Embodied Spatial Knowledge Acquisition in Immersive Virtual Reality: Comparison of Direct Experience and Map Exploration

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Abstract

Investigating spatial navigation in virtual environments enables to study spatial learning with different sources of information. Therefore, we designed a large virtual city and investigated spatial knowledge acquisition after direct experience in the virtual environment and compared this with results after exploration with an interactive map (König et al., 2019). Our results suggest that survey knowledge measured in a straight line pointing task between houses resulted in better accuracy after direct experience in VR than tasks directly based on cardinal directions and relative orientations. In contrast, after map exploration, the opposite pattern evolved. Taken together, our results suggest that the source of spatial exploration influenced spatial knowledge acquisition.

Introduction

According to theories of embodied/enacted cognition spatial navigation unfolds in the interaction of the navigator with his real-world surroundings (Engel, Maye, Kurthen, & König, 2013; O'Regan & Noë, 2001). Bodily movement provides information about visual, motor, proprioceptive and vestibular changes, which are essential for spatial cognition (Grant & Magee, 1998; Riecke et al., 2010; Ruddle, Volkova, & Bülthoff, 2011; Ruddle, Volkova, Mohler, & Bülthoff, 2011; Waller, Loomis, & Haun, 2004). Interaction with the environment is a crucial part of acquiring spatial knowledge, thus becoming more and more important for spatial navigation research (Gramann, 2013).

When getting to know a large-scale real-world environment, people combine direct experience during exploration with spatial information from indirect sources such as cartographical maps (Richardson, Montello, & Hegarty, 1999; Thorndyke & Hayes-Roth, 1982). While moving in an environment, knowledge about landmarks and their connecting routes develops, which is rooted in an egocentric reference frame (Meilinger, Frankenstein, & Bülthoff, 2013; Montello, 1998; Shelton & McNamara, 2004; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982). Through the integration of this spatial knowledge, a map-like mental representation called survey knowledge may develop (Montello, 1998; Siegel & White, 1975). Acquisition of survey knowledge is supported by using maps and is supposed to be coded in an allocentric reference frame (Meilinger et al., 2013; Montello, Hegarty, & Richardson, 2004; Taylor, Naylor, & Chechile, 1999; Thorndyke & Hayes-Roth, 1982). Previous studies also found that spatial knowledge acquired from a cartographical map is learned with respect to a specific orientation, whereas orientation specificity is much less consistent in spatial knowledge gained by direct experience (Burte & Hegarty 2014; Evans & Pezdek 1980; McNamara 2003; Meilinger, Riecke, & Bülthoff, 2006; Montello et al. 2004; Presson & Hazelrigg 1984; Shelton & McNamara 2001; Sholl, Kenny, & DellaPorta, 2006).

Thus, the acquired spatial knowledge is shaped by the employed source of spatial information, but which spatial knowledge of a large-scale environment derives from which source is still not fully understood.

Experiments in large-scale real-world settings are challenging to perform because of their complexity and problems of reproducibility. The rapid progress of technology allows designing virtual realities (VRs) that highly support the investigation of spatial navigation and controlled spatial learning also for embodied navigation. Thus, VR provides the possibility to reduce the gap between lab conditions and the real world (Coutrot et al., 2019; Jungnickel & Gramann, 2016). A wide variety of virtual environments, from desktop setups to fully immersive setups, are used to investigate spatial learning (e.g. Coutrot et al., 2018; Ehinger et al., 2014; Goeke, König, & Gramann, 2013; Gramann, Müller, Eick, & Schönebeck, 2005; Mallot, Gillner, Van Veen, & Bülthoff, 1998; Starrett, Stokes, Huffman, Ferrer, & Ekstrom, 2019; Zhang, Zherdeva, & Ekstrom, 2014). They reach from a few corridors to complex virtual layouts as far as virtual cities. Virtual environments have gained in popularity through the gaming industry that builds more and more complex and realistic immersive environments. Also, the amount of naturalistic movement varies a lot in different VR settings reaching from controller movements in VR without any physical body movement to physical walk and body turns on an omnidirectional treadmill (Darken, Cockayne, & Carmein, 1997; Ekstrom, Huffman, & Starrett, 2019; Kitson, Prpa, & Riecke, 2018; Kitson, Riecke, Hashemian, & Neustaedter, 2015; Liang, Starrett, & Ekstrom, 2018; Nabiyouni, Saktheeswaran, Bowman, & Karanth, 2015; Riecke et al., 2010; Ruddle & Lessels, 2006; Ruddle, Payne, & Jones, 1999; Ruddle, Volkova, & Bülthoff, 2011). Therefore, virtual environments offer the possibility to investigate spatial learning under controlled conditions, also considering embodied interaction with immersive setups and designs that include close to naturalistic sensory information.

In the present paper, we use VR technology for a direct comparison of spatial knowledge acquisition by direct experience and cartographic material. Following this line of thought, we built a large-scale immersive virtual city (Clay, König, & König, 2019) and created an interactive map thereof (König et al., 2019). Seahaven is a relatively large and complex virtual environment to enable an analogy to real-world cities. With the help of an HTC Vive headset, participants were immersed in the VR, which allowed a direct experience of the environment from a pedestrian perspective during the free exploration. While participants explored the city, we recorded their viewing behavior (Clay et al., 2019). After each exploration, we evaluated participants acquired spatial knowledge investigating three tasks: knowledge of the orientation of houses facing directions towards cardinal north, the orientation of houses facing directions in relation to a prime house's facing direction, and straight-line pointing from one house to another. We tested all tasks with spontaneous response and time for cognitive reasoning. Additionally, we explored whether spatial orientation strategies based on egocentric or allocentric reference frames that are learned in everyday navigation, measured with the "Fragebogen Räumlicher Strategien" (FRS, translated as the „German Questionnaire of Spatial Strategies“) (Münzer, Fehringer, & Kühl, 2016b; Münzer & Hölscher, 2011), had an impact on learning of spatial properties tested in our tasks after exploring a virtual city. The set of tasks aimed at investigating the influence of action relevant aspects. In our project, we investigated the spatial exploration of the virtual environment with different sources. Here, we report the results after direct experience in the city as described above and compare these with results after exploration with an interactive city map (König et al., 2019).

Methods

The experiment reported here was performed in close analogy to a previous study using an interactive map for the spatial exploration of Seahaven (König et al., 2019). We briefly report the full experiment procedure of the present study below.

Participants

In this study, we measured 22 participants (11 female, mean age = 22,86 years, SD = 6,69), who explored our virtual city Seahaven with direct experience in virtual reality for spatial learning. All participants performed three 30-minute sessions within ten days leading to an overall exploration time of 90 minutes, respectively. At the beginning of the experiment, participants were informed about the purpose and the procedure of the investigation and gave written informed consent. Each participant was either reimbursed with nine Euros per hour or earned an equivalent amount of "participant hours", which are a requirement in most students' study programs at the University of Osnabrück. Overall, each session took about two hours. The ethics committee of the University of Osnabrück approved the study in accordance with the ethical standards of the Institutional and National Research Committees.

Experiment Procedure

Our experiment consisted of four major phases, which are described in detail below (Table 1). The first was the introductory phase, which lasted approximately 45 minutes. Here, participants were informed about the experiment and gave written informed consent. Then, they performed the response training and received instructions and training for the spatial tasks, with example trials for all spatial tasks and time conditions. Next, participants were introduced to VR and instructed how to move in Seahaven. They were especially informed about the risk of motion sickness. After this, an HTC Vive headset with integrated eye tracker was mounted giving an immersive VR experience. With this, participants practised their movement in VR, which was followed by calibration and validation of the eye tracker. For the second phase, participants were placed on a predefined place in Seahaven and started the exploration phase, in which they freely explored the virtual city for 30 minutes. Every 5 minutes, the exploration was shortly interrupted for validation of the eye tracker. The third, the testing phase followed lasting for approximately 45 minutes. Here, participants were tested on three different spatial tasks (absolute orientation-, relative orientation- and pointing task) in two time conditions (3 seconds and infinite response time). Fourth and finally, the participants filled out a questionnaire on spatial strategies (FRS questionnaire), which concluded the experiment.

