by other stimuli and the participant must actively look for the target stimulus in a scene with distracting stimuli surrounding it. As soon as they find the target, they should press a button. There have been quite a few studies on how different sensory cues - visual, auditory, vibrotactile - can alter performance in visual search tasks (e.g., Binetti et al., 2021; Burg et al., 2008; Brungart et al., 2019; Lehtinen et al., 2012). Cues are defined as "a stimulus, event, or object that serves to guide behavior, such as a retrieval cue, or that signals the presentation of another stimulus, event, or object, such as an unconditioned stimulus or reinforcement" in the APA Dictionary of Psychology (n.d.). Both van der Burg et al. (2008) as well as Brungart et al. (2019) used auditory cues to further help with the visual search. Lehtinen and colleagues (2012), on the other hand, used dynamic tactile cues in visual search tasks. In a dual task scenario, with one of the tasks being a visual search while the other one was an auditory task, Hopkins et al. (2016) examined how effective crossmodal auditory and tactile stimuli can be in guiding and found that those did result in faster responses. Binetti and colleagues (2021), while still also using visual cues, used spatialized auditory stimuli as a help to locate out-of-view objects in an augmented reality setting. But those studies still dealt with tasks focused on the visual system. The performance of auditory and tactile stimuli can be a good way to determine how powerful both those sensory systems can be when the visual system cannot be used. Lokki and Grohn (2005) showed that auditory stimuli can be used for navigation without visual feedback. Similarly, Nardi and colleagues (2019) tested how blindfolded participants performed in spatial reorientation using auditory landmarks. In their study, participants managed to reorient based on auditory landmarks alone.

The present study sets out to examine how vibrotactile and auditory cues can help in a non-visual search task with static as well as moving target objects using a self-developed VR game. Furthermore, Grinyer and Teather (2022) mentioned that the current state of research on searching hidden and out-of-sight objects in VR is relatively scarce. As stated by Hutmacher (2019) before, there might be an inherent bias in researching the visual system. Hutmacher (2019) and Grinyer and Teather (2022) as well as the following related work led this study to focus on non-visual cues and a non-visual search task.

6.2. Related Work

6.2.1. Auditory Feedback Cues

Fialho and colleagues (2021) studied the spatial navigation of blindfolded but sighted participants using audio sources in a virtual environment (VE). Fialho et al. designed three virtual scenes where the participants had to locate a target position and then return on the same path. The three VEs differed in their level of difficulty, i.e., in the number of obstacles in the VE and the arrangement of obstacles in the VE. The environments were used for two different trials, a learning and a retrieval trial. In the learning trial, the participants had to move to the location of a sound source and return to the starting point. In the retrieval trial, this sound source was removed, and participants had to rely on auditory cues of the obstacles instead. Fialho et al. (2021) observed that participants navigated better in the retrieval trial. Another area where auditory feedback can be important is 360° videos which can be used with a VR headset. In a study by Meghanathan et al. (2021) participants had to locate targets in a VE. The VE consisted of a 360° video which showed a handball arena. To study the effect of auditory and visual noise on search tasks, the videos were available in two versions, one with an empty arena and one with a match being played. The auditory feedback consisted of either no sound, stereo sound or binaural sound. Meghanathan et al. (2021) discovered that participants performed best with binaural audio.

Other factors could also influence the localization of audio sources. A study by Brungart et al. (2019) showed that walking could improve auditory localization in comparison to standing. Participants were asked to perform four tasks twice, once standing and once walking on a treadmill. In front of them was a canvas on which the VE was projected. Behind this canvas was an array of 64 speakers. During the first task participants had to locate the source of the auditory cue. The second task was a visual discrimination task in which the participants had to answer whether one or three dots were displayed. The third task was a visual search task on the VE canvas, supported by audio cues coming from the speakers behind the canvas. The fourth task was like the third task, but without audio cues. Participants were faster in tasks 1 and 3 and fastest in those tasks when walking. Brungart et al. (2019) suggested that this was partly due to the increased activity during walking and partly due to the slight head movements that resulted in auditory cues being located more easily or at all.

Semionov et al. (2020) studied effects of various spatial auditory cues on the perception of threat in games, specifically in a first-person shooter game. One of their findings is that a lack of audio source could contribute towards inaccurate enemy localization in the game. Lokki and Gröhn (2005) used a game-like application in two experiments on navigation with auditory cues. The results of their first experiment showed the possibility to use auditory cues in navigation when visual cues are not available. The second experiment suggested that auditory cues help more in navigation if they give additional information like elevation of the sound source. They argued that auditory cues could make navigation almost as easy as with visual cues when those auditory cues were designed carefully. Morelli and colleagues (2010) examined an exergame called VI-Tennis that combined vibrotactile and auditory cues. In that exergame, they tested auditory cues against a combination of auditory and vibrotactile cues in a study with blind children. The participants scored significantly better in the version with both auditory and vibrotactile cues.

6.2.2. Vibrotactile Feedback Cues

Vibrotactile feedback, i.e., vibration passively felt on the skin, is a subcategory of tactile feedback. One aspect of vibrotactile cues are patterns (e.g., Kaul et al., 2020; Kaul et al., 2021; Plouzeau et al., 2016; Wang et al., 2021). Vibrotactile patterns can either be comprised of static or dynamic vibration. In dynamic patterns, actuators are alternated, and different amplitudes and frequencies are used to create dynamic vibration on the skin. Kaul et al. (2020) designed and evaluated spatial tactile patterns on the head. They found that their participants could more easily recognize static patterns they constructed. The dynamic patterns, however, were preferred by the participants. Plouzeau et al. (2016) compared two different vibrotactile patterns in a task. The patterns were delivered through vibrating ankle bracelets. In the compass pattern, only the actuator closest to the target vibrated. The push pattern, as the name suggests, vibrated either on the front or back as well as left or right to “push” the participant in the right direction. They observed that a compass pattern was more efficient than a push pattern on the back of the ankles. In another study, Kaul and Rohs (2016) found that vibrotactile cues on the head led to faster performance than auditory cues in a VR search task.

The placement of the actuators on the body is also an important aspect of vibrotactile feedback cues. While Kaul and Rohs placed actuators on the head

(2016), Tsukada and Yasumura (2004) integrated eight actuators into a wearable belt. Panëels et al. (2013) placed the actuators on wrist worn bracelets. Other studies also used vibrotactile bands that were attached to the ankles (Plouzeau et al., 2016) or to the upper arms of the participants (Stratmann et al., 2018). De Jesus Oliveira et al. (2017a, 2017b) integrated seven actuators directly into the head strap of a head-mounted display (HMD). Their study consisted of search tasks in which the participants had to select various objects around them. The direction of the target was presented by vibration of one of the actuators on the horizontal plane. The height of an object was indicated by the vibration frequency. De Jesus Oliveira et al. (2017b) results suggested a strong learning effect when using a quadratic growth function as frequency modulation of the vibrotactile feedback cue.

Nonino et al. (2021) used the vibrotactile actuators of VR controllers to help participants locate targets. In their study, they compared vibrotactile feedback and Temporal Luminance Modulation (TLM). TLM is defined as flickering signals near the edge of the screen that appear in the direction in which the user was supposed to turn. Their participants could move freely in a VE and had to find ten hidden objects in succession, always starting from the same location. Nonino et al. (2021) used the actuators of both controllers, and only the controller closest to the target vibrated. Even when the controllers pointed in the opposite direction of the target, vibrotactile feedback was generated. The vibration amplitude and frequency were determined by the distance between the controller and the target. One limitation was that the vibrotactile feedback could not provide information about the object's elevation. Nonino et al. (2021) concluded that the two methods of attention guidance improved the target search, in contrast to no feedback at all.

As mentioned before, Morelli et al. (2010) evaluated an exergame that offered both vibrotactile and auditory cues to better engage visually impaired individuals in exercising and physical activities. Another study by Morelli and Folmer (2011) presented a real-time video analysis solution to substitute visual cues into tactile cues. In their experiment, they found no difference in player performance between visual and vibrotactile cues in a gesture-based game. Tessendorf et al. (2012) used vibrotactile cues to help locating sound sources in a game. Their results showed that hearing impaired users achieved similar performance to users with normal hearing.

6.3. Research Questions

The related work mostly used static targets in the tasks of their studies. This study, however, consisted of search tasks with both static and moving invisible objects, i.e., ghosts. To assist in finding the targets, auditory feedback cues, vibrotactile feedback cues and the combination of both types of feedback have been implemented. The approach of Nonino et al. (2021) served as inspiration and attempts were made to improve it, e.g., by supporting the localization of objects in the vertical plane.

This study was designed to answer whether vibrotactile cues, auditory cues or a combination of both are better in the absence of visual cues in a search setting in a VR game. Based on the literature by Semionov and McCregor (2020) as well as Lokki and Gröhn (2005), auditory cues should be more helpful, while Kaul and Rohs (2016) found that vibrotactile cues led to better search performances than auditory cues. Furthermore, multimodal cues, i.e., the combination of both, should lead to better performance than unimodal cues, i.e., only auditory or vibrotactile, even if the target is moving (Morelli et al., 2010). This study should have similar results regarding performance and feedback type in all the three levels. There should also be a learning or training effect involved in the search task, as the literature suggested a learning effect for feedback types in other tasks (Islam & Lim, 2022; Sigrist et al., 2012; Stepp et al., 2012) as well as a training effect in search tasks (Ahissar & Hochstein, 2000; De Jesus Oliveira et al., 2017b).

Thus, the research questions are as follows:

- How does different feedback affect the time to catch a static object or a moving object in a non-visual setting? (**RQ1**)
- How does training affect the time to catch a static object or a moving object in a non-visual setting? (**RQ2**)
- How does the task difficulty affect the time to catch the object in a non-visual setting? (**RQ3**)

6.4. Materials and Methods

6.4.1. Hardware, Overall Game Design and Data Collection Implementation

The VR game was developed using the Unity3D Engine and the SteamVR Unity Plugin. The HMD used in this study was the HTC Vive Pro virtual reality headset in combination with the Valve Index controllers. Any sound used in the game, including the auditory cues, were played through the built-in headphones of the HTC Vive Pro.

Three different levels were created. Furthermore, a tutorial was created where players learned the controls and the different types of feedback before they played the actual game. Each level consisted of a 6x6 meter room where participants could move freely. In addition, a lobby (see Figure 34) was designed as a hub between the levels. To start a level, a participant had to go to the door and touch it. The participant was then transitioned into that accompanying level. This was done so that the participants started each level from the same position. To complete the tutorial, each player had to catch a visible ghost with each of the three kinds of feedback cue conditions to ensure that the controls and feedback types were understood by each participant.

Figure 34

Lobby of the VR Environment

[Figure from Beese et al. (accepted)]

Blocky cartoon style assets were used for the design of the game (*Ghost Mega Toon Evolution Series | 3D Creatures | Unity Asset Store*, n.d.; *Simple Fantasy Interiors - Cartoon Assets | 3D Fantasy | Unity Asset Store*, n.d.). The design style was specifically chosen so that it did not scare players. Each room had its own concept and was decorated with appropriate objects. To prevent the participants from walking through in-game objects, the HMD's display blanked out as soon as the player's head touched one of these objects and showed the level again as soon as the player stepped back.

Each of the three levels had a different degree of difficulty. In the first level there was a single static ghost to be found. Each time the participants played the level, the static ghost would be in a different position. These positions were the same for all participants. In the second level, there was a single dynamic ghost. To prevent participants from finding the ghost by accident, the ghost continuously flew away from the player. However, the ghost moved slower than walking speed. The ghost could also move up and down, as well as fly through objects. In the third level, participants had to find two dynamic ghosts that moved and behaved identically to the ghost in the second level. The starting position for a dynamic ghost was the corner of the virtual room farthest from the player's current position.

The sequence of events in the three ghost levels was the same. Shortly after entering a level, a grandfather clock started striking midnight, signaling to the players that the trial had begun. At the same time, the visible ghost(s) came through the ceiling of the room, briefly flew around and then became invisible. This served as a way to show players how many ghosts they needed to catch to complete the level. Once the ghosts were invisible, players could start catching them. To prevent the trials from becoming unreasonably long for the participants, a time limit of five minutes was set for each level. The participants could check the grandfather clock at any time to see how much time they had left. Just before the deadline, the clock started ticking loudly to signal the players that time was about to run out. Once the time was up, the clock rang one more time and the level ended automatically. In contrast, when a level was completed by capturing all ghosts, a short jingle was played signaling success.

All levels had objects that could be opened by the players, such as chests or cabinets. The dynamic ghost(s) could hide in these objects. When a ghost touched the object, it teleported to its center, lingered there for ten seconds and then flew on. Only one ghost at a time could hide in the same object. After a ghost left the object, it could not use another hiding place for 15 seconds. To catch a hidden ghost, the player had to open the chest or cabinet. If the participants wanted to open either a chest or cabinet, they had to touch its handle with their left hand.

The game recorded the time taken to find the ghost(s) in seconds and the distance travelled per level. Additionally, it stored which feedback type was used and how the level was completed, i.e., whether the ghost was caught or whether the timeout occurred.

6.4.2. Catch Mechanics

In the game, the participants held a ghost vacuum weapon in their right hand. When the player pressed the trigger button on the right controller, the gun's suck-in function was activated. As soon as the trigger button was released, the weapon was deactivated. To suck in a ghost, a participant had to be near a ghost, point the gun directly at it and activate the suck-in function. If this was the case, the ghost became visible (see Figure 34), and a short sound was played signaling that the ghost was being sucked-in. The sucking-in lasted a few seconds, during which the ghost became continuously more transparent until it was caught. If the participant stopped pointing at the ghost while sucking it in, the capture process was aborted. The ghost became invisible again. If this happened in one of the levels with one or two moving ghosts, their movement was resumed.

To prevent participants from catching ghosts by simply waving the ghost weapon around the room, a cool-down period was implemented. The weapon's suck-in function could only be used for five seconds at a time. After this period, an error sound was played, and then there was a five second cool-down. If the player released the trigger after less than five seconds, the cool-down was prolonged for the time the trigger was pressed.

Figure 35

Ghost being caught by a participant using the ghost vacuum weapon.

Note: The ghost(s) are only visible while they are being sucked in and during the entrance animation of every level. Otherwise, they are invisible and can only be found using feedback cues. *[Figure from Beese et al. (accepted)].*

6.4.3. Implementation of Feedback Cues

The three different feedback conditions were auditory, vibrotactile and a combination of both.

With auditory feedback, the ghost emitted a sound every three seconds. Unity’s built-in sound engine was used to create the 3D sounds. The closer the player was to the ghost’s sound source, the louder the sounds became. Players could hear from which direction and distance the sounds were coming. If a ghost hid in an object, like a crate or cupboard, its sound was muffled. If there were two ghosts in a room, they made different sounds so that the player could distinguish between them.

In a trial with vibrotactile feedback, participants had to find the ghosts with the help of vibration of the right controller. The vibrotactile feedback in this study was only generated when the user pointed in the approximate direction of the target. The strength and repetition of vibration was based on the distance to the target and direction of the target. When the player pointed the weapon in the approximate direction, the weapon began to vibrate at an interval. The more accurately the player pointed in the ghost's direction, the shorter the vibration interval was. If the player pointed directly at the ghost, the controller vibrated continuously. The closer the player was to the ghost, the stronger the vibration was.

To implement this, the ghost was surrounded by six invisible spheres of different sizes. The smallest inner sphere was exactly as large as the ghost, while the outermost and largest sphere took up one fifth of the virtual space. A raycast thrown into the scene from the right controller determined the vibration frequency based on the smallest colliding sphere. If the raycast hit the largest sphere, the actuator vibrated every two seconds. For the smallest sphere, vibration occurred every 0.05 seconds. The frequency of the vibration was between 10Hz and 200Hz. If the participant did not point in the direction of the ghost, no vibrotactile feedback was generated.

6.4.4. General Procedure

A within-subject design was chosen for this study. The procedure of the experiment was first explained to each participant. Subsequently, participants signed a consent form.

At the beginning of the experiment, participants completed the pretest questionnaire. This included a demographic questionnaire, the Karolinska

Sleepiness Scale (KSS; Shahid et al., 2012) and the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993).

After participants answered all pretest questions, the head-mounted display (HMD) was fitted to their head. The participants played the tutorial to familiarize themselves with the hardware and controls. Afterwards, they started the first level, in which they had to catch a static ghost. The static ghost hid in a different location each trial but stayed there during each trial. The second level was catching a dynamic ghost, making it more difficult compared to level one. The third level was more difficult compared to level two, as two dynamic ghosts had to be caught.