Another group of participants explored the city in VR with the feelSpace belt, a device supplying information about magnetic north (Kaspar, König, Schwandt, & König, 2014; König et al., 2016; Nagel, Carl, Kringe, Märtin, & König, 2005). However, the data of this group are not covered in the present report.

Table 1: Experiment Procedure

	Single Steps in the Experiment	**Phases of the Experiment**
1	Subject information, written informed consent	Introductory phase (45 minutes)
2	Response training	
3	Spatial tasks instructions	
4	Task training with example trials of all tasks in both time conditions	
5	Introduction of VR city and how to move in VR	
6	Set up of VR headset and eye tracker calibration	
7	Movement practice on small VR practice island	

8	Free exploration directly moving in Seahaven, recalibration of the eye tracker	Exploration phase (30 minutes)
9	Spatial tasks (absolute orientation-, relative orientation-, pointing tasks) in two time conditions (3 seconds or infinite time to respond)	Test phase (45 minutes)
10	FRS Questionnaire	Questionnaire phase (5 minutes)

Response Training

To familiarize participants with the 3 seconds response, the interpretation of the directional arrow on the screen and the required behavioral responses, each participant performed a response training. In this training, two arrows pointing into different directions, each surrounded by an ellipsoid, appeared on two stacked screens. The participants had to compare the two arrows and then select within 3 seconds the arrow that pointed more straight upward on the screen. To choose the arrow on the upper screen, participants had to press the "up" button. To select the arrow on the lower screen, they had to press the ‘‘down’’ button. On each trial, they received feedback as to whether they decided correctly (green frame), incorrectly (red frame), or failed to respond in time (blue frame). The response training was finished, when the participants responded correctly without misses in 48 out of 50 trials (accuracy > 95%). This response training ensured that participants were well acquainted with the response mechanism of the two-alternative forced-choice (2AFC) responses that our spatial tasks used.

Spatial Tasks’ Instructions and Tasks’ Training

A separate pilot study, in which participants did not know the tasks before the exploration phase, revealed that during their free exploration they sometimes focused more on aspects like a detailed house design that would not support spatial learning. As it is known that during spatial learning paying attention to the environment or the map supports spatial knowledge acquisition (Montello, 1998), each participant received task instructions and task training before the start of the free exploration time in Seahaven to support intentional learning. Please note that none of the subjects of the pilot study is included in the main study and that no subjects of the main study were excluded for reasons of their spatial exploration behavior. The instructions were given by written and verbal explanations using photographs of houses in the city of Osnabrück that were used as stimuli in a previous study (König et al., 2017). Participants then performed a pre-task training with one example of each spatial task in both time conditions to gain a better insight into the actual task requirements. Except for the stimuli, the pre-tasks exactly resembled the design of the spatial tasks (see sections “Stimuli” and “Spatial Tasks” below). We performed the pre-task training to familiarize participants with the type of spatial knowledge that was later tested in the spatial tasks.

VR City Design

To minimize the gap between the investigation of spatial tasks under laboratory conditions and in real-world environments, we built a large-scale virtual city (Figure 1), named Seahaven. Seahaven is located on an island to keep participants in the city area. Seahaven was built in the Unity® game engine using houses, streets, and landscape objects acquired from the Unity asset store. Seahaven consists of 213 unique houses, which had to be distinguishable for the spatial tasks and thus have different styles and looks. The street layout includes smaller and bigger streets and paths resembling a typical European city without an ordered grid structure and specific city districts. Seahaven would cover about 21,6 hectare in real-world measure and is designed for pedestrian use. Herewith, Seahaven is relatively large and complex compared to many virtual environments used for spatial navigation research (e.g. Goeke et al., 2013; Gramann et al., 2005; Riecke, Veen, & Bülthoff, 2002; Ruddle, Volkova, & Bülthoff, 2011). For the performed spatial navigation tasks, the number of houses sharing a specific orientation towards north is approximately equally distributed in steps of 30° (0° to 330°). During the direct city exploration in VR, information about cardinal directions could be deduced from the trajectory of a light source representing the sun over the course of one day. Therefore, the light source's position indicated a sunrise in the east at the beginning of the city exploration, the sun's course during a day and ended with the sunset in the west at the end of one exploration session. As the light source's (sun's) position on the sky changed during the exploration session, the shadows of the houses and other objects in the virtual city changed in relation to the sun's position as in a real environment.

Figure 1: Top-left: Experimental set-up of the participant with the HTC Vive, controller and swivel chair (written informed consent was obtained from the individual for the publication of this image). Top-middle: Overview of the virtual city from a bird's eye view. The remaining photographs show three examples of views in the city from a pedestrian or oblique perspective.

Exploring Seahaven

To display the virtual environment in an immersive fashion, we used an HTC Vive headset (https://www.vive.com/eu/product/) (Figure 1, top left) with an integrated Pupil Labs eye tracker (https://pupil-labs.com/vr-ar/). Participants were instructed about the virtual city and the potential risk of motion sickness. Additionally, they were informed that they could terminate their participation at any time without giving reasons. During the exploration phase, participants were seated on a swivel chair. For moving in VR, they were instructed to move forward in the VR by touching the forward axis on the HTC Vive's handheld controller touchpad and to turn in the VR by turns of their physical body on the swivel chair in the real world. We decided on this way of moving as a compromise of available space and natural body movement and as it was shown to produce results in close analogy with full-body movement (Riecke et al., 2010). After these instructions, the HTC Vive Headset was mounted, and participants themselves adjusted the interpupillary distance. To support immersion in VR and avoid distraction by outside noises, participants heard the sound of ocean waves over headphones. Participants started in the VR on a small practice island where they practised their movements in VR until they felt comfortable. This was followed by the calibration and validation of the eye tracker (see section "Eye Tracking in Seahaven" below). Then, they were placed in the virtual city at the starting position, the same central main crossing for all participants. Participants unconsciously faced the north direction at the beginning. From there, they freely explored Seahaven for 30 minutes by actively moving within the virtual environment. Before starting, they were informed that it was morning in Seahaven when they began their exploration, and at the end of the 30-minute exploration, it would be around sunset.

Eye and Position Tracking in Seahaven

During the free exploration, we recorded the viewing behavior and the position in the VR city of the participants. For directly measuring eye tracking in VR, we used the Pupil Labs eye tracker, which gets plugged into the HTC Vive headset (Clay et al., 2019). To ensure reliable eye-tracking data, we performed calibration and validation of the eye tracker until a validation error below 2° was achieved. We performed a short validation every 5 minutes to check the accuracy, which might slip due to head movements. If the validation error was above 2°, we repeated the calibration and validation procedure. From the eye-tracking data, we evaluated where participants looked. For this, we calculated a 3D gaze vector and used the ray casting system of Unity, which detects hit points of the gaze with an object collider. With this method, we get information about the object that was looked at and its distance to the eye. The virtual environment was differentiated into three categories: houses, the sky and everything else. We defined houses as the regions of interest. This enabled us to determine how many, how often, for how long, which and in which order houses were looked at giving us information about participants' exploration behavior. For the position tracking, we recorded all x and y positions in Seahaven, which a participant visited during the free exploration.