The participants played three trials per level, one per each feedback cue condition (auditory, vibrotactile, combination of both). Since each participant played two playthroughs and each of those consists of three levels with three feedback cue conditions, every participant played a total of 18 trials plus one tutorial level at the beginning. Between the two playthroughs, participants were given a five-minute break to rest. The order of feedback types used in the levels was evenly distributed and counterbalanced among all participants and levels. In the first and second playthrough, each participant had two different feedback type sequences, i.e., no level in the second playthrough had the same sequence of feedback types as the first playthrough.

At the end of the experiment, participants completed the posttest questionnaire. The posttest questionnaire included the Igroup Presence Questionnaire (IPQ; Schubert, 2003) and the posttest version of the SSQ.

6.4.5. Questionnaires

The pretest questionnaire contained demographic and health information on age, gender, level of education and possible visual or hearing impairments. The participants were also asked about their experience with video games and VR. If they already had experience with VR, they were asked to list the VR systems and technologies they were familiar with. Another part of the pretest questionnaire was self-reported level of fatigue and possible cybersickness symptoms. The KSS (Shahid et al., 2012) and the SSQ pretest version (Kennedy et al., 1993) were used for these aspects. The SSQ includes 16 questions about common cybersickness symptoms. The participants had to indicate on a 4-point scale (*none* to *severe*) how strongly each symptom is currently experienced.

After the VR part, the participants answered a posttest questionnaire. The posttest questionnaire consisted of a posttest version of the SSQ, and the IPQ (Schubert, 2003). In the IPQ, participants rated on a 7-point scale how much they agree with 14 statements about immersion in VR concerning the experience they have just had.

6.4.6. Sample

Forty-two participants (26 male, 16 female, 0 diverse/non-binary) took part in the study. All participants received either money or study credits as a reward after completing the experiment. The participants' age ranged from 19 to 32 years old (M = 24.52, SD = 5.15, Mdn = 25). Of the 42 participants, 29 have had prior experience with VR. Of these 29, 26 reported that they play VR games less than once a month, two play once a month and one participant reported playing VR games several times a week. All participants reported normal or corrected-to-normal vision. None of the participants reported auditory impairments. According to the KSS (Shahid et al., 2012), participants were *rather alert* to *alert*.

6.4.7. Analysis

The aforementioned expected effects of feedback condition, level and playthrough are formulated as a linear mixed effects model. This is then analyzed using R 4.3.1 (R Core Team, 2023) with the lme4 (Bates et al., 2015) and afex (Singmann et al., 2023) packages for the computation of the linear mixed effect models and the emmeans (Lenth, 2024) package for post hoc tests and effect sizes of the possibly underlying effects.

The linear mixed effects model is defined as follows:

$$level\ time_{ij} = b_0 + u_{0j} + b_1(feedback)_{1ij} + b_2(playthrough)_{2ij} + b_3(level)_{3ij} + e_{ij}$$

This linear mixed effects model should be able to describe any fixed effect of feedback, playthrough and level on the time to finish a level. It should also account for random effects that might be present regarding variance in performance between participants. The model will be tested against a null model to test if the linear mixed effects model is significant. If there are significant effects, post hoc tests and effect size calculations will be conducted.

6.5. Results

Table 5. Descriptive Statistics for the 7-point Likert scales version of the IPQ.

IPQ Subscale	*N*	*M*	*SD*	*Mdn*	*Min.*	*Max.*
General Presence	42	4.12	1.58	4.5	0	6
Spatial Presence	42	3.93	0.83	4	1.8	5.8
Involvement	42	3.03	0.99	3	1	5.75
Experienced Realism	42	2.55	0.75	2.50	0.75	4

[Table from Beese et al. (accepted)]

The descriptive statistics for the IPQ subscales can be seen in Table 5. The posttest SSQ showed no noticeable problems regarding simulator sickness. According to Melo et al (2023), the participants rated the General Presence as being very good (grade B). To test whether the participants' previous VR experience influenced the performance, a Wilcoxon test was calculated. There were no significant effects of prior VR experience on performance in any of the three levels, $p > .05$.

Figure 36

Raincloud Plots of Time to Catch the Ghost(s) per Feedback Condition.

Top Left: Over all Three Levels. Top Right: Level 1. Bottom Left: Level 2.

Bottom Right: Level 3. [Figure from Beese et al. (accepted)]

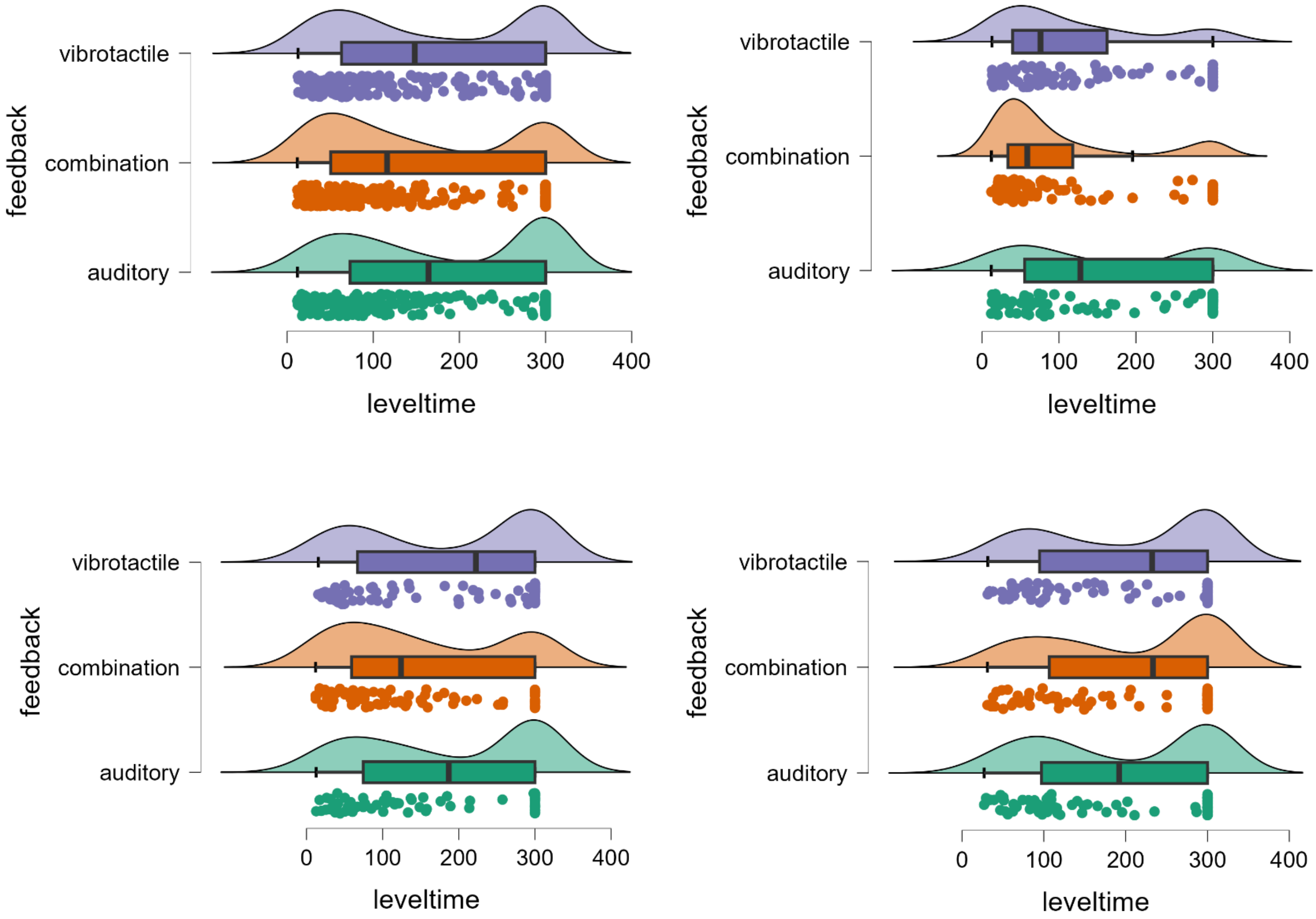


Table 6. Descriptive Statistics for Time to Catch the Ghost(s) per Playthroughs, Levels and Feedback Conditions.

Playthrough	Feedback	Level	*N*	*M*	*SD*	*SE*
1	Auditory	1	42	180.110	110.520	17.054
		2	42	207.769	108.185	16.693
		3	42	195.885	102.718	15.850
	Combination	1	42	109.995	103.436	15.961
		2	42	155.861	107.796	16.633
		3	42	209.825	102.494	15.815
	Vibrotactile	1	42	121.302	93.856	14.482
		2	42	186.775	111.750	17.243
		3	42	199.491	108.686	16.771
2	Auditory	1	42	137.551	118.216	18.241
		2	42	167.118	113.774	17.556
		3	42	189.663	107.297	16.556
	Combination	1	42	85.014	81.639	12.597
		2	42	149.649	108.549	16.749
		3	42	195.444	103.207	15.925
	Vibrotactile	1	42	110.873	98.615	15.217
		2	42	186.674	118.331	18.259
		3	42	203.326	96.619	14.909

Note: Mean, SD, SE in seconds. *[Table from Beese et al. (accepted)]*

Table 6 shows the descriptive statistics for the time needed to catch the ghost(s) per playthrough, feedback condition and level. Figure 36 shows raincloud plots per feedback conditions. The assumption of normality of the residuals was checked via QQ-Plots and the Shapiro-Wilk Test. The residuals were normally distributed for this model, Shapiro-Wilk $p = 0.08$. Testing the model against the null model revealed that the model fit of the linear mixed effects model is significant, Chi^2 (5) = 120.8, $p < 0.001$. The p-values computed by the afex package, using the Satterthwaite approximation, revealed significant effects for feedback (F(2, 709) =

7.72, $p < 0.001$), playthrough ($F(1, 709) = 6.88$, $p = 0.009$) and level ($F(2, 709) = 54.19$, $p < 0.001$).

The post hoc test for feedback conditions (**RQ1**) showed that the combination of both kinds of cues led to significantly faster completion of the task ($p < 0.001$) in comparison to just using the auditory cue over all levels, Cohen’s $d = 0.35$, 95% CI [0.17, 0.53]. Furthermore, the combination cue condition also led to a shorter time to catch the ghost compared to the vibrotactile cue. While this was not significant, there was a trend ($p = 0.0528$), Cohen’s $d = 0.21$, 95% CI [0.03, 0.39]. The difference between auditory cues only and vibrotactile cues only was not significant ($p = 0.25$). The post hoc test for the playthrough (**RQ2**) revealed a significant effect of playthrough ($p = 0.009$). The participants were faster in the second playthrough, Cohen’s $d = 0.19$, 95% CI [0.04 0.34]. The post hoc test for the levels (**RQ3**) showed significant differences between the different levels. Participants were significantly faster in level 1 than level 2 ($p < 0.001$), Cohen’s $d = 0.62$, 95% CI [0.44 0.81], significantly faster in level 1 than level 3 ($p < 0.001$), Cohen’s $d = 0.91$, 95% CI [0.72 1.09], as well as significantly faster in level 2 than level 3 ($p = 0.005$), Cohen’s $d = 0.28$, 95% CI [0.10 0.46]. The model statistics of the linear mixed effects model can be seen in Table 7.

Table 7. Model Statistics for the Linear Mixed Effects Model.

Random Effects	**σ^2**	***SD***	
Subject Intercept	4486	66.98	
Residuals	6812	82.54	
Fixed Effects	**b**	***SE***	***t* value**
(Intercept)	145.456	12.684	11.468
feedback combination	-28.718	7.353	-3.906
feedback vibrotactile	-11.609	7.353	-1.579
2^{nd} playthrough	-15.745	6.004	-2.622
level 2	51.500	7.353	7.004
level 3	74.798	7.353	10.172
Model Fit	**marginal**		**conditional**
R^2	0.09		0.454

R syntax of the specified model:

```
lmer(leveltime ~ feedback + playthrough + level + (1|participant))
```

[Table from Beese et al. (accepted)]

6.6. Discussion and Conclusion

This study examined how different kinds of feedback can help the player in localizing invisible objects, in this case ghosts in a ghost hunting setting. This study also took into account possible training and difficulty effects. A linear mixed effects model showed that the effects of feedback, playthrough and level on time to catch the ghost(s) were significant.

Regarding the three research questions defined a-priori, taking a closer look into the post hoc tests and effect sizes is necessary. For the first research question on the effect of different kinds of feedback, **RQ1,** the post hoc tests revealed that the combination of both auditory and vibrotactile cues was significantly faster than the auditory cues and trended towards being significantly faster than the vibrotactile cues. There was no significant difference in performance between the two cues on their own. The effect sizes for the combination vs auditory were small to medium and small for the combination vs vibrotactile, according to Cohen (2013). Regarding the second research question on the effect of training, **RQ2**, training did make participants significantly faster, but the effect would be considered small (Cohen, 2013). Last but not least, the third research question on task difficulty, **RQ3**, showed a significant difference between the levels, level 1 being by far the easiest with a medium to large effect size when compared to the other two more difficult levels (Cohen, 2013). The difference between level 2 and level 3 was significant, but the effect size was only small (Cohen, 2013). The training effect was the smallest of the effects. The feedback effects, while still only small and small to medium (Cohen, 2013), sat in-between.

Bringing these results into the bigger picture, task difficulty played the biggest part in performance when searching for invisible objects. Taking the effect sizes into account and looking at the plots in Figure 36, it can be argued that the static invisible ghost of level 1 was considerably easier to find and catch than the moving ghost(s) of level 2 and 3. This considerable difference in difficulty can also be seen in Figure 36. The distribution of the time needed to finish is skewed towards the deadline of 300 seconds in level 2, even more so in level 3. This seems to suggest ceiling effects, especially in conjunction with the calculated effect sizes. It is likely that finding dynamic invisible objects was too hard as a task. This might also add to the findings of Grinyer and Teather (2022). They found that field of view (FOV) had a stronger influence on performance than movement in an out-of-view, but still visual search. When searching for an invisible object like in this study, movement does seem to strongly influence performance. The results of this study also do support other literature concerning multimodal vs unimodal cues (e.g., Morelli et al., 2010), showing the combination of cues to be better than both unimodal variants on their own.

This study, however, did not explicitly look into the different levels of the tasks on their own. When analyzing the collected data in an exploratory manner on a level basis, the statistical power was too small to meaningfully analyze it further. Considering this and the aforementioned ceiling effects in level 2 and level 3, future research should look closer into the relationship between the different feedback cues in a static invisible search task. The descriptive statistics and Figure 36 seem to suggest that vibrotactile cues might be better than auditory cues in such a setting. This should warrant further investigation.

Considering the design of this study and its statistically significant results, applications, and implications of these findings in real-world settings seem to be hard to find. Since completely invisible objects are only found in gaming settings, the findings suggest using multimodal cues to enable the player to find these objects without too much frustration. If we extend the findings to temporarily invisible, hidden or out-of-view objects, however, applications are easily defined. While navigating to an out-of-view building, the combination of a vibrotactile cue, e.g., a smartwatch that vibrates based on the target position, and an auditory cue, e.g., the voice of the navigation system, might make finding the building easier. The findings of this study also show that situations that do not allow for visual cues might benefit from vibrotactile and auditory cues. This could be used for training of hazard situations for firefighters, similar to what Feder et al. (2023) did. Although their setting did use visual cues and visual auxiliary equipment, this setting and the equipment might be enhanced by also using vibrotactile and auditory cues to detect the source of a fire in a smoke-filled room. There might also be a case for using the findings to further research the impact of non-visual feedback cues for visually handicapped people.

Chapter 7: Design, development, and evaluation of a virtual reality- based distance learning application in manual medicine and therapy – Study 4

After introducing the auditory and tactile aspects of virtual reality and its experience in the previous chapter, the next chapter will focus on an application of tactile gloves in a training context for manual medicine. To be used in such a setting, both the application and the gloves need to be in an easy-to-use state as well as offering a good user experience. The studies described in this chapter were part of the BMBF funded project grant *SmartHands* (grant number #01PG20006). This has been published in Lecture Notes in Computer Science vol 14708 and was reproduced with permission from Springer Nature.

7.1. Introduction

Traditional medical education has long relied on lecture-centered and didactic approaches that emphasize attendance and memorization (Kamei et al., 2012). While theoretical learning is critical, the limitations of such methods, including monotony and lack of standardization, prevent students from fully mastering practical skills (Izard et al., 2018). The advent of digital technology has provided a promising avenue for modernizing medical education and training (Kyaw et al., 2019).

Digital media, which includes web-based training, collaborative platforms, mobile applications, and educational videos, has experienced significant growth in various educational contexts over the past decade (Tamim et al., 2011). Among these, virtual reality (VR)-based technologies have gained traction in various fields, driven by increased commercial availability (Scavarelli et al., 2021), advances in visualization and interaction, and the immersive experience provided by head-mounted displays (HMD) (Radianti et al., 2020). VR technologies create immersive, interactive, and imaginative environments (Alzahrani, 2020) and provide dynamic and adaptive learning opportunities in remote learning contexts (Alzahrani, 2020).

While VR systems primarily provide visual and auditory feedback, the incorporation of haptic interaction has been identified as essential to enhance the immersive experience (Caiero-Rodriguez et al., 2021; Ozioko & Dahiya, 2022). Haptic technologies, particularly data gloves equipped with sensors and actuators, have emerged as a key component. They enable users to touch or manipulate virtual objects and receive haptic feedback, including vibration and pressure changes (Caiero-Rodriguez et al., 2021; Ozioko & Dahiya, 2022).

Including more intuitive and direct interaction opportunities, coupled with haptic feedback, allows learners to be immersed in a virtual environment that closely mirrors their real-world practice or exam settings (Krakauer et al., 2006; Smith & Vela, 2001). This proximity to authentic scenarios increases the likelihood that learners will retain actions and knowledge. Previous studies suggest that skill recall is more effective when the learning environment replicates the original context (Krakauer et al., 2006; Smith & Vela, 2001). In the field of health education, digital technologies have become versatile tools capable of meeting a wide range of educational needs of professionals. These needs cover a broad spectrum, including different teaching and training requirements, clinical competencies, and skills such as therapeutic, diagnostic, and communication (Barteit et al., 2021). Modern technologies provide a realistic training experience without compromising patient safety (Barteit et al., 2021). Their scalability and repeatability, independent of time and location, establish a standardized quality for medical technical skills, ensuring that proficiency is achieved before practical application (Barteit et al., 2021). For example, Wan et al. (2023) developed an immersive VR training system for orthognathic surgical education to improve technical proficiency, decrease operation time, and increase the attractiveness and degree of participation in surgical training.

The domain of manual medicine (MM) could also benefit from the advantages of VR. MM aims to treat dysfunctions of the musculoskeletal system, relieve pain, and restore mobility and performance based on clinical reasoning (Cerritelli et al., 2021). This approach utilizes highly specific treatment approaches, including manual techniques and therapeutic exercises, such as various types of massage and osteopathic manipulative treatment, which focus on the manipulation of tissue (Field, 2016). Consequently, MM and manual therapy (MT) fundamentally relies on touch to elicit tactile, proprioceptive, and interoceptive stimulation. Despite the integration of VR in physiotherapy, there is a notable lack of research evaluating its application in MT (Cerritelli et al., 2021).

Hence, the objective of this study was to develop and evaluate a prototype VR-based distance learning application for MM and MT. Throughout the research, particular attention was given to exploring the potential effects of VR in MM and MT for educational purposes, specifically concentrating on the learning scenario involving the 'mobilization of the cervicothoracic junction (CTJ)'. Additionally, the investigation included the exploration of the application of data gloves for enhancing this scenario.

This article proceeds as follows: First, the applied materials and methods are described, including two design loops to capture the requirements from the perspective of experts, teachers, and students (qualitative interviews) and their assessment of usability (quantitative questionnaires). Subsequently, the results of the two design loops are presented and the VR application designed and developed on this basis is showcased. Finally, the results are critically discussed in the context of potentials and limitations and an outlook on further research steps is given.

7.2. Materials and Methods

7.2.1. Ethical and Legal Aspects of the Research

The study was approved by the ethics committee of social sciences faculty of the University of Kaiserslautern (Ethics Committee Vote Number 30) without any further requirements or restrictions. Furthermore, the study was also approved by the ethics committee of the Universitätsklinikum Halle. This study is also in compliance with the WMA Declaration of Helsinki (World Medical Association, 2013) and the APA Code of Ethics (American Psychological Association, 2017) including all respective amendments at the time of this study.

7.2.2. Hardware and Software for the prototype VR Application

A Meta Quest 2 (Meta Platforms Inc., USA) HMD was used. The Meta Quest 2 has a resolution of 1832 by 1920 pixels per eye and a refresh rate of up to 90 Hz. The data gloves used in this study were the SenseGlove Nova (SenseGlove, Netherlands) (Figure 37). These haptic data gloves use a nine-axis sensor in the wrist for the absolute orientation of the hand as well as four sensors, one for each finger except the little finger, to measure the flexion and extension of the fingers. There is also a sensor to measure adduction and abduction of the thumb (SenseGlove, n.d.). For force feedback, the data gloves use four modules to provide force in the direction of finger flexion at the fingertips. Furthermore, there are three actuators for vibrotactile feedback, one each for tips of the index finger and the thumb, while the third is located in the palm hub of the gloves.

The software application was programmed using the Unity engine 2021 (Unity Technologies, USA). In addition, the software wit.ai (Meta Platforms Inc., USA) was used to transform user voice commands into actions within the VR environment.

Figure 37

A Valve Index VR Headset used together with the SenseGlove Nova. [Figure from Steffny et al. (2024)]

7.2.3. Qualitative Interviews (Design Loop 1)

Interview Guideline. A semi-structured interview guideline was developed in conjunction with MM and MT practitioners as well as teaching experts. The guideline was constructed to ensure that each expert, teacher, and student would get the same overarching topics. Questions were framed in a manner to avoid bias, leading questions and to invite detailed responses from the participants.

Procedure of Interviews. The interviews were conducted with experts, teachers and students. The interviews with the experts and teachers were done in one-on-one sessions, while the students' interviews were done as focus group sessions. All sessions were conducted online and were recorded for later transcription and analysis. All participants received general information about the process and gave their written consent on the participation as well as recording beforehand.

The sessions started with a short introduction by the interviewer about the project and the general procedure of the interview. All participants were asked about the following topics:

- general teaching and training practices and weaknesses in MM and MT
- experience with digital solutions in teaching and training in MM and MT

For the last topic, the participants saw videos and some mockups of an early prototype of an application for MM and MT. The feedback on this early prototype concept was used for the next design loop. A session usually lasted about 120 minutes.

Sample of the Interviews. Five experts, in this case two doctors of MM and three teachers of MT at vocational colleges and further education institutions, were interviewed in one-on-one interviews. Eight students were interviewed in two focus groups of four students each. The first focus group consisted of one emergency medicine specialist with further education in MM, two students of MT at a university of applied sciences and one MT apprentice. The second focus group consisted of four trained MT that enrolled in medical studies after their training and were in their eighth semester at the time of the focus group session.

7.2.4. Quantitative Prototype Usability Testing (PUT, Design Loop 2)

Questionnaires from the PUT. The questionnaires used in the usability tests were the Igroup Presence Questionnaire (IPQ; Schubert, 2003), the pretest and posttest versions of the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993), the System Usability Scale (SUS; Brooke, 1995) and the User Experience Questionnaire (UEQ; Laugwitz et al., 2008).

IPQ. The IPQ is a 14-item questionnaire that is used to assess the feeling of presence in virtual reality. The IPQ is constructed out of the three subscales Spatial Presence, Involvement, and Experienced Realism and a single item on General Presence. The participant answers on a 7-point Likert scale, from 0 (strongly disagree) to 6 (strongly agree), on how much they agree or disagree with the given statements.

SSQ. The SSQ is a 16-item questionnaire, each item referring to a symptom commonly associated with simulator sickness and typically given both during the pretest and posttest phases of an experiment. For each of the 16 symptoms, the participants report how strongly the symptom currently affects them on a 4-point scale (none, slight, moderate, or severe).

SUS. The SUS is a 10-item scale used to assess the usability of a system. Participants use a 5-point Likert scale to rate how strongly they agree with the given statements about the system they are asked about.

UEQ. The UEQ is a 26-item questionnaire consisting of contrastive pairs of terms that can describe the user experience. For example, one of these items would be the pair of "attractive" and "unattractive". These pairs are scaled in seven steps, from -3 to +3, with -3 being the most negative, 0 being a neutral and +3 is the most positive response. The UEQ is divided into six subscales: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty.

Procedure of the PUT. After incorporating some of the feedback from the interviews and testing several versions of a prototype VR application internally, a working version was tested in the field. The working prototype had a patient in the examination room as the setting. Participants had to do an examination of the patient's CTJ mobilization.

The PUT started with a pretest questionnaire about what technical devices they had and if they have any prior experience with VR. After filling out this questionnaire, the participants completed a small online course on the cervicothoracic transition which was used as a precursor to the patient examination in VR.

Before starting the VR application, participants were fitted with the Meta Quest 2 HMD and the SenseGlove Nova. The data gloves were then calibrated using the SenseGlove calibration app. The participants opened the prototype VR application and started the examination after a brief introduction on the general control scheme by the experimenters.

The VR examination began with the virtual patient sitting on a MT treatment table (Figure 38). The participants then had to examine several joints and their mobilization both through haptic examination using the data gloves and through voice commands. The joints that needed to be examined were both highlighted on the patient's body (Figure 39 top) and written down on a checklist visible in the VR application. The joints were highlighted as gray dots on the spine that turned red when touched by the participants' hands in VR. The examination could be done in any order and without a time limit. Voice commands were used to let the VR patient move their head to the right, to the left, tilt it forwards as well as tilt the head backwards. A voice command was also required to trigger the ability to perform an active MT exercise with the patient.

After completing the examination application in VR, the participants had to answer a short quiz about the examination in the online course. After this quiz, the participants had to answer a posttest questionnaire about their user experience using the UEQ and the SSQ, the usability of both the application and the data gloves using the SUS, their immersion in VR using the IPQ as well as demographic questions, e.g., age, occupation, and education.

Sample of the PUT. Thirty-two participants (13 male (40.62 %), 19 female (59.38 %), 0 diverse/non-binary (0.00 %)), ranging in age from 20 to 79 years (M = 36.56 years, SD = 15.3 years, Md = 32.00 years) tested the VR prototype. Of the 32 participants, 15 were students (46.88 %), twelve were teachers (37.50 %) and five were practitioners (15.62 %). Of these 32 participants, four had prior experience with VR (12.50 %), 25 had no prior experience with VR (78.12 %), and three did not answer this question (9.38%). Prior to the VR part of the testing, the SSQ showed no significant problems with symptoms of simulator sickness.

7.3. Analysis

R 4.3.1 was used to analyze all questionnaires except for the UEQ. For the analysis of the UEQ, the UEQ Analysis Tool Excel spreadsheets, as available on their website (UEQ, n.d.), were used.

7.4. Results

7.4.1. Results of Interviews (Design Loop 1)

Experts and Focus Groups on the Topic of Current Practices and Weaknesses. The experts mentioned several aspects of the current practices in teaching MT. A major part of teaching is teaching the different manual techniques. According to the experts, this is mainly done by showing the techniques to the students, then letting the students repeat the techniques and giving them feedback on what needs to be improved. One of the experts also said that they want *“more variety in their teaching methods”* than what they currently have.

One of the weaknesses in this regard, according to the experts, is that there are terminologies and concepts that vary between the different educational institutions which in turn makes communication and work more difficult. The students in the focus groups agreed on this point. One of the students in the focus groups said that *"there are differences in each of the schools [...] differences in ordering of the courses, but also in material and content"*.

Experts and Focus Groups on the Topic of Using Digital Technologies in Teaching and Learning MT. Both experts and focus groups said that digital technologies can help in teaching and learning if done correctly. While they said they already use video conferencing, learning management systems and have a wiki-style database of different manual techniques, there are things and procedures that can be further digitalized. The experts and teachers mentioned they could envision parts of the curriculum, e.g., fundamentals of joints and anatomy as well as practicing techniques, in VR and AR.

Experts and Focus Groups on the Early Concept of the Prototype. Concerning the early concept of the prototype shown in screenshots, experts pointed out that a structured approach based on the different steps is a meaningful way to use AR and VR in teaching in MM and MT. The experts said that the prototype should show the different steps as an overlay and indicate if the correct part of the body is being gripped or not. One expert reiterated the idea of using it to showcase the anatomy of the body and how the different joints actually work and move after being shown the early concept.

The focus groups also thought that the prototype could be used to show the anatomy. Another use case for them was to use it to practice some of the rarer cases to be prepared when they occur.

Both experts and focus groups agreed that a VR or AR application similar to the early concept prototype can help with practice and feedback in teaching and learning. Both also agreed that haptic feedback is needed to use it in a meaningful and sustainable way.

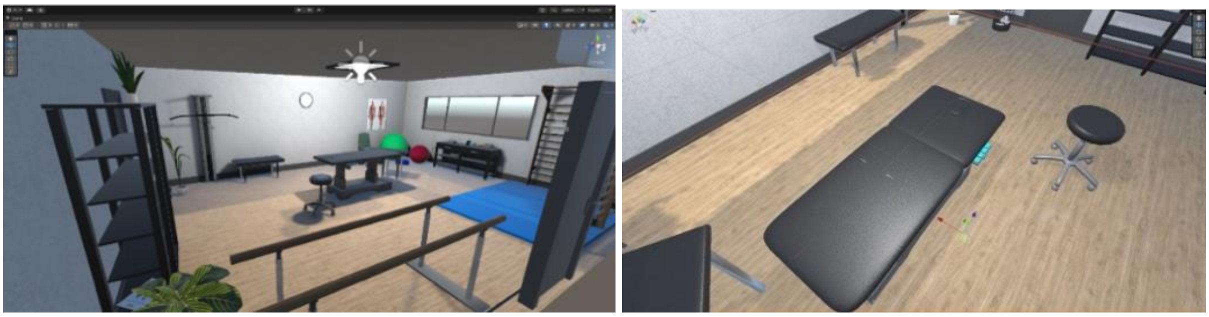
7.4.2. Results of Implementation of Prototype VR Application

The early-stage mockups were iteratively adapted, considering the results of the interviews mentioned in 3.1. Based on this, a realistic treatment room, an interactive virtual patient and a tablet for the VR environment were implemented, which are presented in detail in the following.

Treatment Room. Using the identified professional and technological requirements, a 3D VR environment was developed to replicate a treatment room (Fig. 38). This VR environment provides the flexibility to control various elements, including an adjustable therapy table and an integrated tablet for managing and displaying information.

Figure 38

VR Environment that replicates a MT treatment room. [Figure from Steffny et al. (2024)]



Tablet for Control and Display Functionalities. Furthermore, a tablet was integrated into the VR environment for control and display functionalities. Hand tracking was integrated using the data gloves, eliminating the need for a touch controller. The interaction with the tablet and other objects, such as the control function of the therapy table, is done by touch through the virtual hands of the hand tracking.

The tablet was iteratively equipped with additional functions during the course of the project. A login function allows users to log in during the evaluations with preconfigured user accounts. A checklist was used to keep track of all the steps carried out and their progress.

Movement in the virtual environment can be done either by moving around in the real room if sufficient space is available or by interacting with the tablet. For this purpose, certain areas of interest have been defined in relation to the virtual patient, to which the user can teleport by touching input on the tablet. The tablet always stays close to the user so that it is within reach even if the user teleports or moves.

Virtual Patient. A virtual patient has been developed to perform various MT diagnostic and treatment procedures (Figure 39). These include passive examinations (cervical spine flexion/extension/rotation/lateral tilt) as well as an active preliminary examination to mobilize the CTJ and check the isometric resistance of the cervical spine. In addition to the haptic interactions in the environment, the VR application also allows voice interaction with the virtual patient, e.g. for the patient to perform the cervical spine rotation.