Stimuli

The stimuli for the spatial tasks were front-on screenshots of 193 houses of the overall 213 houses in Seahaven (examples are shown in Figure 1 and 2). In the orientation tasks, we compared the orientations of the facing directions of the houses. The facing direction of a house was determined by the direction from which the photographer took the screenshot. The heading of a house is the angle between the facing direction of the house and a reference direction, in our study cardinal north. The photographer took the screenshots in the virtual environment from a pedestrian viewpoint that would resemble approximately 5-meter distance to the corresponding house from a position on a street or path in the VR city. For some houses, this was not possible, and so they were excluded as stimuli. Furthermore, a few houses looked somewhat too similar to each other and therefore had to be excluded as well. All screenshots were shown in full screen with a resolution of 1920 x 1080 pixels on one screen of a six-screen monitor. For the prime stimuli in the relative orientation and pointing tasks, we used the screenshots of 18 houses that were most often viewed in a VR pilot study. These prime houses' orientations were equally distributed over the required orientations from 0° to cardinal north, increasing in steps of 30° and were spread well across the city. Each prime house was used twice in the tasks. The screenshots that were used as target stimuli were only used once and not shown repeatedly.

Spatial Tasks

Participants had to perform three spatial tasks after city exploration. The absolute orientation task evaluates participants' knowledge of the orientation of houses facing directions towards the north direction. The relative orientation task assesses participants' knowledge of the orientation of two houses facing directions relative to each other. The pointing task evaluates participants' knowledge of the location of two houses relative to each other (for a detailed description of the tasks see also (König et al., 2019, 2017). All tasks were designed as 2AFC tasks. In one trial of the absolute orientation task, two screenshots of the same house overlaid with a compass arrow were presented, one correctly pointing towards the north and one randomly pointing into another direction deviating from the north in steps of 30°. Participants had to choose the arrow that pointed correctly to the north (Figure 2, top left). In one trial of the relative orientation task, participants saw screenshots of a prime house followed by two different target houses that differed in the orientation of the facing direction in steps of 30° from each other. Participants had to choose the target house that had the same orientation as the prime house (Figure 2, middle left). In one trial of the pointing task, first, a screenshot of a prime house was presented, followed by two screenshots of the same target house. This target house was depicted twice, once overlaid with a compass arrow, correctly pointing into the direction of the prime house and once overlaid with a compass arrow randomly pointing into another direction deviating from the correct direction in steps of 30°. Participants had to choose the compass arrow on the target house that correctly pointed back to the prime house (Figure 2, bottom left). All tasks were performed in two response time conditions, with 3 seconds and infinite time to respond. This resulted in six task/time conditions that were presented in blocks. Every block consisted of 36 trials. Order of blocks was randomized over subjects. For more detailed information, see König et al. (2017, 2019).

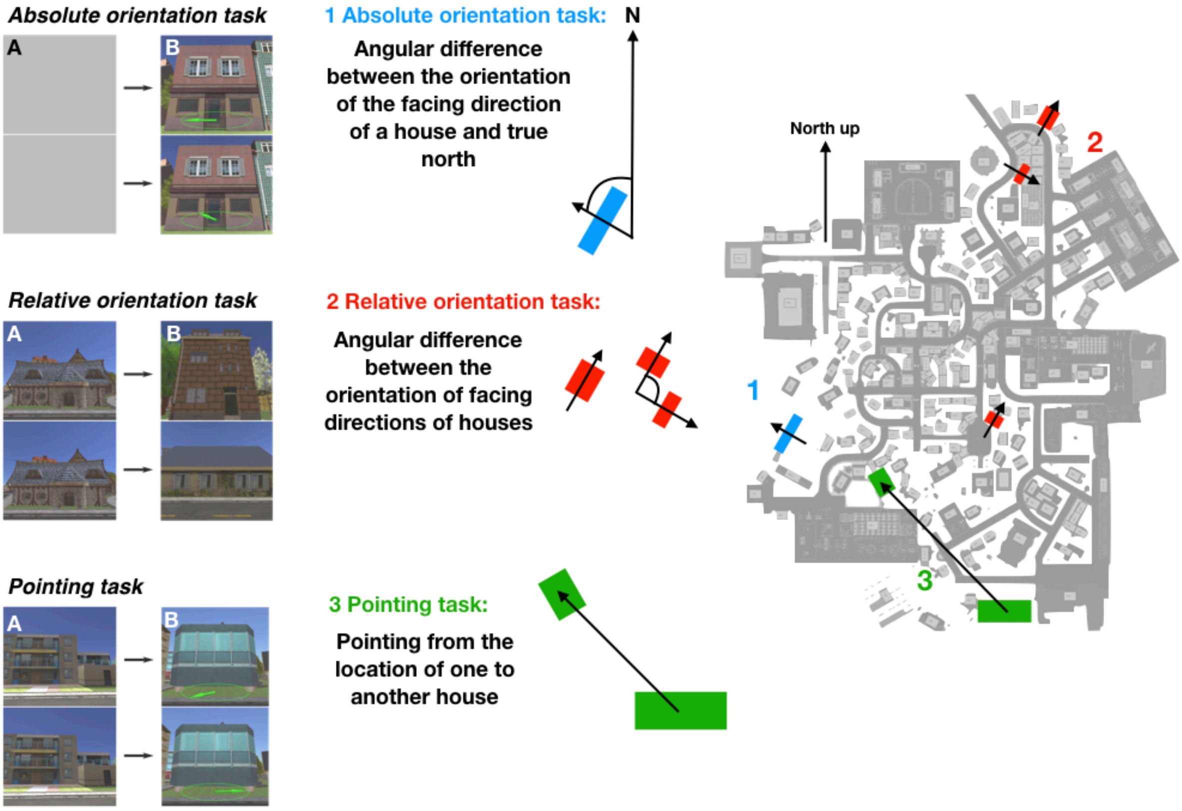

Figure 2: Design of the spatial tasks depicting example trials of the spatial tasks on the left and schemata of the tasks in the middle: absolute orientation task in blue (1), relative orientation task in red (2) and pointing task in green (3). On the right, the schemata of the tasks are mapped onto the city map of Seahaven for illustration. First, a prime stimulus (A) is shown for 5 seconds in the relative and in the pointing task, which is substituted by a grey screen in the absolute orientation task to fit the trial layout in the other tasks. Then a target stimulus (B) is shown until button press either in max 3 seconds or infinite time. In the absolute orientation task, participants had to choose the arrow depicted on the stimuli that correctly pointed to the north. In the relative orientation task, they had to select the target house that had the same orientation as the prime house. In the pointing task, participants had to choose the target stimulus on which the arrow pointed correctly to the prime house — adapted from (König et al., 2019).

FRS Questionnaire

To compare participants' abilities of spatial orientation strategies learned in real-world environments with their accuracy in the spatial tasks after exploration of a virtual city, participants filled in the "Fragebogen Räumlicher Strategien" (FRS questionnaire, translated "German Questionnaire of Spatial Strategies") (Münzer & Hölscher, 2011) at the end of the measurements. The FRS questionnaire imposes self-report measures for spatial orientation strategies learned in real environments. It captures one strategy that is based on an egocentric reference frame and two strategies that are based on an allocentric reference frame (Münzer et al., 2016b; Münzer, Fehringer, & Kühl, 2016a; Münzer & Hölscher, 2011). The "global-egocentric scale" evaluates global orientation abilities and egocentric abilities based on knowledge of routes and directions. The evaluation of allocentric strategies is separated into the "survey scale", which assesses an allocentric strategy for mental map formation and the "cardinal directions scale", which evaluates knowledge of cardinal directions. All scales consist of Likert items with a score ranging from 1 ("I disagree strongly.") to 7 ("I agree strongly."). Thus, the FRS questionnaire enables us to obtain insights into participants' preferred use of egocentric or allocentric spatial strategies and to investigate whether spatial abilities learned in the real world are used for spatial learning in a virtual environment.