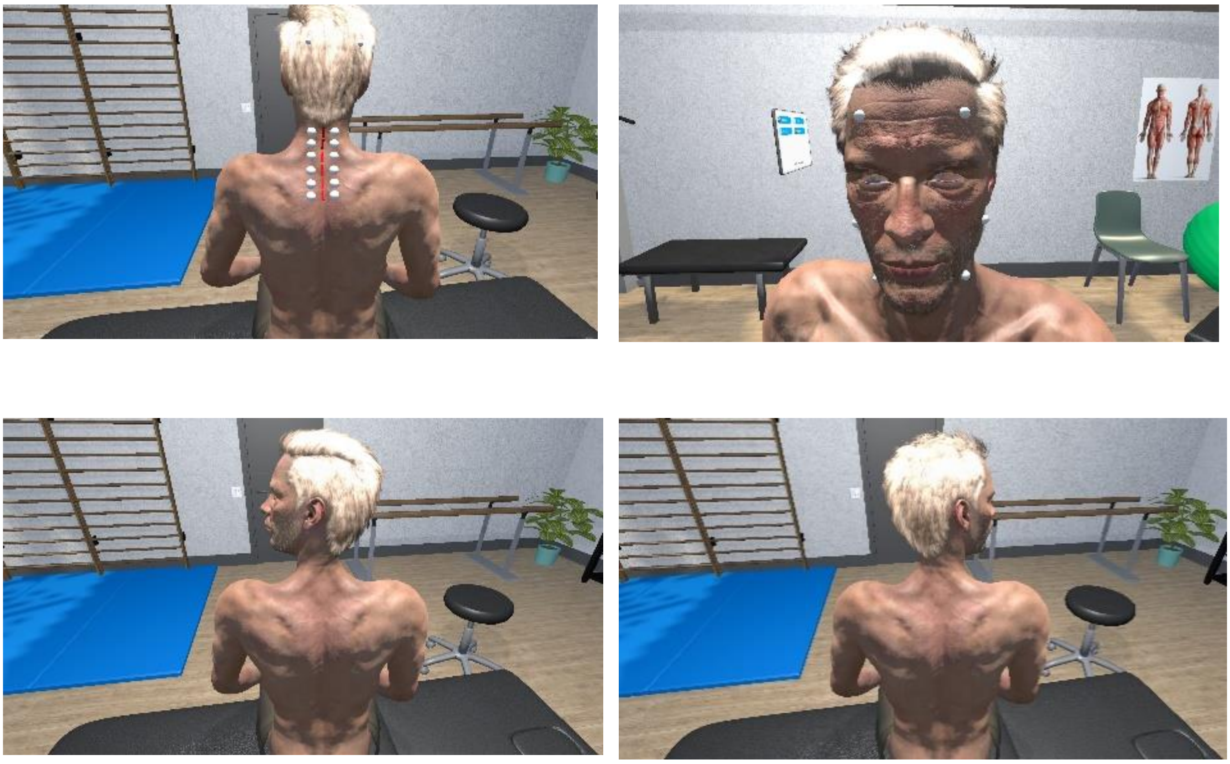
For passive examination tasks, the user must instruct the virtual patient to move his head in a certain way and in the correct order to visually see movement restrictions of the cervical spine and correctly diagnose the underlying issue (Fig. 40 bottom).

To check the isometric resistance of the cervical spine, the user has to perform certain grip techniques on the patient’s head and tell him to resist against his own movement. The haptic feedback of the data gloves should allow the user to determine if there are any underlying issues with a weak resistance of the cervical spine.

For the CTJ, the user must touch the correct vertebral segments of the cervical spine and then instruct the virtual patient to move his head to one of the possible directions (forward, backward, left, right). By moving the head and the corresponding movement of the vertebral segments, the user should be able to visually see and physically feel abnormalities of specific segments.

Figure 39

Sketch of the vertebrae and vertebral segments of the virtual patient as a preliminary test for mobilization of the CTJ (top). Illustration of head rotation with full (bottom left) and limited (bottom right) range of motion. [Figure from Steffny et al. (2024)]



7.4.3. Results of the PUT

There were no noticeable problems with simulator sickness according to the posttest SSQ, similar to the pretest SSQ.

The results of the IPQ by subscales are shown in Table 8. According to Melo et al. (2023), the General Presence in the VR application can be considered *excellent* (grade *A*). While the Spatial Presence and Experienced Realism subscales could still be considered *marginally acceptable* (grade *E* and *D*, respectively), the grading of Melo et al. would describe the Involvement as *unacceptable* (grade *F*).

Table 8. Descriptive Statistics for the 7-point Likert scales version of IPQ.

IPQ Subscale	*N*	*M*	*SD*	*Mdn*	*Min.*	*Max.*
General Presence	32	4.50	1.57	5.00	1	7
Spatial Presence	32	4.13	0.99	4.20	1.6	6
Involvement	32	3.34	0.92	3.25	1.75	5.25
Experienced Realism	32	3.15	0.7	3.00	2	4.25

[Table from Steffny et al. (2024)]

Regarding user experience, the SUS and the UEQ were analyzed. The SUS was used for the data gloves exclusively, while the UEQ was used for both the VR application and the data gloves.

The SUS scores for the SenseGlove Nova, *M* = 58.44 *SD* = 15.42 *Mdn* = 61.25, can be considered *ok* or grade *D* according to Bangor et al. (2009).

Figure 40 and Figure 42 show the mean values per item of the UEQ for the VR application and the data gloves, respectively. Items belonging to the same subscales are color matched. In both cases, the UEQ values are on the positive spectrum of the opponent pair items. Figure 41 and Figure 43 show the UEQ results for the VR application and the SenseGlove Nova, respectively, and compare these results to the UEQ benchmark data set. Of Compared to the benchmark data, the VR application can be considered *good* regarding Attractiveness, Stimulation and Novelty, but *below average* regarding Perspicuity, Efficiency and Dependability. The SenseGlove Nova, on the other hand, can be considered *above average* in Attractiveness, Perspicuity, Efficiency and Dependability, *excellent* in Stimulation and *good* in Novelty.

Figure 40

Means per UEQ item on the experience of using the prototype VR application [Figure from Steffny et al. (2024)]

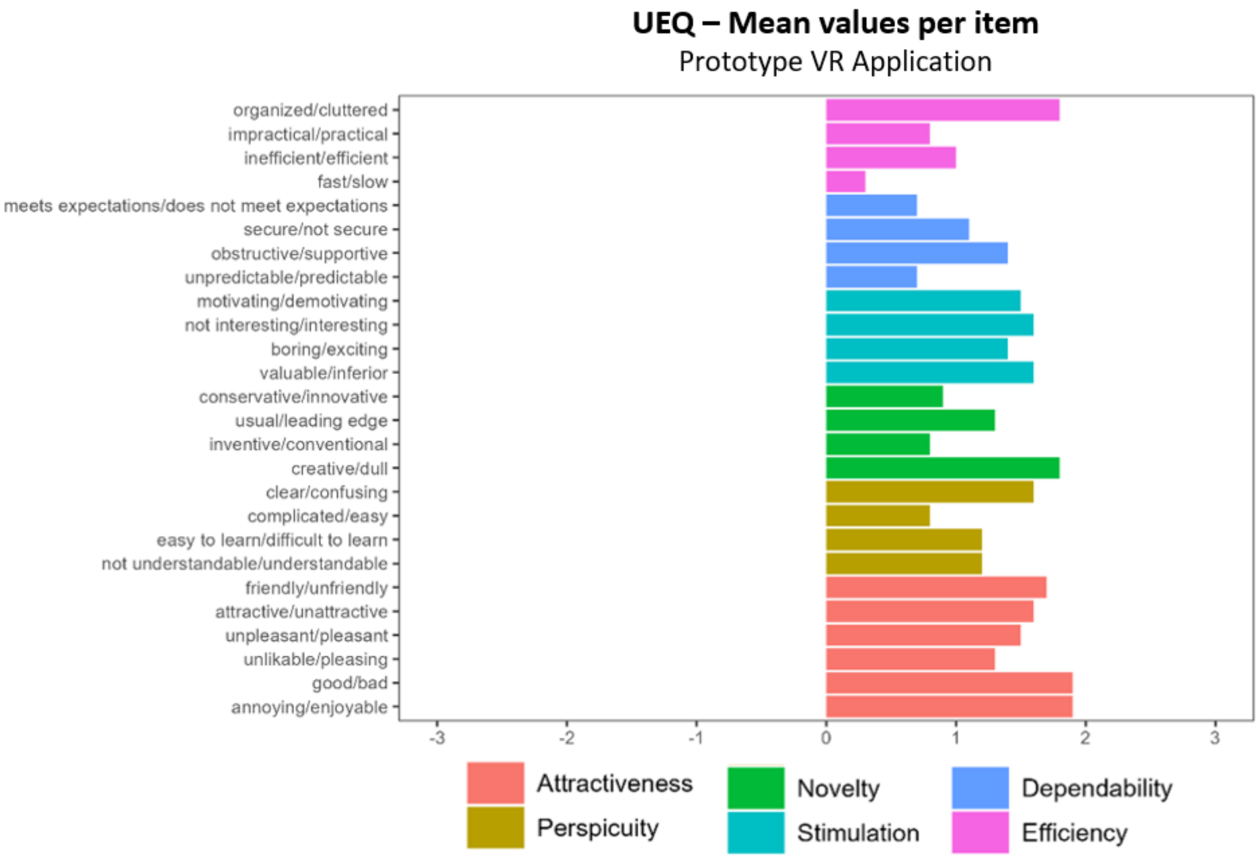


Figure 41

UEQ results on the experience of using the prototype VR application compared to the UEQ Benchmark dataset [Figure from Steffny et al. (2024)]

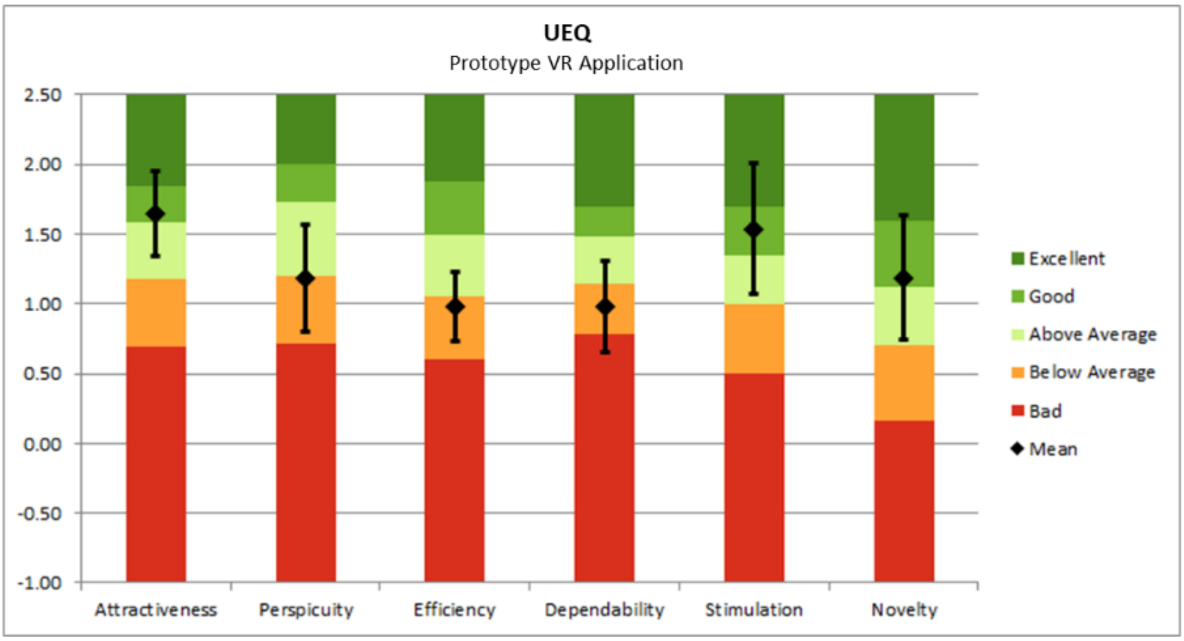


Figure 42

Means per UEQ item on the experience of using the SenseGlove Nova for interacting in the prototype VR application [Figure from Steffny et al. (2024)]

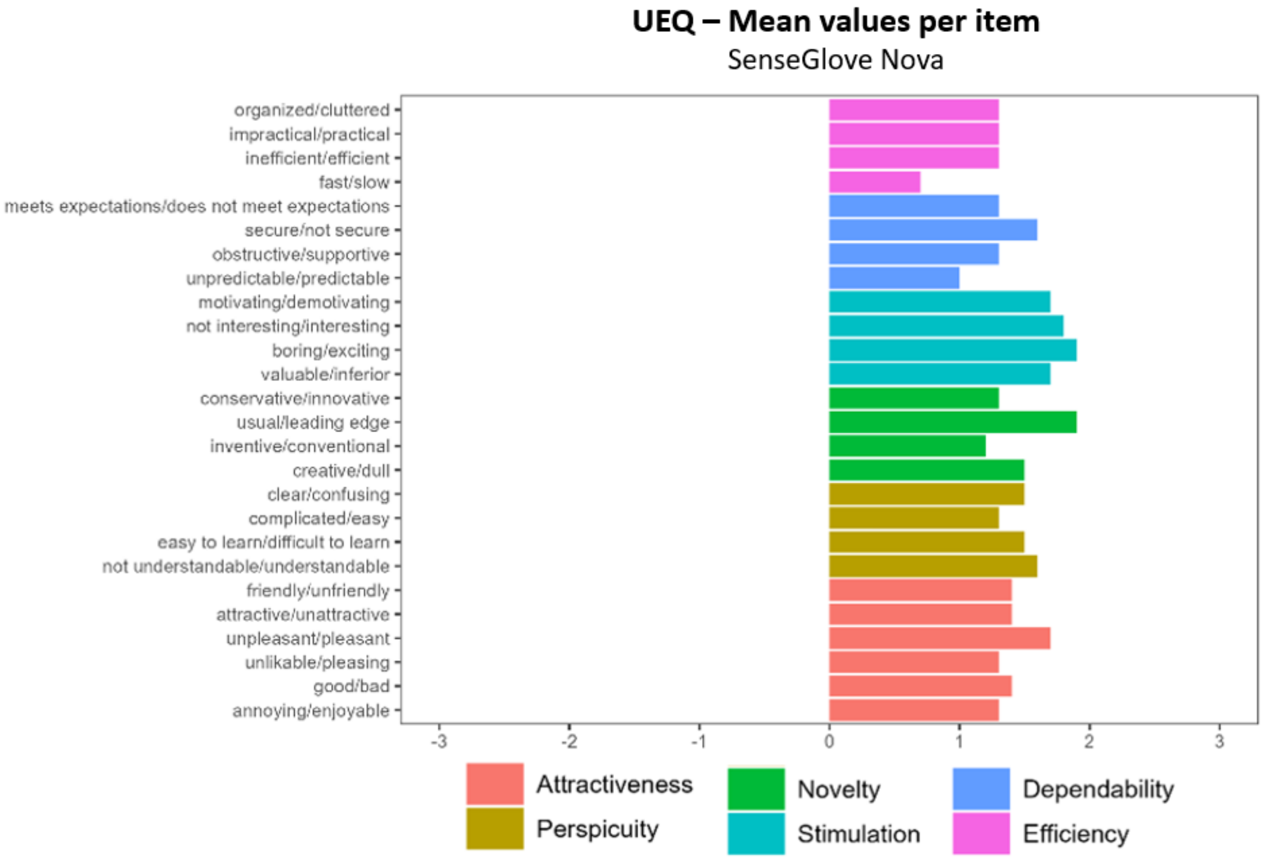
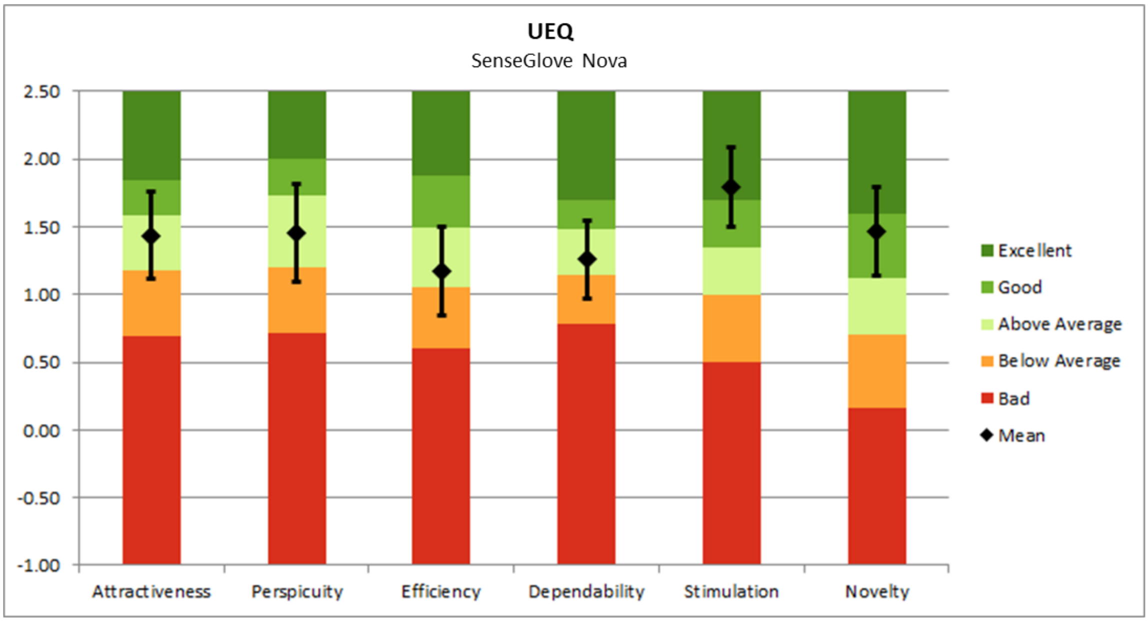


Figure 43

UEQ results on the experience of using the SenseGlove Nova for interacting in the VR application compared to the UEQ benchmark dataset [Figure from Steffny et al. (2024)]



In addition to the results of the questionnaires, some participants also gave free text feedback on the application and the hardware. When writing about the VR application, some participants mentioned the possibility of *"going or touching through the patient"* and the *"lack of feedback"* as confusing and bad, while also mentioning that "*it would be nice if it was more realistic"*. Another participant said that they would like their avatar in VR to have legs. Concerning the data gloves, they said that "*the vibration mode of the gloves was partially inappropriate",* that they *"wanted to have resistance in [their] fingers"* and that they would have liked "*more precision in their coordination"* of the hand movements.