Results

In this paper, we investigated city exploration and acquisition of spatial knowledge by direct experience in a large-scale virtual city. We report the results of 22 participants after 90 minutes of free city explorations. The results of spatial learning of Seahaven with the use of an interactive city map were published before (König et al., 2019). Here, we compare the results after exploration by direct experience in VR to those acquired by the city map.

Results of Exploration Behavior in VR

While participants freely explored the virtual city, we measured their viewing behavior and tracked their positions, which summed up to their walked path.

Analyzing the viewing behavior, we focused on looks onto houses, as they were the relevant objects for the spatial tasks. Here, we were interested in for how long a house was viewed. We calculated the summed up dwelling time on a house averaged over subjects (Figure 3, left) and took this as a measure of familiarity of the respective house (see analysis below). The distribution of the dwelling time onto houses in the city revealed that houses that were looked at the longest were not centered in a particular city district but were located all over the city. For comparison to the distribution of most often clicked-on houses when exploring Seahaven with the city map (Figure 3, right), we performed a Spearman's rank correlation between dwelling time and the number of clicks on houses. The result revealed a moderate significant correlation ($\rho(114) = 0{,}364$, $p < 0{,}001$) between looked at houses while exploring Seahaven in VR and clicked-on houses when exploring the city with a map (Figure 4, left).

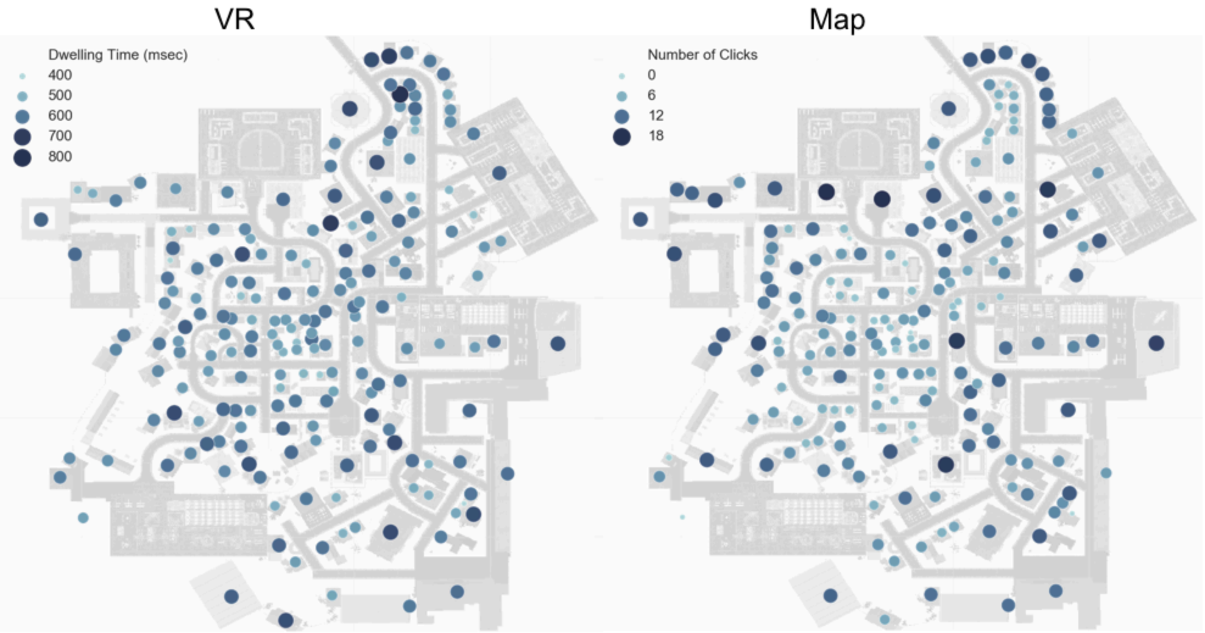

Figure 3: Heat map depicting how long participants looked at a house with direct exploration in VR (left) and how often participants clicked on houses with map exploration (right) on a gradient going from deep blue (most) to light blue (least).

For the walked path, we analyzed all x and y positions in Seahaven which a participant visited and displayed this as a density distribution of "presence at a location" plotted onto the city map (Figure 4, right). The density map of "presence at a location" revealed that participants visited all possible locations, central and big streets a little more often than more peripheral and smaller paths.

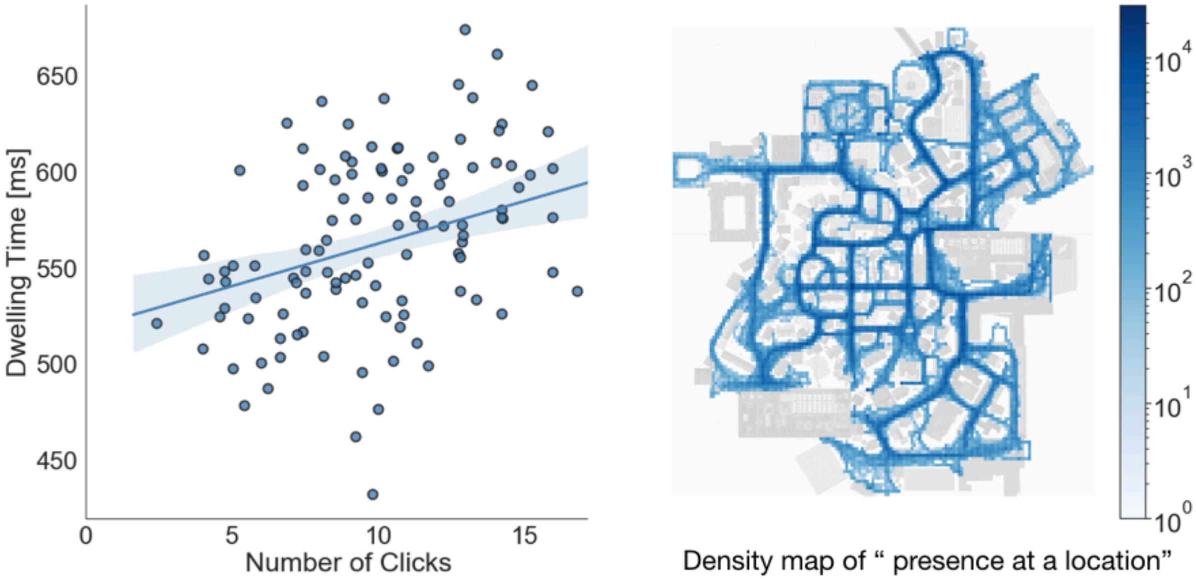

Figure 4: Left: Correlation between dwelling time on houses in ms with VR exploration and number of clicks on houses with map exploration. Each dot depicts a dwelling time x click combination of a house averaged over subjects. The blue line depicts the regression line and the shaded area the 95% confidence interval. Right: Density distribution of "Presence at a location" after exploration in VR over all participants.

Spatial Task Results

For the performance in the spatial tasks, we evaluated the accuracy of response choices in the 2 AFC spatial tasks after direct experience in the virtual city. We analyzed the accuracy in the different task and time conditions comparing the results after direct exploration in VR with the results after exploration with an interactive city map (König et al., 2019). Subsequently, we investigated the influence of how long (dwelling time) a house was looked at (familiarity of houses), the angular difference between choice options, alignment of stimuli towards the north, the distance between tested houses and abilities of spatial strategies (FRS questionnaire) onto task accuracy.