7.5. Discussion

An iterative design process with in-between evaluations was used. The aim was to ensure that the iterations achieved the desired effect and that the prototype met the requirements of the target group. The first design loop consisted of semi-structured interviews with the target group, i.e. MM teachers and learners, in which they were asked about the requirements for a potential VR application. Furthermore, they were asked to evaluate a very early concept prototype in terms of its suitability for MT learning scenarios. The second design loop started with the implementation of a working VR application prototype showing a patient examination. The VR application utilized haptic data gloves to attempt to replicate the haptics in MM. Following implementation, this prototype was tested for usability and user experience of both the VR application itself and the data gloves. The results of the questionnaires showed promising results in terms of the general presence in VR and the user experience of the SenseGlove Nova. However, opportunities were also identified to optimize both technologies, the VR application and the SenseGlove Nova, concerning certain aspects of presence and user experience.

The UEQ results of the SenseGlove Nova showed above-average suitability of the gloves for the VR application. The VR application, on the other hand, was rated lower on average by the participants. However, the SUS results, which only rated the usability of the gloves as ‘ok’, must be taken into account when interpreting the results.

A possible explanation for the rating of the VR application could therefore lie not in the VR application itself, but in the interaction with the Sense Glove Nova. Beese et al. (2023) compared two kinds of VR controllers and found differences in user preference but not in performance. They argued that it is about more than just the design of a controller. They also noted that the interplay of assets and the kind of interactions you want to enable in VR could play a bigger role in some cases. Reviewing the comments of the participants in the usability test of this study provides further insight into the possible causes of the differences in the results. The comments pointed to an imbalance between interactions in the physical and virtual worlds. For example, they stated that it was possible to move their hands through the patient. In addition, they stated that in some cases they were confused by the lack of feedback and inappropriate vibrations. These comments explain why the Involvement and Experienced Realism subscales were rated comparatively low.

Concerning the implementation of the SenseGlove Nova in the VR application, we found that the haptic feedback of the data gloves should be able to let the participants feel if there are issues with weak resistance in the spine in the examination. However, some participants pointed out the unrealistic feedback. One reason for this could be that the data gloves are either not good enough for the task or that some forms of implementation are not possible in the current state. Potentially, the gloves are the biggest limitation of this study, as the haptic capabilities of a human hand, such as the resolution of haptic detections (Louw et al., 2000, 2002), are higher than what SenseGlove Nova can provide. This is particularly important to consider when dealing with a topic from the fields of MM and MT. Müller and Grunwald (2013) have shown that manual therapists have a higher perceptual performance in terms of haptics. They argued that daily training in MM may have led to higher performance and a slower decline in this performance in older therapists. They also concluded that training programs for people with inherently low sensitivity could lead them to have higher haptic perception. Combined with our results from the questionnaires as well as the comments of the participants, the SenseGloves Nova in its current state could not satisfy all aspects needed in the MT setting in this study, which is in accordance with the argument made by Certinelli et al. (2021) that the technology is still lacking.

Studies show that haptic data gloves may not need to realistically mimic human hands to train certain actions. Zhao et al. (2021) found in their meta-analysis that the use of VR applications in medical education resulted in a higher pass rate for learners than for learners using traditional training approaches. They mentioned that learners have more confidence by gaining more hands-on experience and a better understanding of the procedures being practiced (Zhao et al., 2021).

Regarding the effects of a realistic learning experience, Hekele et al. (2022) found no differences in learning outcomes between a 2D video and a non-interactive 360° video shown in VR. Niedermayr et al. (2023) found no significant differences in learning in VR when comparing interaction with realistic tools versus non-realistic tools in VR. However, they also stated that their qualitative evaluation showed higher engagement when using the realistic variants. This is also in accordance with the comments in our study that they wished the hand interactions and feedback would be more realistic. Then again, our study was only focused on usability for the time being.

In conclusion, the mixed-methods approach combined with iterative feedback and usability testing design loops helped to identify the target group's requirements for the VR application to practice MM and MT learning scenarios, and the main areas in which there is currently room for improvement to realize the full potential of this type of application. Further research should focus on the interaction between VR and data gloves. Special attention should be paid to the involvement of MM and MT teachers in the development process of haptic data gloves to meet the high requirements of this professional group. With respect to the current state of the art of haptic data gloves, it should be further evaluated for which learning scenarios in MM and MT the use of immersive VR applications already represents a real added value for learners and what impact the use of such technologies has on learning outcomes.

Chapter 8: General Discussion

The previous chapters dealt with different aspects of the experience in Virtual Reality. In this chapter, the results will be briefly summarized, and discussed in the bigger picture of current research.

When discussing the underlying experiments, this chapter will refer to the study behind the chapter and its accompanying number in this work, i.e., study 1, study 2, study 3 and study 4, as seen in the respective chapter titles. As a reminder, the connection between the chapters and the underlying studies will also be reintroduced in the following part.

8.1. Summary of Study Results from Chapters 3 – 7 (Study 1 – 4)

The pilot described in chapter 3, i.e., study 1, did set out to examine how the number of rooms, the locomotion technique as well as the visual quality and presence of landmarks can change the experience of spatial navigation in an office-like building. Participants' performance benefitted from two factors, locomotion technique and presence landmarks, but did so exclusively in the harder condition that had a longer minimum shortest possible way. The effect of visual quality on performance was unexpected, seemingly having better performance with no textures present, but the differences were not statistically significant. The arm swinging technique showed better performance, but again not statistically significant. The participants also did better when they had landmarks present versus no landmarks. Thus, the performance of participants was best when participants used arm swinging in trials where landmarks were present, and it was the worst when participants had to teleport without landmarks being present. This difference was statistically significant.

Chapter 4 and 5, i.e., study 2, used the insights gathered from the previous chapter and focused on the effect of different kinds of landmarks on both behavioral as well as physiological aspects of spatial navigation in a complex office building. Being based on the pilot study, the experiment of study 2 kept the locomotion technique, visual quality and complexity of the building in the experiment constant, only varying the presence of different kinds of landmarks. Chapter 4 was concerned with behavioral data, measuring time to reach the target, number of rooms traversed, time to draw a sketch map as well as accuracy of the sketch map, i.e., difference between the sketch map and the actual way in Euclidean distance. To measure this difference, a method was developed that accounted for the difference in Euclidean distance for every room of the sketched path and the shortest path. This meant that every single room deviation was accounted for, not just the difference from the sketched end room to the actual end room. The accuracy of the map was significantly better in conditions with landmarks, confirming the pilot study in that regard. Differences in accuracy and time to draw the sketch map between indoor and outdoor landmark conditions were not statistically significant. Other assumed possible differences between outdoor only and the combination of indoor and outdoor landmarks were also not significant. Chapter 5 then analyzed movement and eye-tracking data collected during the course of the study 2. Neither the movement nor the eye-tracking data showed any patterns pertaining to the different landmark conditions, likely due to very basic implementation of both those measurements.

Chapter 6, i.e., study 3, then investigated the effects of auditory and vibrotactile cues as well as training and difficulty on finding hidden objects in VR. The task was embedded in a ghost hunting setting. Participants had to find ghosts in three different levels with the help of auditory cues, vibrotactile cues and a combination of both those cues in each level. The objective of level 1 was to catch a single static ghost. In level 2, a single dynamic ghost needed to be caught. And in level 3, two dynamic ghosts should be caught by participants. Participants played two playthroughs of each level with each of the feedback cue conditions. Results showed that task difficulty had the biggest effect on the time needed to catch the ghosts. Training had the smallest effect on time, while the feedback effect was placed between the two. The biggest effect feedback-wise was the multimodal combination cue. While still not as big of an effect as difficulty on time, the combination of auditory and vibrotactile cues yielded the fastest times among the three feedback conditions.

In chapter 7, i.e., study 4, the user experience of data gloves in a haptic heavy MM/MT setting using a purpose-built VR application was examined. The requirements for the purpose-built VR application were established through the UCD approach. This was done via two design loops. The first loop was based on interviews with experts, teachers and students. In these interviews, they were asked questions pertaining to different aspects of the strengths and weaknesses of current practices in teaching and learning, as well as the use of digital media and technologies in teaching and learning. Last but not least, they were asked to give feedback on an early prototype concept designed in collaboration with partners of the project consortium with a background in MM/MT. The second design loop then used the information gathered through these interviews and a first prototype VR application incorporating this information was developed. The VR application used a typical MM/MT examination as a setting. This prototype VR application also incorporated haptic data gloves in a meaningful way. Both the haptic data gloves as well as the VR prototype application were then evaluated by MM/MT teachers, students and practitioners. The results of this evaluation were positively promising in terms of presence in VR as well as UX of the haptic data gloves. The evaluation also unearthed points on what should be overhauled regarding the UX of the gloves and the VR prototype. The gloves were rated above average on the UEQ subscales, but only “ok” on the SUS (Bangor et al., 2009). The VR prototype application was rated lower than the gloves on the UEQ with some aspects even being rated below average, but “excellent” regarding general presence. Then again, the other aspects of presence were rated as only being marginally acceptable or even unacceptable. The comments of some participants then shed some light on the minute details of what exactly needed to be overhauled for the UX to get better. This also showed why mixed methods as well as UCD as a design approach is a good method to develop usable systems.

Regarding the overall UX in studies 1 to 4, the presence and cybersickness symptoms were recorded. The cybersickness symptoms were reported via the SSQ. In study 1 and study 2, participants showed some symptoms of cybersickness, leading some to abort the experiment before completion. Participants had no noticeable problems with cybersickness in study 3 and 4. Concerning presence, the IPQ was used throughout all of the studies. According to rating guidelines by Melo et al. (2023), study 1 had satisfactory general presence, but unacceptable spatial presence, involvement as well as experienced realism. The general presence of study 2 could be described as satisfactory (Melo et al., 2023). Study 3 had very good general presence, but unacceptable spatial presence, involvement and experienced realism (Melo et al., 2023). Last but not least, the study of chapter 7 had excellent general presence, unsatisfactory - yet still marginally acceptable - spatial presence, marginal experienced realism, but the involvement was unacceptable (Melo et al., 2023).

8.2. Discussion of Results and Limitations

8.2.1. Study 1 and Study 2

Study 1, i.e., the pilot study, as well as study 2, the follow-up, showed some expected results. The arm swinging locomotion technique used in the pilot was better in the orientation task at the end than teleportation. Coomer and colleagues (2018) had similar findings when comparing teleportation and arm swinging among others. They also found that the UX of arm swinging was rated slightly better than the UX of teleportation. The study of Loup and Loup-Escande (2018) showed important differences in UX. They found that arm swinging was more effective than teleportation, in line with Coomer et al. (2018). However, contrary to the findings of Coomer et al. (2018), Loup and Loup-Escande (2018) found that arm swinging leads to a more negative UX. This also included more cybersickness in the arm swinging condition. While the pilot study as well as the follow-up study in this dissertation did collect data on cybersickness, it was not set up to cleanly measure differences between teleportation and arm swinging in the pilot. The findings of Loup and Loup-Escande (2018) could explain why participants in the pilot and follow-up did abort due to severe cybersickness, though. Another aspect in both of the studies was how the presence of landmarks positively affected performance (e.g., Jansen-Osmann, 2002; Ruddle et al., 2011), even though there were mostly statistical trends but no statistical significance.

This also leads to the limitations of the pilot and the follow-up study. Post hoc tests as well as statistical power analysis suggest that the sample size needed to be bigger for both studies, at the very least. It is also likely that the complexity of the pilot did not help with achieving a robust sample size. In the case of complexity of experimental design, the follow-up did try to make the experimental design simpler, but still did not achieve enough statistical power in all of the analyses.

Another point of limitation already mentioned earlier might be the arm swinging locomotion technique. As mentioned above, there is evidence that arm swinging might lead to worse motion sickness (Loup and Loup-Escande, 2018), but there is also evidence that this might not be the case (Coomer et al., 2018). But while it is a possibility that this technique exaggerated cybersickness symptoms, there might be even more to it. Wilson and colleagues (2016) found that distance estimation differed substantially while using arm swinging for locomotion. Both Gao and colleagues (2022) as well as Loup and Loup-Escande (2018) found that arm swinging also potentially led to higher cognitive load. Since in study 2, eye tracking data was recorded to measure cognitive load, this might have also influenced the findings of study 2 described in chapter 5. The very basic movement tracking implementation could have also been made more comprehensive with another form of locomotion. Arm swinging was used in the pilot and follow-up studies because of economic and space constraints. Future research should aim for more natural locomotion techniques and equipment like omnidirectional treadmills or friction-free platforms like the Virtuix Omni (e.g., Virtuix, n.d.; Nilsson et al., 2018) in conjunction with a more fleshed out implementation of tracking movement and eye data. These aspects, a bigger sample size and probably an even less complex experimental design should alleviate some of the encountered problems and it might then be revealed if it was just noise in the data of chapter 4 or not. More precise tracking hardware in conjunction with a comprehensive data collection implementation might also reveal actual differences in the movement and eye gaze behavior described in chapter 5.

Another aspect that should be investigated further is the method of measurement of sketch map differences in tasks similar to chapter 4. In chapter 4, a method to measure these differences was introduced. While this method is easy to implement in VR and the results seem promising, there is merit to compare it against other methods of orientation accuracy measurements as well as with other spatial orientation tasks in VR. This should reveal possible strengths and weaknesses as well as further the development of this method.

8.2.2. Study 3 and Study 4

Both study 3 and study 4 put their focus on non-visual modalities and sensory systems. Both studies had interesting and expected results as well as offering some new insights regarding haptic as well as auditory aspects of VR.

Study 3 showed that multimodal cues were better than unimodal cues. This is in line with parts of the body of research (e.g., Gray et al., 2013; Martin et al., 2022; Morelli et al., 2010; Ngo et al., 2012; Santangelo & Spence, 2007; Schwarz & Hamburger, 2023). Morelli and colleagues found that participants performed better when getting multimodal cues instead of unimodal cues as guidance. The results of a study by Schwarz and Hamburger (2023) showed better wayfinding performance in the multimodal condition. While the accuracy was not better in their multimodal setting, the participants of the study of Ngo and colleagues (2012) responded more quickly than in their unimodal settings. Santangelo and Spence (2007) also found that multimodal cues attract spatial attention even when the cognitive load is high.

However, multimodal being better than unimodal cues is a point of contention. While the aforementioned studies show that multimodal cues have benefits regarding performance, others show the opposite or no effect on performance at all (e.g., Arena & Hamburger, 2023; Ngo & Spence, 2010; Torta et al., 2015; White et al., 2009). Arena and Hamburger (2023) found that multimodal did not change performance. Similarly, the findings of White et al. (2009) also suggest no improved performance for multimodal cues when compared with unimodal cues. Furthermore, they reported no improvement in workload as well (White et al., 2009). Contrary to the findings of Santangelo and Spence (2007), Arena and

Hamburger (2023) argue that the zero effect of multimodal cues might be because of a higher cognitive load. Torta and colleagues (2015) discovered that multimodal cues led to longer reaction times in their study, while the study of Ngo and Spence (2010) saw no difference between unimodal and multimodal cues regarding performance enhancement. Taking the findings of both sides of the debate into account, at the very least it can be stated that the multimodal cues, a combination of vibrotactile and auditory, have a positive effect when searching for an invisible or out-of-view object. This might also be due to the implementation of the cues in study 3, since we made sure to transport as much location information with the cues as possible. Future research might examine if the strength of this effect persists in an easier task or a less than optimal implementation. Another point of future research might be the cognitive load of the used cues, similar to what Santangelo and Spence (2007) examined.

Another interesting aspect of study 3 is the existence of a learning or training effect, albeit small. Learning effects have been shown to occur in VR before (e.g., Y.-F. Chen et al., 2018; de Jesus Oliviera, 2017b; Dhimolea et al., 2022; Esteves et al., 2023; Stone et al., 2011). De Jesus Oliviera and colleagues found a strong haptic learning effect in VR. Furthermore, the study by Y.-F. Chen and colleagues (2018) did find a positive relation between using VR for learning, learning outcome as well as learning satisfaction. Stone et al. (2011) compared welding training in VR and traditional welding training methods. Participants using the VR training performed just as well as the group with traditional training, in some cases VR training even significantly outperformed the traditional. These results as well as the results of study 3 bode well for haptic learning and training of manual techniques using VR. This could also arguably be extended to any follow-ups to the study 4.

Study 4 was a usability study based on a User Centered Design (UCD) process, trying to both incorporate haptics in a meaningful way in VR as well as incorporate future users in the design process of such an experience. This was deliberately done in collaboration with experts, teachers and students in a haptic heavy area, the realm of education in manual medicine and therapy (MM/MT). The use of UCD integrating teachers was pivotal to construct a meaningful and usable prototype (Matuk et al., 2016). The integration of different groups of potential users into the development process arguably puts this study into the domain of Multi-user Centered Design (MCD) as proposed by Fleur and Chaniaud (2024). The MCD approach is a new concept based on UCD to factor in the different requirements of different user groups of a single technology.

The first step in study 4 was getting to know the requirements of a typical scenario in MM and MT as well as what kind of capabilities teachers, experts and students need in this scenario. Based on this a prototype was developed and tested. The prototype usability test (PUT) provided insights on strengths and weaknesses of both the VR application as well as the used haptic data gloves. Especially the mixed methods approach of using standardized questionnaires as well as open questions helped during the PUT to get minute details. This combination revealed that it was likely the interaction of the haptic gloves, the VR application as well as expectations of what should be possible in the created scenario that led to mixed results. The prototype had some inconsistencies regarding the use of the gloves and its technical and feedback capabilities. According to Machover and Tice (1994) as well as Van Gisbergen et al. (2019), the realism of a VR experience might not be as crucial as the consistency of the experience. As mentioned in the discussion part of study 4 (see chapter 7.5.), the technical capabilities of the gloves might potentially be the biggest current limitation. The haptic data gloves do not offer the same kind of resolution as a human hand, especially when talking about MM/MT practitioners (Louw et al., 2000, 2002; Müller & Grunwald, 2013).

However, the general experience of using the gloves was rated as above average, so there is merit to further develop and refine both the prototype as well as the used haptic data gloves. Study 4 was only a prototype test looking at the UX and usability of said prototype. In the future, a follow-up study should look into the learning outcome using the refined version of this VR prototype. As mentioned above, a learning effect in VR as seen in study 3 and other studies might also be present in the MM/MT setting in VR, thus offering MM/MT teachers, students and practitioners a new tool for education and training.

8.2.3. Discussion of the Overall User Experiences in Study 1 to 4

Study 1 and Study 2 depicted and examined several aspects of navigating through office buildings in VR with different configurations, changing and analyzing parts of the experience. Study 3 examined aspects of an invisible object search task in VR while collecting data of the task and about the general UX. Study 4 then had the development and evaluation of a usable experience as the main goal. While the UX might not always be at the forefront as the main research objectives of a study in VR, most times it still plays a vital part in those studies.

A typical side effect of VR is cybersickness. While study 3 and study 4 did not have participants drop out because of cybersickness, study 1 and study 2 did. Although the SSQ (Kennedy et al., 1993) did not show noticeable symptoms in study 1 and study 2, there were still some participants who got cybersickness during those experiments. A probable reason for this might have been the locomotion technique, since the locomotion techniques in study 3 and 4 were different. In study 3, participants could move freely and naturally in the VE. The VE was purposely built to fit the actual size of the VR lab in which it was conducted. In study 4, the participants were mostly standing, and the task did not involve a lot of locomotion, just movement of the hands and upper body. In the other experiments of this work, the arm swinging locomotion technique was used. As mentioned earlier, there is both evidence against (Coomer et al., 2018) as well as evidence for worse cybersickness due to arm swinging (Loup and Loup-Escande, 2018). While this is definitely a point of debate, the experiments in this work would point towards the arm swinging technique worsening cybersickness. However, since this was not the main point of focus for the experiments, it can only be seen as a possibility. Since there is evidence for both sides of the argument, there is also an argument to further research this area of UX to see which is more likely. Furthermore, there is still the need to establish how well natural walking systems like omnidirectional treadmills and friction-free platforms actually perform regarding different aspects of UX (Martinez et al., 2022; Nilsson et al., 2018).

Studies 1 to 4 also captured the participants' feeling of actually being present in the virtual world. This was done by using the IPQ (Schubert, 2003), a questionnaire that aims to measure the feeling of presence in a VR experience. All studies used the 7-point Likert scale version of the IPQ. Regarding the four subscales of the IPQ, i.e., general presence, spatial presence, involvement and experience realism, the studies presented in this work did show quite mixed results. To compare these results in an easy-to-understand manner, the qualitative interpretations for the subscales by Melo et al. (2023) will be used. General presence consistently had the highest scores among the subscales, but according to Melo et al. (2023) only studies 3 and 4 can be described as acceptable regarding general presence. The general presence of both study 1 and study 2 would classify as unacceptable (grade F). Using the guideline by Melo et al. (2023), study 3 can be seen as very good (grade B) in this regard and the general presence of study 4 would be excellent (grade A). Spatial Presence, however, can be classified as unacceptable (grade F) for all but study 4. Study 4 had only marginally acceptable (grade E) spatial presence, though. According to Melo et al. (2023), involvement was unacceptable (grade F) in all four studies. Regarding the experienced realism subscale, it is again unacceptable (grade F) in all but study 4. In study 4, it is marginally acceptable (grade D).

The results of study 1 and study 2, i.e., being the worst of the four studies, can be explained by a couple of possible causes. First of all, the sample size is rather small for both, thus making analysis rather unreliable and possibly distorted as the data could be made up of random noise. Another reason in study 1 could also be the change in graphic fidelity, i.e., from textures to no textures and vice versa between trials. Past research did find a connection between visual realism and presence (Hvass et al., 2017; Mania & Robinson, 2004; Slater et al., 2009). As study 2 is the follow-up with only slight changes in visual realism, this probably applies to that study as well. Another reason might be the locomotion techniques in both study 1 and study 2. The findings of Mayor et al. (2021) suggest that this might be a possible explanation. Based on their findings, the slightly better results of study 3 regarding the presence subscales could be because of using a room-scale approach. The setting of study 3 was also less realistic, i.e., graphic style as well as hunting ghost(s), on purpose, possibly explaining the bad experienced realism.

Study 4 scoring best out of all four studies is then basically also accounted for by the aforementioned studies (Hvass et al., 2017; Mania & Robinson, 2004; Mayor et al., 2021; Slater et al., 2009). Furthermore, there are arguments that the haptic gloves made it more realistic as well (Almeida et al., 2019; Moon et al., 2023; Palombo et al., 2024; Shor et al., 2018). Moon and colleagues (2023) did compare standard VR controllers against gloves with vibrotactile feedback regarding presence among others. They found that the gloves did cause a stronger feeling of presence. But as already discussed in chapter 7.5. and chapter 8.2.2., the gloves used in study 4 do have some limitations that make them not as suitable for

MM/MT in their current state. This might be the reason why the experienced realism is only marginally acceptable, and involvement was still unacceptable.

However, Slater (2004) argued that questionnaires might be enough to sufficiently measure presence in VR. Souza et al. (2022) compiled a survey of user studies that measured presence. Out of the analyzed user studies, only 2.5% used objective measures as their only method of presence measurement, while 11.7% used both kinds of measures in combination (Souza et al., 2022). Schirm et al. (2019) examined a way to measure presence objectively. They used a method that evokes startle reflexes and then compares the change in head tracking data to a baseline. Athif and colleagues (2020) used a combination of different physiological methods to develop an objective method. While their methods seems promising, further research is needed to advance their method.

Still, the multimodality or lack thereof might arguably play a major role in the mixed results of the presence questionnaires as well. Study 1 and study 2 were mostly visual studies that did not incorporate the other sensory systems in meaningful ways, also limiting locomotion. Study 3 and study 4, however, explicitly incorporated multimodality. Martin and colleagues (2022) argued that the experience in VR hinges on working multimodal setups. Skarbez et al. (2021) argued even further in their proposed update of the reality-virtuality continuum (Milgram & Koshino, 1994), stating that even with hardware akin to Sutherland's Ultimate Display (1965) multimodal setups would not be considered multimodal VR, but rather mixed reality. In such a scenario, there would be total control of exteroceptive senses, i.e., those responding to external stimuli, but still no control of interoceptive senses, i.e., those monitoring the internal state (Skarbez et al., 2021). Skarbez and colleagues (2021) stated that a true VR and truly multimodal experience needs to be accompanied by direct brain stimulations, similar to the famous Matrix movies. In this way, there would be total control of both interoceptive and exteroceptive senses and, thus, the experience in VR would depict the ultimate multimodality. And I concur with their statement. However, until this is remotely possible, VR experience should strive to incorporate all exteroceptive senses in meaningful and realistic ways. Similarly, research on VR should also strive to incorporate all senses, to “unleash the true potential of this medium” (Martin et al., 2022) as well as overcome the bias towards visual-only research mentioned by Hutmacher (2019).

Chapter 9: General Conclusion

9.1. The Bottom Line - Implications on Future Research

Study 1 and study 2 took a closer look at different aspects of spatial cognition in VR. Study 4 examined what needs to be done in terms of UX to make haptics work in a haptic heavy VR setting. Study 3 bridged the gap between these two sides by shining a light on the effects of haptic and auditory cues in a spatial search task in VR.

Overall, the present work shows that VR is a promising research tool, while also being promising as a learning tool. There is, however, still a need to incorporate all sensory systems with today's technologies. There is still a bias towards the visual system, as pointed out by Hutmacher (2019). The current work does offer some applied insights on the visual system during navigation, but more importantly also on the auditory and haptic sensory systems, trying to fill gaps and trying to not add to the bias mentioned by Hutmacher (2019). Since usability and UX should be factored in as soon as possible in the design process, the User Centered Design or Multi-user Centered Design approaches should be used depending on the target group of the to-be-developed software and hardware. This should, in theory, lead to meaningful, yet efficient systems that the target group has the intentions to use and wants to use.

An all-encompassing VR system like the Sensorama Simulator by Morton Heilig (1962) has not been made commercially available with current hardware. Arguably, the UX in VR could only feel real, if all the senses are equally incorporated into the experience (Martin et al., 2022; Skarbez et al., 2021). Therefore, future research should expand on the knowledge of the different sensory systems and how to apply them in a realistic way in VR.

9.2. Closing Remarks

After spending a good amount of my time as a HiWi at the Cognitive and Developmental Psychology unit during my master's study, I started as a PhD student at the same unit pretty much right after finishing my master's degree. Over those last three to four years as a WiMi, I have learned a lot through teaching students, designing, and conducting experiments, presenting results at conferences, supervising theses, research modules as well as lab rotations and although this ended up being very stressful from time to time, I would not have it any other way.

The beginning of my time as a PhD student did start at an unfortunate point in time for most experimental studies, but especially for those in the realm of education in medicine, namely the end of 2020. Nevertheless, thanks to already existing problem-solving skills of all of us in the SmartHands project and a drive to make the most of our project, we found ways to accomplish our tasks and, in the end, managed to not just develop and evaluate a VR application with haptic gloves, but also wrote a scientific article about it and managed to get accepted at the HCI International Conference. This article also ended up as Chapter 7 in this dissertation. Besides working on this project with stakeholders from different areas of expertise - both private and public sector -, I was also able to design, conduct and analyze experiments with the help of the CGTI Lab at the University of Applied Sciences Bielefeld. Thanks to this collaboration as well as the SmartHands project, I also learned how to bridge the gap between different areas of expertise and know how to make sure that we collect the data we want in a data format that we want and that makes sense. I also learned how to present the data to people outside of my area of expertise in a way that they understand.

Besides meeting and working with wonderful colleagues both outside and inside of our unit at the RPTU, I also managed to further deepen my statistical knowledge accompanied by a better understanding of R, learned coding in Python, refreshed my knowledge of coding in Unity with C# and using MATLAB as well as getting to know how eye trackers work and collect eye tracking data with both the Tobii Glasses as well as the HTC Vive Pro Eye.

While all this sounds like a lot of accomplishments, this time was also full of doubts and insecurities: Thinking about experiments, problems that could arise and make the data meaningless; a weird feeling of competition among peers, even when there was no competition, just cooperation; the constant feeling of “I should have done more”. In the end, though, this does not seem to matter that much. What matters is what you make of it, how you overcome those doubts and come out on top of those. Be it through reflecting on yourself, your work, your goals and your accomplishments, or transforming your former weaknesses into strengths through learning and training. This is what it means to be a research scientist for me. And this is why I feel able to call myself a research scientist after all these years.

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Appendix

Figure APX1

Heatmap of Mean of Rooms Traversed in the Second Building with No Landmarks, n = 5

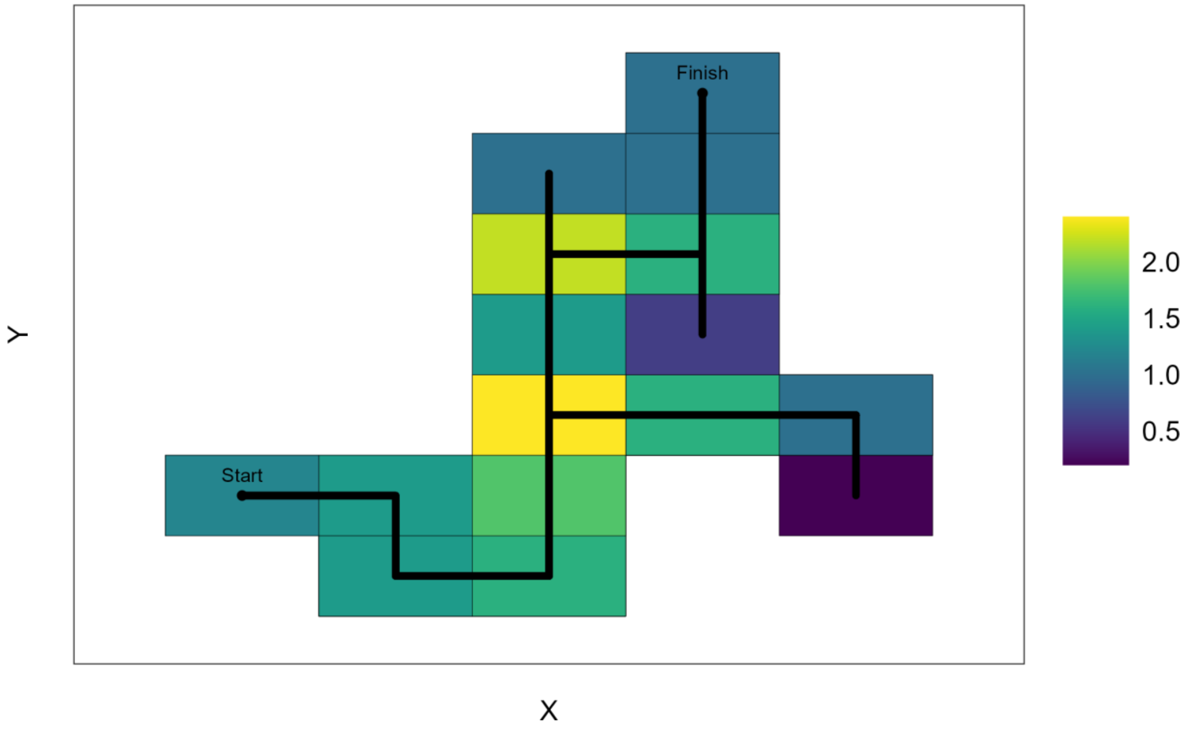


Figure APX2

Heatmap of Mean of Rooms Traversed in the Second Building with Outdoor Landmarks, n = 6