Task Accuracy in Different Time Conditions

We hypothesized that direct experience in Seahaven would support action relevant tasks and therefore reveal a better accuracy for the pointing task. Furthermore, we hypothesized that the accuracy with infinite time for a response would be better than with spontaneous response within three seconds. After VR exploration, the mean accuracy for the different conditions was: absolute orientation task/ 3 sec = 50,88 %, absolute orientation task/ infinite = 57,2 %, relative orientation task/ 3 sec = 49,75 %, relative orientation task/ infinite = 55,43 %, pointing/ 3 sec = 52,02 % and pointing/ infinite = 60,61 %. After exploration with the map, the mean accuracy for the different conditions was: absolute task/ 3 seconds = 54,67%, absolute task/ infinite = 60,10%, relative tasks/ 3 seconds = 59,21%, relative task/ infinite = 60,35%, pointing/ 3 seconds = 48,11% and pointing/ infinite = 57,70%.

To evaluate differences in accuracy in the time and task conditions comparing the groups that explored Seahaven in VR or with a map, we performed a 2 x 3 x 2 mixed ANOVA with accuracy as the dependent variable and time (3 sec/ infinite) and task (absolute orientation/ relative orientation/ pointing task) as the within-subject repeated factors and group (VR-group/ map-group) as the between-subject factor. The accuracy was calculated for each participant as the fraction of correct choices for each time and task condition. The mixed ANOVA showed no significant main effects for task (F(84) = 0,696, p = 0,501, η^2 = 0,016) or for group ((F(42) = 1,086, p = 0,303, η^2 = 0,025), but we found a significant main effect for time (F(42) = 28,356, p < 0,001, η^2 = 0,403). Two-way interactions revealed a significant task*group interaction (F(84, 42) = 7,645, p = 0,001, η^2 = 0,154), but no significant interactions for time*group (F(42, 42) = 0,410, p = 0,525, η^2 = 0,010) or task*time (F(84, 42) = 2,157, p = 0,122, η^2 = 0,049). The three-way interaction task*time*group was also not significant (F(84, 42, 42) = 0,530, p = 0,591, η^2 = 0,012). As we have no significant two- or three-way interaction for time, we do not need to further analyze our time effect. For a better understanding of the significant task*group interaction, we performed two-way ANOVAs with pairwise comparisons of the task accuracies (absolute orientation/ relative orientation task; absolute orientation/ pointing task; relative orientation/ pointing task) to investigate the difference between groups (VR group/ map group) in a 2 x 2 (task/group) design. For this, we investigated accuracies averaged over time as the dependent variable, task as the within-subject factor and group as the between-subject factor in three separate ANOVAs. These ANOVAs revealed no main effects for task or group (absolute orientation/ relative orientation task: main effect task (F(42) = 0,123, p = 0,727, η^2 = 0,003), main effect group (F(42) = 3,599, p = 0,065, η^2 = 0,079; absolute orientation/ pointing task: main effect task (F(42) = 0,563, p = 0,457, η^2 = 0,013), main effect group (F(42) = 0,000, p = 0,989, η^2 = 0,000); relative orientation/ pointing task: main effect task (F(42) = 1,494, p = 0,228, η^2 = 0,034), main effect group (F(42) = 0,739, p = 0,395, η^2 = 0,017). For the comparison between the absolute orientation and the relative orientation task, we found no significant task*group interaction (F(42, 42) = 2,037, p = 0,161, η^2 = 0,046), whereas the task*group interactions were significant in the comparison between the absolute orientation and the pointing task (F(42, 42) = 5,262, p = 0,027, η^2 = 0,111) and the relative orientation and the pointing task (F(42, 42) = 16,862, p < 0,001, η^2 = 0,286). Taken together, our results showed a significant difference between the 3 seconds and infinite time condition with a better accuracy with time for cognitive reasoning. We found a significant interaction between task and group. Further analyses revealed that accuracy in the pointing task compared to absolute and relative orientation tasks differed significantly between groups. Specifically, after direct exploration of the city in VR accuracy was better by +3% for the pointing task than for the absolute and relative tasks. In contrast, after exploration with the map, we found a reversed pattern with a worse accuracy in the pointing task by -5,7% than in the absolute and relative orientation tasks (Figure 5).

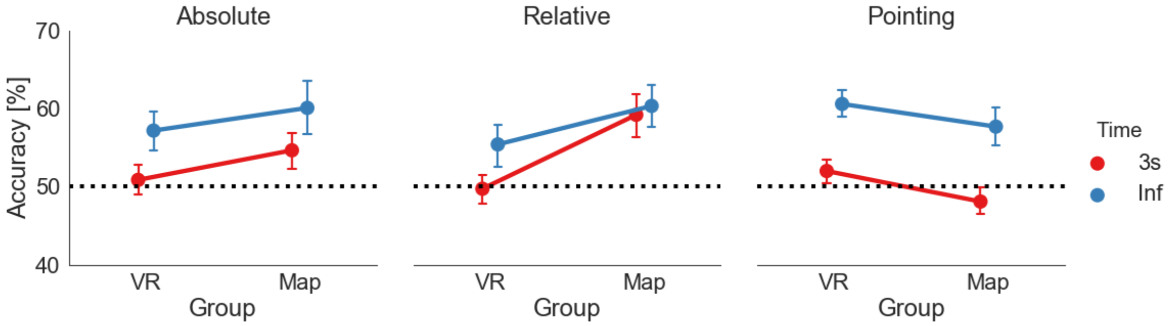

Figure 5: Accuracy of absolute orientation (left), relative orientation (middle) and pointing task (right) in 3 seconds (red) and infinite time (blue) condition. In each task, the dots on the left depict the mean accuracy level after VR exploration and the dots on the right the mean accuracy level after map exploration. The black dashed line marks the level of 50%. The error bars indicate standard error of the mean (SEM).

Accuracy as a Function of “Dwelling Time on a House”

We hypothesized that houses with a longer dwelling time would be better known and that this would increase the familiarity of the house and subsequently the task accuracy. We calculated the dwelling time by counting the consecutive samples on a house recorded by the eye tracker. We considered at least seven consecutive samples on a house as one gaze event, which sums up to 233 ms as the minimum time for viewing duration. We used median absolute deviation based outlier detection to remove outlying viewing durations. Furthermore, we defined dwelling time as the cumulative time of such gaze events spent on a particular house by a subject. In this manner, we calculated the mean dwelling time for each subject for each house. The absolute orientation task only consisted of one house in a trial. However, as each trial in the relative orientation task consisted of a triplet of houses, we compared the dwelling time on the prime and the two target houses and considered the smallest value as an estimate of the minimum familiarity. Each trial of the pointing task consisted of a prime and a target house, for which we compared the dwelling time on the two houses. In these tasks, we then conservatively used the house with the lowest dwelling time in a trial as the relevant indicator for the respective trial. With this, we calculated the average accuracy of all trials over subjects with a specific dwelling time. We calculated a Pearson correlation between accuracy and dwelling time on a house over all task and time conditions (Figure 6, left). We repeated the same analysis for comparison with the data after map exploration using the number of clicks on a house as a similar factor for familiarity with a house (Figure 6, right). After VR exploration, we found a weak significant correlation between accuracy and dwelling time (rho(216) = 0,140, p = 0,039), similar to the correlation after map exploration (rho(216) = 0,165, p = 0,015). With both exploration sources, we found a positive correlation between the increased familiarity of houses and task accuracy.

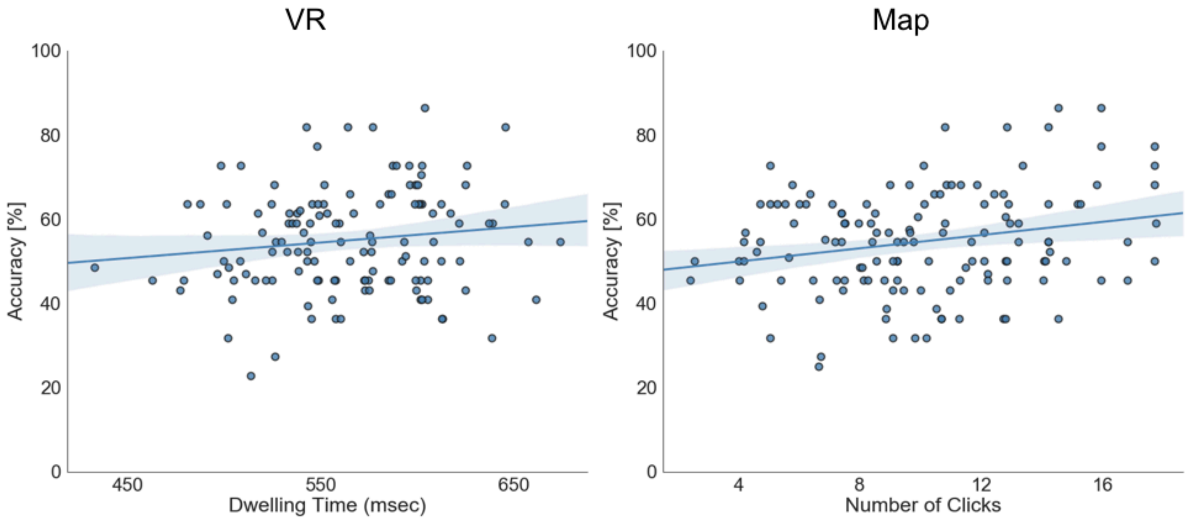

Figure 6: Pearson correlation between overall task accuracy and the dwelling time on a house after VR exploration (left) and the number of clicks on a house after map exploration (right). One dot represents the average accuracy of all trials over subjects with a specific dwelling time (left) or the number of clicks (right) on a house. The blue line depicts the regression line and the shaded area the 95% confidence interval.

Accuracy as a Function of Angular Difference

We investigated the angular difference between choices in our 2 AFC tasks to see whether orientation differences were also learned while directly exploring a virtual environment. We hypothesized that accuracy would improve with larger angular differences between choices. In analogy to the tasks after map exploration (König et al., 2019), participants had to choose between two alternative choices that differed from each other in varying angular degrees in steps of 30°. The analysis combines deviations resulting from clockwise or anti-clockwise rotations, i.e., matching bins from 0°-180° and 180°-360° deviations are collapsed. In the absolute orientation task, participants had to choose between two arrows indicating north on the stimuli, one correctly and one incorrectly, for which we calculated the angular difference. In the pointing task, we calculated the angular difference of two arrows on the target stimuli, which pointed correctly or incorrectly from the target house to the prime house. In the relative orientation task, we computed the angular difference between the orientations of facing directions of two target houses. Due to small variations in the orientation of the houses in the virtual city design, the angular difference between these angles varied in the relative task from a minimum of 30° in steps of 30° with a maximal deviation of +/- 5° in each step. This design resulted in bins of 30°, 60°, 90°, 120°, 150°, and 180° angular difference. For each bin, the accuracy was calculated combining all tasks, but separately for the 3 seconds and infinite time condition. The above hypothesis should hold for exploration within VR as well as with the map. Therefore, we investigated the effect of angular differences between decision choices. For this purpose, we performed a 6 x 2 x 2 mixed ANOVA with accuracy as the dependent variable and angle (angular difference) (30°, 60°, 90°, 120°, 150°, 180°) and time (3 seconds/infinite time) as the within-subject factors and group (VR group/ map group) as the between-subject factor (Figure 7). Our analysis revealed a significant main effect for angle (F(210) = 3,510, p = 0,005, η^2 = 0,077) and for time (F(42) = 28,356, p < 0,001, η^2 = 0,403) as well as a significant angle*time interaction (F(210, 42) = 3,116, p = 0,010, η^2 = 0,069). We found no significant main effect for group (F(42) = 1,086, p = 0,303, η^2 = 0,025), no significant two-way interaction for angle*group (F(210, 42) = 0,926, p = 0,465, η^2 = 0,022) or time*group (F(42, 42) = 0,410, p = 0,525, η^2 = 0,010) and no three-way interaction angle*time*group (F(210, 42, 42) = 1,510, p = 0,226, η^2 = 0,035). Because of the significant angle*time interaction, we performed post hoc pairwise comparisons separately for each time condition but, as we have no group effect, averaged over groups. With Bonferroni correction, we found no significant differences between angles in the infinite time condition (p >= 0,079). In the 3 second time condition, we found a significant difference between 90° and 120° (p = 0,024). All other angles were not significantly different (p >= 0,070). To summarize, independent of the source of exploration, we found a significant angular difference effect with better accuracy between 90° and 120° angular difference between response choices with a spontaneous response.

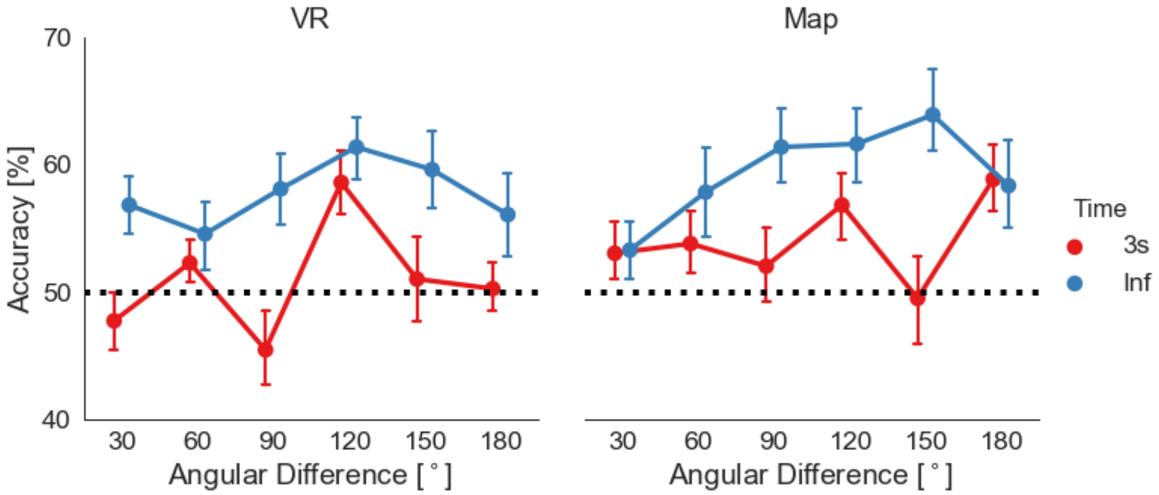

Figure 7: Overall task accuracy in relation to the angular difference between choices in the task stimuli after VR exploration (left) and map exploration (right). Dots depict mean accuracy in respect to 30°, 60°, 90°, 120°, 150°, and 180° categories, with a response within 3 seconds in red and with infinite time in blue. Error bars represent SEM. The black dashed line marks the level of 50%.