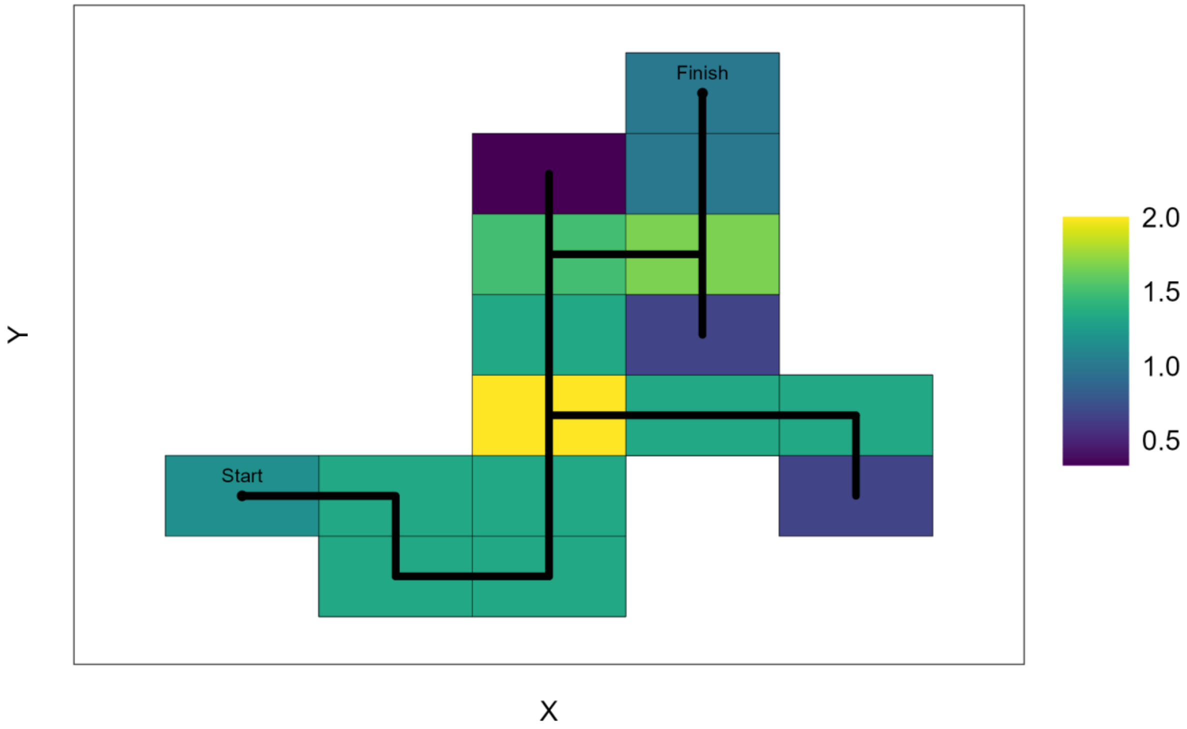


Figure APX3

Heatmap of Mean of Rooms Traversed in the Second Building with Indoor Landmarks, n = 5

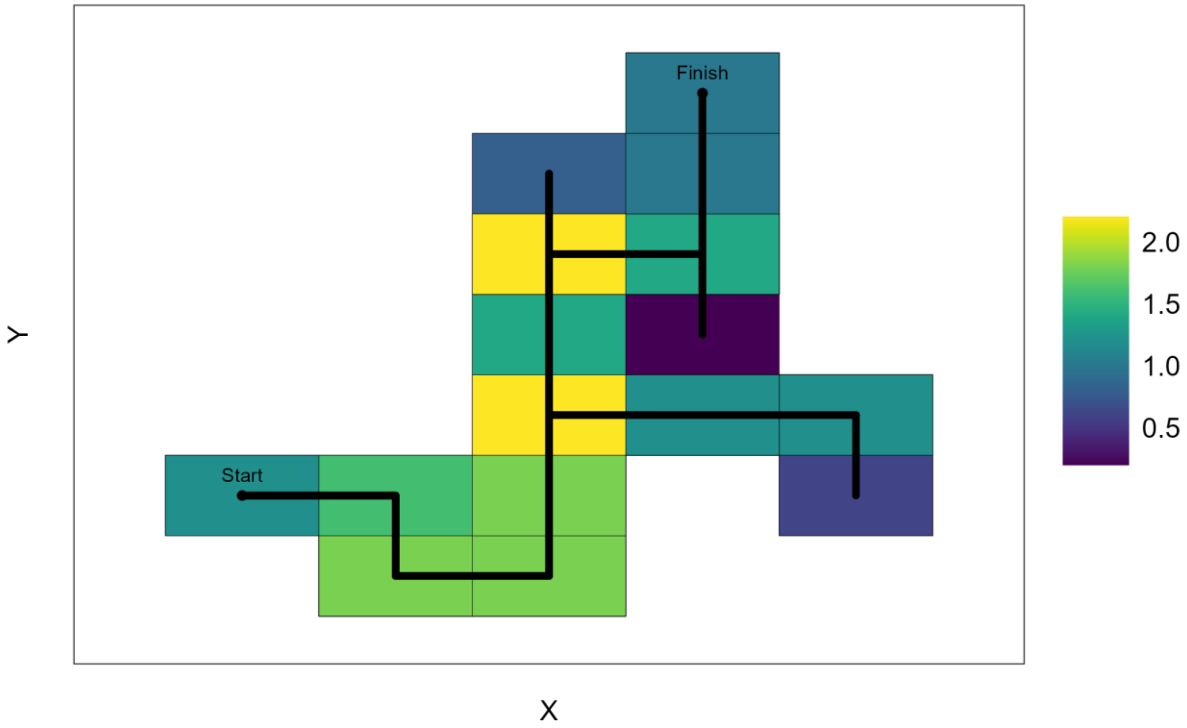


Figure APX4

Heatmap of Mean of Rooms Traversed in the Second Building with Outdoor and Indoor Landmarks, n = 6

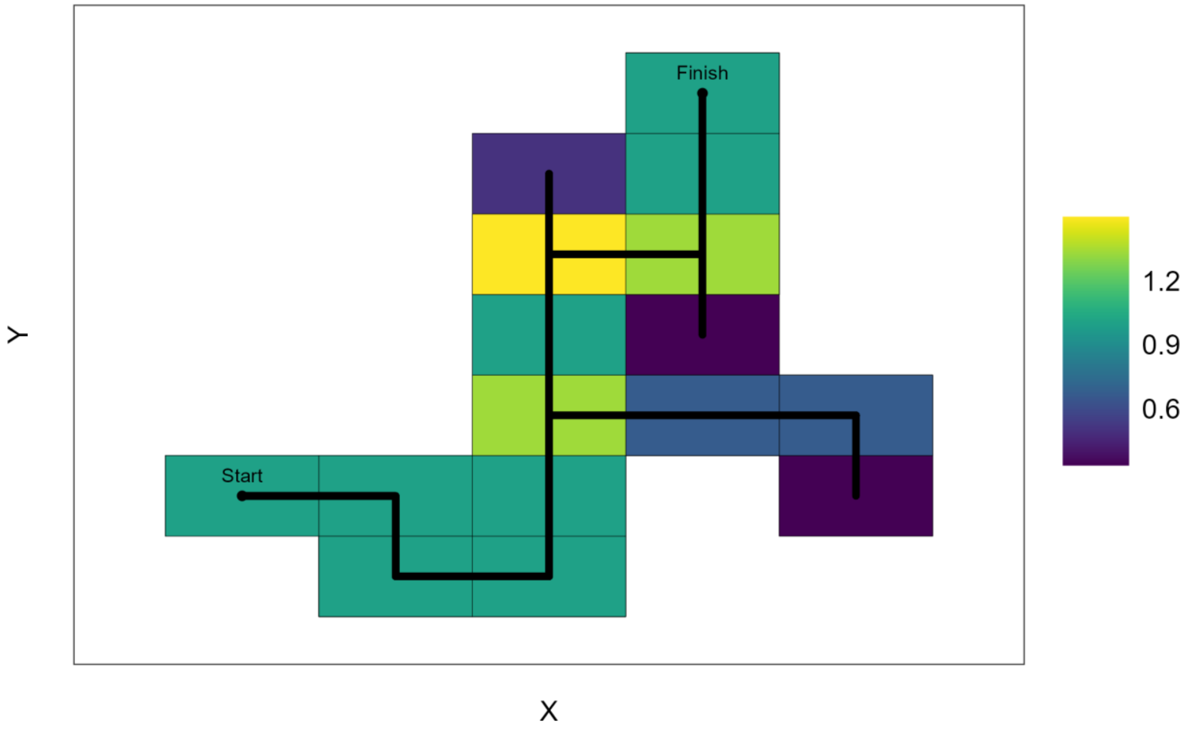


Figure APX5

Heatmap of Mean of Rooms Traversed in the Third Building with No Landmarks, n = 6

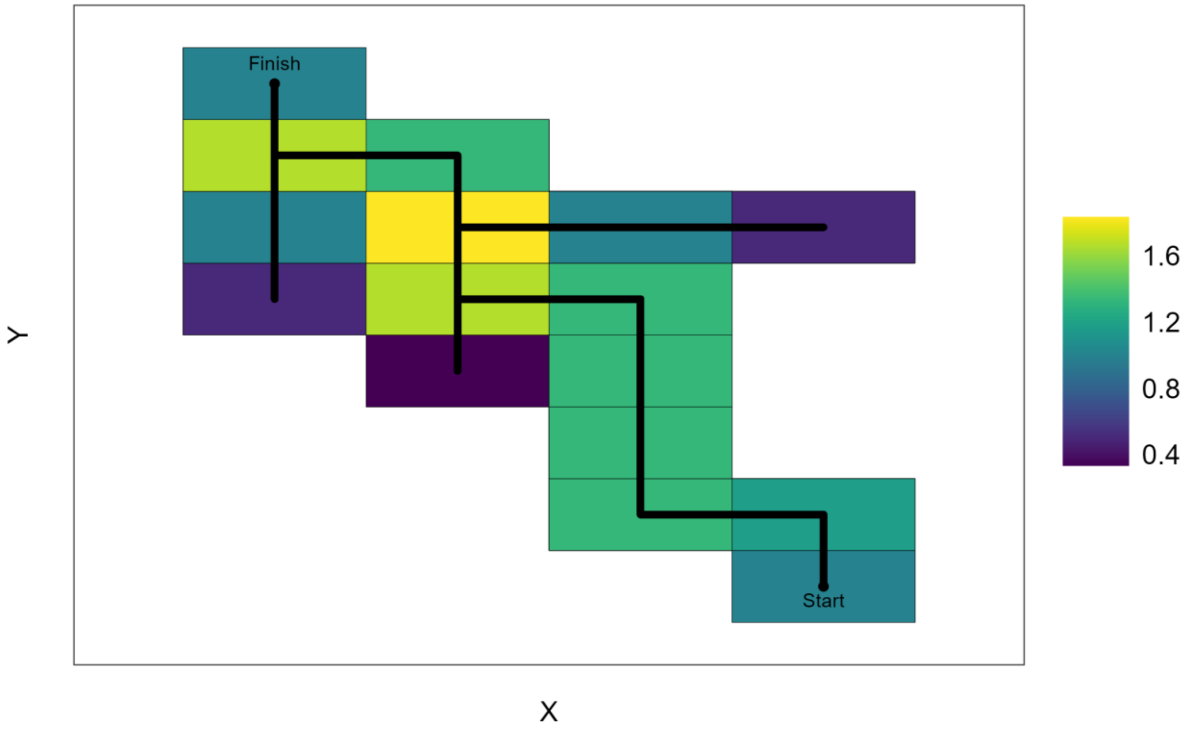


Figure APX6

Heatmap of Mean of Rooms Traversed in the Third Building with Outdoor Landmarks, n = 5

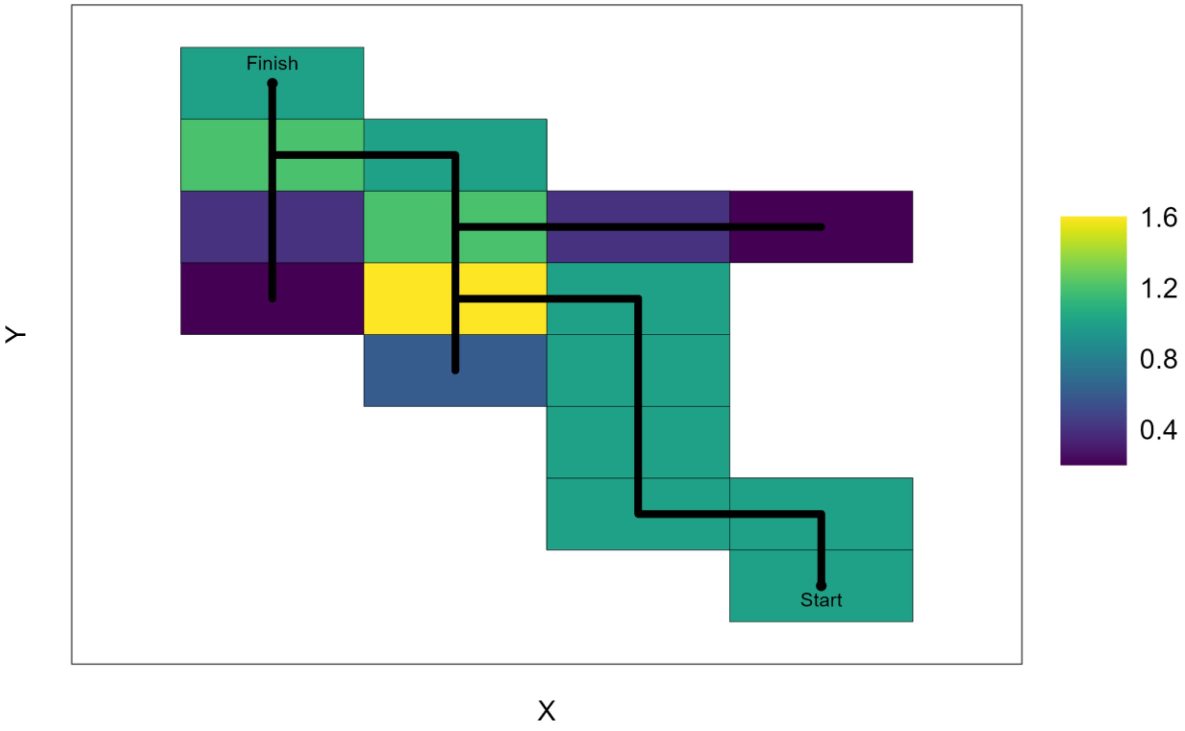


Figure APX7

Heatmap of Mean of Rooms Traversed in the Third Building with Indoor Landmarks, n = 6