Accuracy as a Function of Alignment

Following previous research (e.g. König et al. 2019; Montello et al. 2004), who found a consistent alignment effect after spatial learning with a map, which was less reliable after spatial learning by direct experience (e.g. Burte & Hegarty, 2014; Presson & Hazelrigg, 1984), we did not expect to find an alignment effect revealing orientation specificity after direct experience in the virtual city. To investigate orientation specificity, we tested whether task accuracy was better, when the orientation of the house's facing direction in the absolute orientation task was aligned with north. To get clear results, we only considered the absolute orientation task as participants had to judge separate single houses only in this task. As before, the analysis combined deviations resulting from clockwise or anti-clockwise rotations, i.e. matching bins from 0°-180° and 180°-360° deviations were collapsed. We compared the results after exploration within the VR with those after map exploration performing a 7 x 2 x 2 mixed ANOVA with accuracy as the dependent variable, angle (angular difference of 0°, 30°, 60°, 90°, 120°, 150° and 180°) and time (3 seconds/ infinite response time) as the within-subject factors and group (VR group/ map group) as the between subject factor (Figure 8). We found a significant main effect for angle (F(252) = 4,815, p < 0,001, $\eta^2 = 0,103$) and a main effect for time (F(42) = 10,780, p = 0,002, $\eta^2 = 0,204$) as well as a significant two-way interaction for angle*group (F(252, 42) = 2,577, p = 0,019, $\eta^2 = 0,058$) and angle*time (F(252, 42) = 2,318, p = 0,034, $\eta^2 = 0,052$). We did not find a significant main effect for group (F(42) = 1,372, p = 0,248, $\eta^2 = 0,032$) nor a significant two-way interaction for time*group (F(42, 42) = 0,482, p = 0,491, $\eta^2 = 0,011$) or significant three-way interaction for angle*time*group (F(252, 42, 42) = 1,282, p = 0,266, $\eta^2 = 0,030$). To get more insight into the angle*group and angle*time interaction effects, we performed repeated measure

ANOVAs with accuracy as the dependent variable and angle and time as the within-subject factors separately for VR and map exploration. After VR exploration, we found a significant main effect for angle (F(126) = 2,344, p = 0,035, η^2 = 0,100) but no significant effect for time (F(21) = 2,606, p = 0,121, η^2 = 0,110) or angle*time interaction (F(126, 21) = 1,995, p = 0,071, η^2 = 0,87). Post hoc pairwise comparisons for angle averaged over time revealed with Bonferroni correction no significant angular differences. After map exploration, we found a much more pronounced main effect for angle (F(126) = 4,850, p = 0,000, η^2 = 0,188) and a main effect for time (F(21) = 11,081, p = 0,003, η^2 = 0,345) but no angle*time interaction (F(126, 21) = 1,605, p = 0,151, η^2 = 0,071). Post hoc comparison for angle, separately for the two time conditions, revealed a significant difference in the 3 second response condition between 30° and 180° (p = 0,016) and 60° and 180° (p = 0,026) with Bonferroni correction. All other comparisons were not significant. For the infinite time condition, we found no significant angular difference with Bonferroni correction (p >= 0,084). Our results suggest that angle and time have a significant effect on task accuracies. We found a differential effect of angle between groups, which revealed a better accuracy after map exploration for smaller angular differences between north and aligned houses (alignment effect) with spontaneous response (Figure 8, right) whereas after VR exploration we did not find an alignment effect (Figure 8, left).

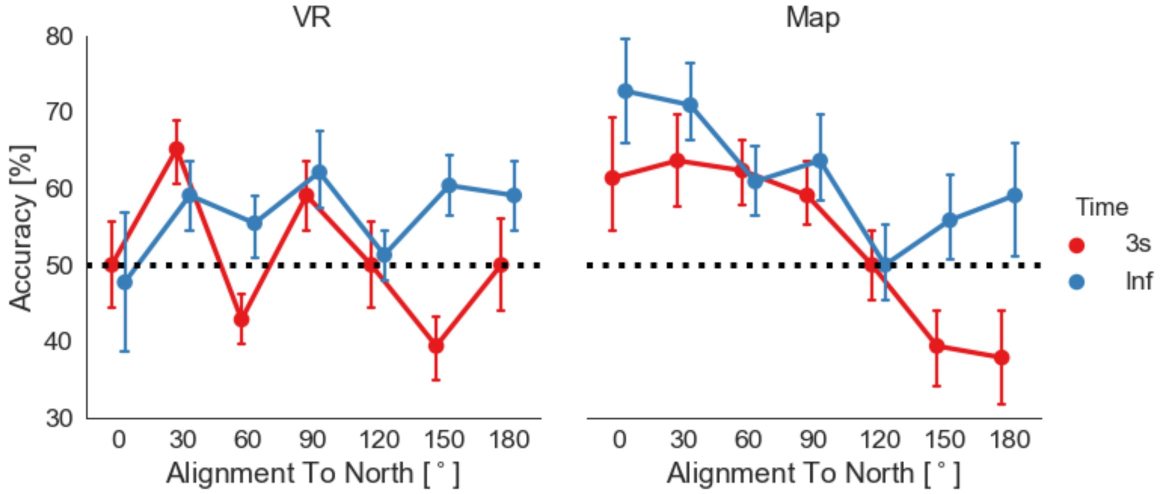

Figure 8: Task accuracy in the absolute orientation task in relation to the angular difference between north and tested stimuli orientation (alignment), on the left after VR exploration and on the right after map exploration. Dots depict mean accuracy in respect to 0°, 30°, 60°, 90°, 120°, 150°, and 180° categories. Error bars depict SEM. The black dashed line marks the level of 50%.

As one reason for the lack of an alignment effect towards the north after VR exploration, we assumed that participants did not know where the defined north was in the virtual city. To investigate how well participants deduced the cardinal directions from the virtual sun's position in VR, we asked them at the end of each exploration to turn so that they would face their subjectively estimated north (Figure 9, left). Comparing participants' subjective estimations of the north after the third exploration of Seahaven with true north in the virtual city, revealed that overall their knowledge of north was astonishingly good. The estimations of 16 out of 22 participants lay within 45° deviation from true north and six even below 3°. Nevertheless, we found no correlation between deviation from true north and accuracy (Pearson correlation between the accuracy in the absolute orientation task and deviation from north with 3 seconds: rho(22) = 0,0645, p = 0,776 and with infinite time: rho(22) = -0,017, p = 0,941) (Figure 9, right). Therefore, our results indicate that in spite of having a relatively good estimation of the north direction in the virtual city, participants could not use it to increase their knowledge of the orientation of houses in Seahaven.

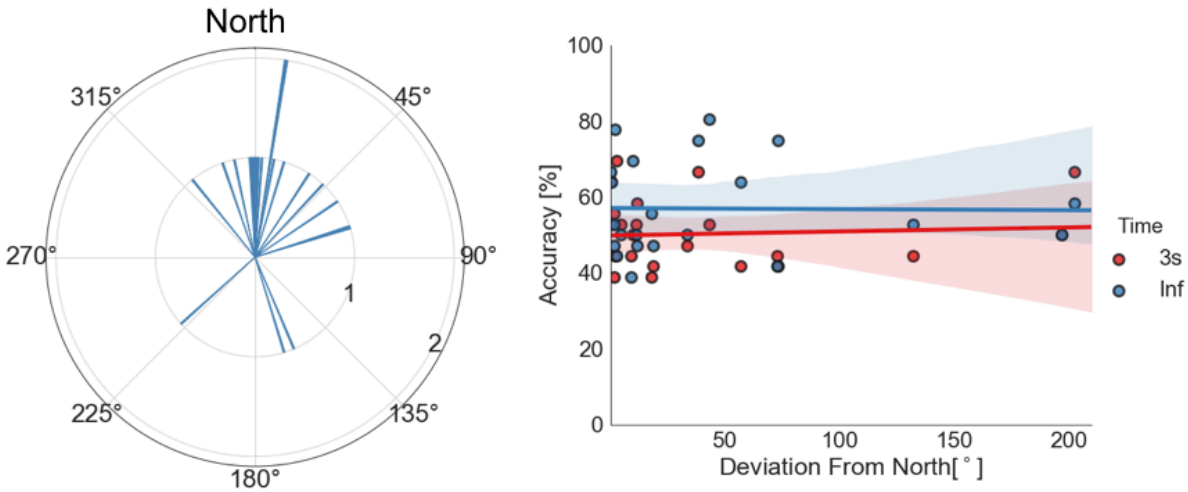

Figure 9: Left: Polar histogram with bin size 1° showing the subjective estimation of the north after VR exploration of the participants. Up is true north. The inner ring shows the subjective north orientation of single participants and the outer of two participants with the same bin. Right: Correlation between accuracy in the absolute orientation task and deviation from the north for the 3 seconds response condition in red and infinite response condition in blue. One dot depicts the accuracy/ deviation from the north combination for one participant. Lines depict regression lines (to respond within 3 seconds in red and with infinite time in blue). Colored shaded areas depict the respective 95% confidence intervals.