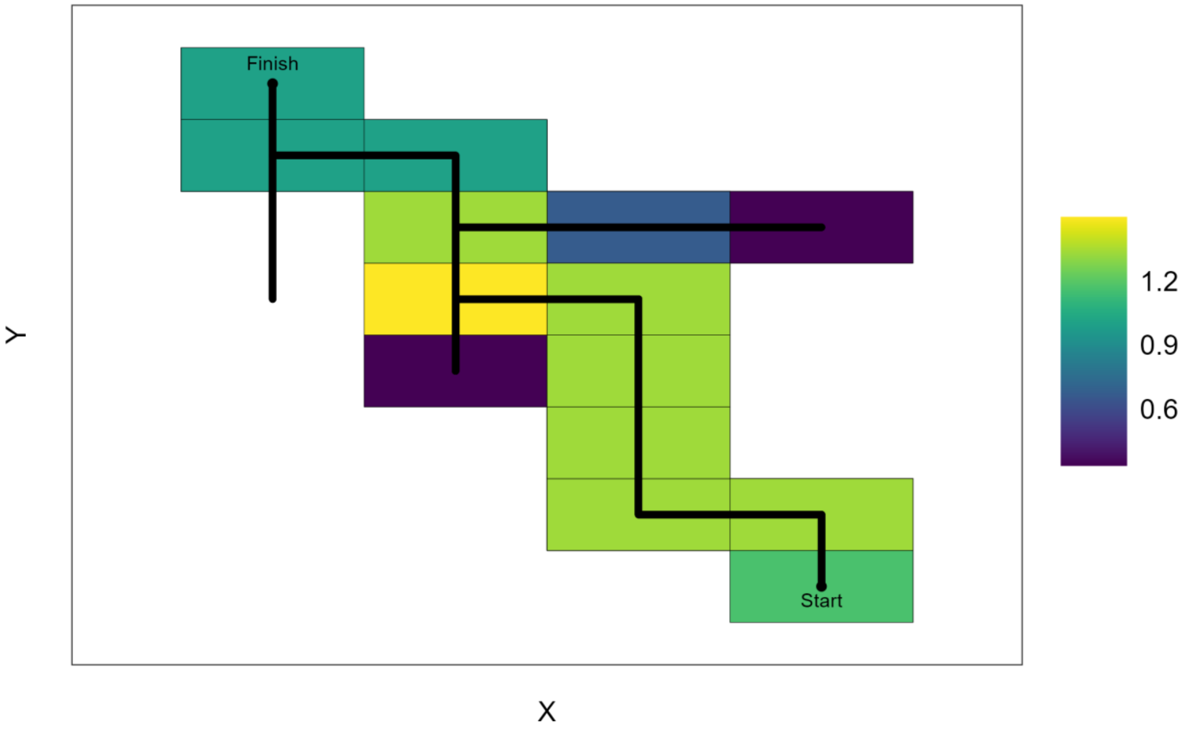


Figure APX8

Heatmap of Mean of Rooms Traversed in the Third Building with Outdoor and Indoor Landmarks, n = 5

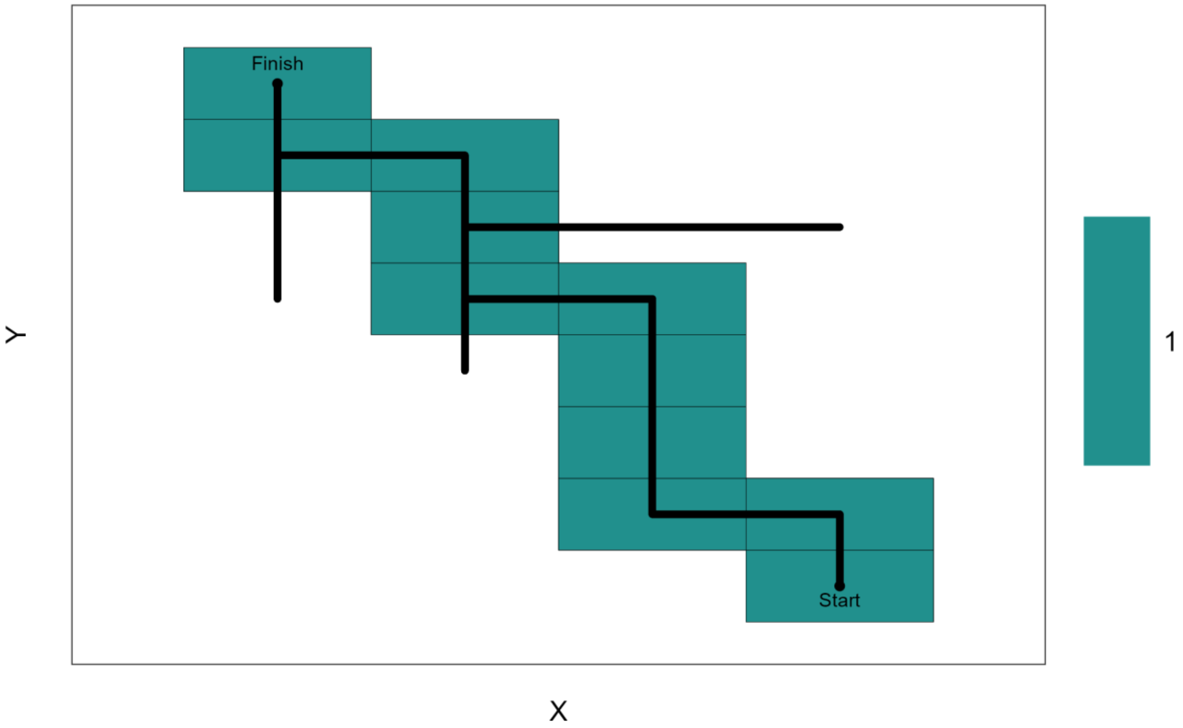


Figure APX9

Heatmap of Mean of Rooms Traversed in the Fourth Building with No Landmarks, n = 5

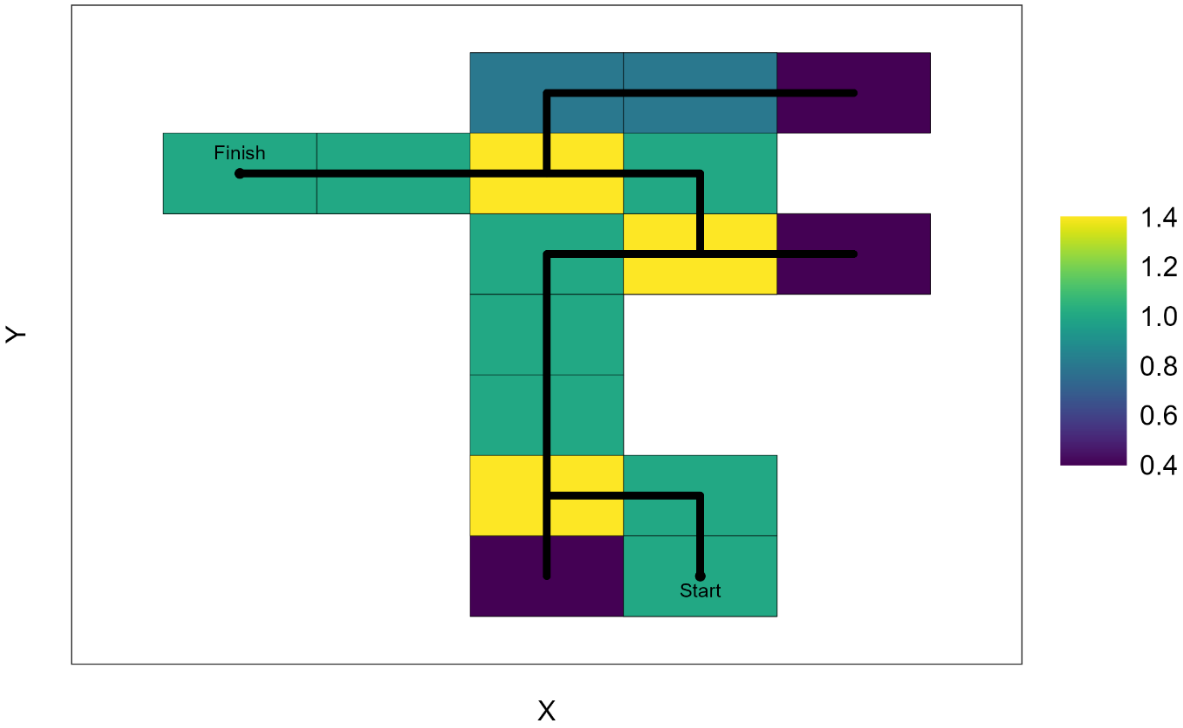


Figure APX10

Heatmap of Mean of Rooms Traversed in the Fourth Building with Outdoor Landmarks, n = 6

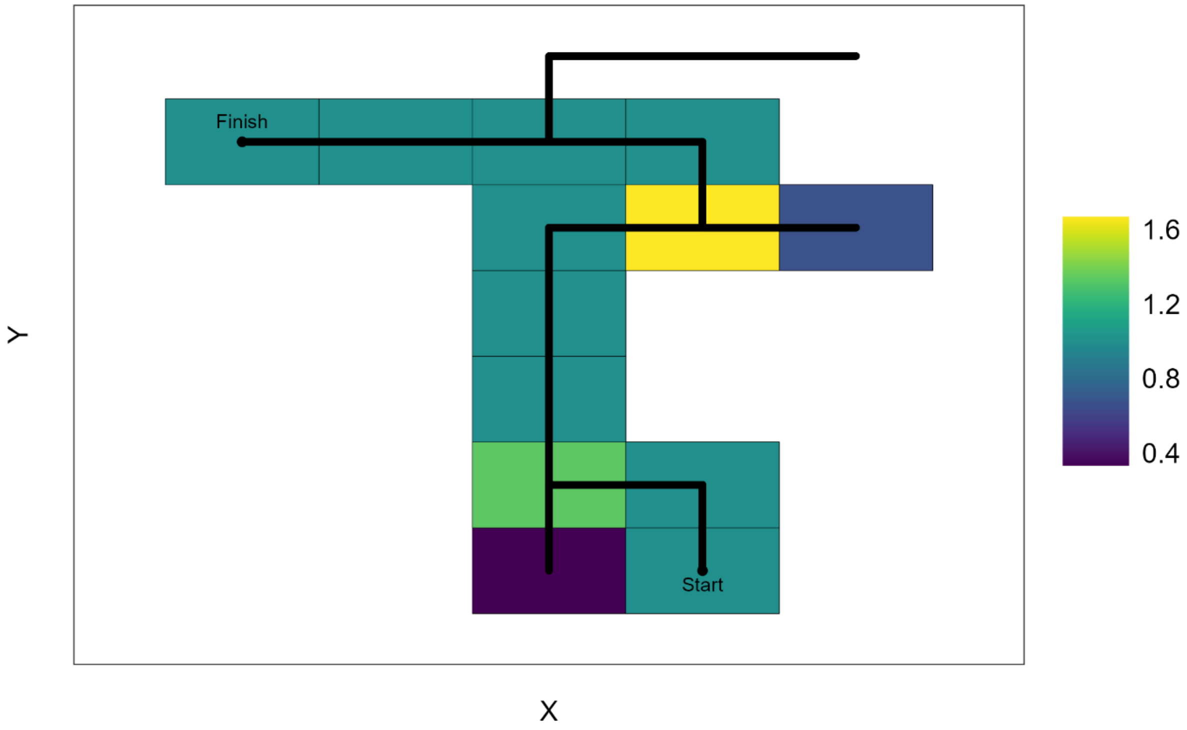


Figure APX11

Heatmap of Mean of Rooms Traversed in the Fourth Building with Indoor Landmarks, n = 5

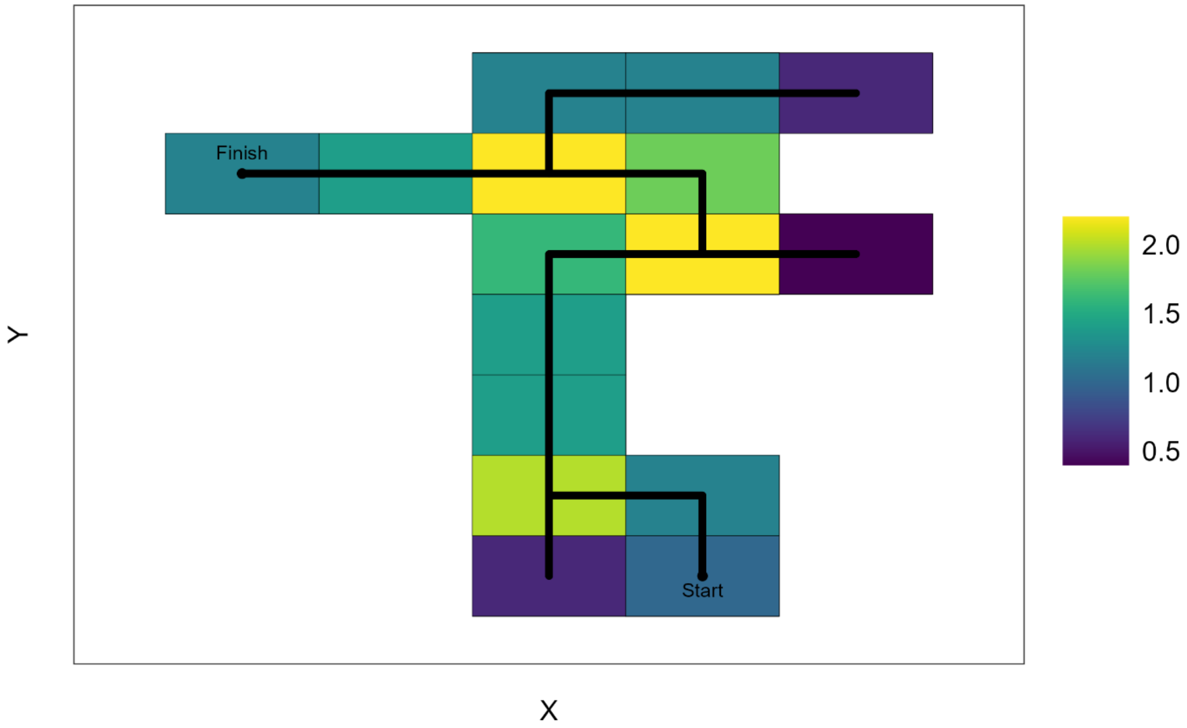
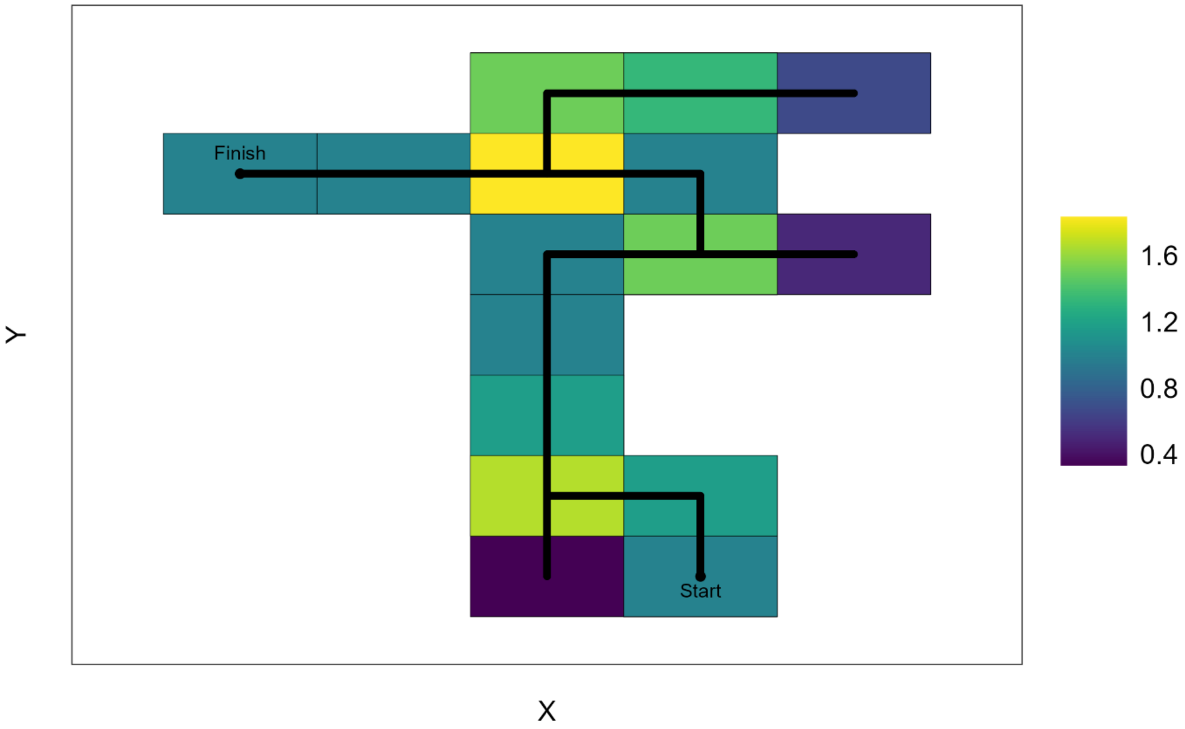


Figure APX12

Heatmap of Mean of Rooms Traversed in the Fourth Building with Outdoor and Indoor Landmarks, n = 6



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Hiermit versichere ich,

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- dass diese Dissertation bisher nicht von mir als Prüfungsarbeit für eine stattliche oder andere wissenschaftliche Prüfung eingereicht, und
- dass weder eine andere noch die gleiche Abhandlung dieser Dissertation bei einer anderen Universität oder einem anderen Fachbereich der Rheinland-Pfälzischen Technischen Universität Kaiserslautern-Landau veröffentlicht wurde.

02. April 2024, Kaiserslautern

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