Accuracy as a Function of Distance

In line with previous research (Meilinger, Frankenstein, Watanabe, Bülthoff, & Hölscher, 2015), we hypothesized to find a better task accuracy with smaller distances between tested houses (distance effect) with direct experience in Seahaven. As we have to be able to compare the distance between two houses for this analysis, we only considered the relative orientation and the pointing task. In the pointing task, we have only two houses in a trial, the prime and target, whose distance we compared. In the relative orientation task, we compared the distance between the prime and the correct target house only, leaving out the wrong target house for this analysis. So, distance is defined as the distance between predefined house pairs. To investigate the dependencies of accuracy to the distance, we calculated a multiple linear regression model with accuracy as the dependent variable (Figure 10). Here, we focus on the effects of distance, and the modulation by time and group as the independent factors. Our model revealed for the relative orientation task (Figure 10, left) a significant F statistic for our model (F(6) = 4,816, p < 0,001, R^2adj. = 0,138). We found a main effect for distance (beta = -0,042, t(137) = -2,894, p = 0,004,). This revealed that with one unit change of distance accuracy decreased by 0,042%. We found a two-way interaction for time*distance (beta = 0,076, t(137) = 2,588, p = 0,011), which shows that time conditions affected distance differentially with the 3 second response condition resulting in a larger decrease in accuracy by 0,076% for one unit change in distance in comparison to the infinite time condition. We did not find an interaction between group*distance (beta = 0,019, t(137) = 0,679, p = 0,499) as well as no three-way interaction group*time*distance (beta = 0,062, t(137) = 1,070, p = 0,286). For the pointing task (Figure 10, right) the F statistic for the linear model was significant with F(6) = 2,975, p = 0,009, R^2adj. = 0,077). We found no main effect for distance (beta = 0,010, t(137) = 0,750, p = 0,455). Further, we found no two-way interaction for time*distance (beta = 0,0072, t(137) = 0,269, p = 0,789), or group*distance (beta = 0,001, t(137) = 0,044, p = 0,965) as well as no three-way interaction group*time*distance (beta = 0,075, t(137) = 1,398, p = 0,164). Taken together, we unexpectedly found the same influence pattern of distance after exploration within VR and with a map. In both groups, a distance effect was visible with better accuracy for shorter distances between tested houses in the relative orientation task with the spontaneous response time. In contrast, we found no distance effect for the infinite time condition in the relative orientation task or the pointing task.

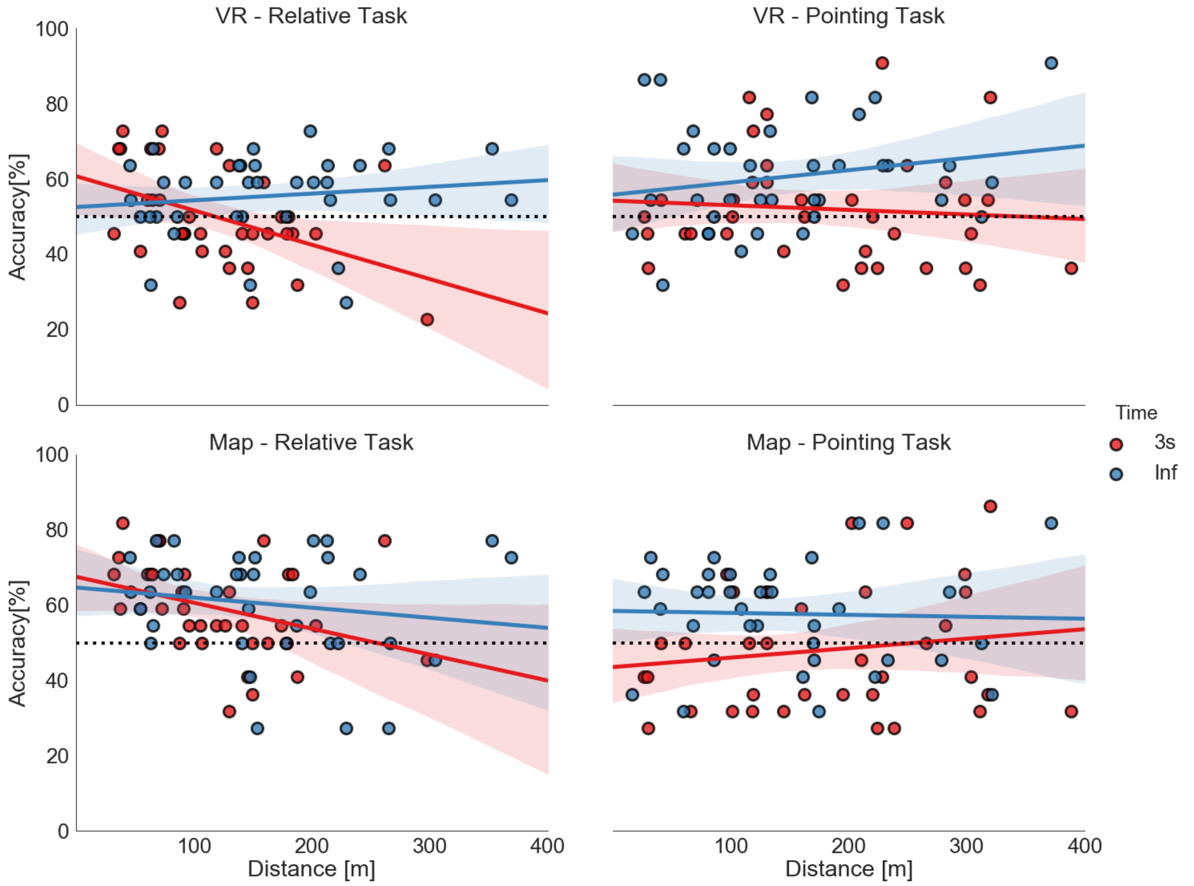

Figure 10: Correlation of distance (abscissa) and task accuracy (ordinate) (top VR, bottom map). The dots depict the combination of time and distance averaged over subjects for a house pair, blue with infinite time to respond and red with 3 seconds response time on the left side for the relative orientation task and on the right side for the pointing task. The straight lines depict the correlation lines and the colored shaded areas the respective 95% confidence interval. The black dashed line marks the level of 50%.

Accuracy as a Function of FRS Scaling

To estimate subjectively rated abilities in spatial orientation strategies learned in real-world environments, we asked subjects to fill out the FRS questionnaire (Münzer et al., 2016b; Münzer & Hölscher, 2011). To investigate the influence of these spatial orientation abilities on task accuracies after exploring a virtual city, we performed the more robust Spearman's rank correlation analysis of the FRS scales and task accuracies and reanalyzed the map data accordingly. After VR exploration, we did not find for scale 1, the "global-egocentric orientation" scale, significant correlations with any of the task and time accuracies (p values between 0,086 and 0,908). Similarly, on scale 2, the "survey" scale, showed no significant correlation (p values between 0,058 and 0,455). For scale 3, the "cardinal directions" scale, we found a correlation with the absolute orientation task with infinite response time (rho(19) = 0,51, p = 0,025). All other correlations for scale 3 were not significant (p values between 0,129 and 0,975). After map exploration, we found a correlation between Scale 1 and the pointing task with 3-second response time (rho(19) = 0,488, p = 0,033). All other correlations were not significant (p values between 0,071 and 0,867). As the p values would not survive

Bonferroni multiple comparison correction (p <0,002), we are cautious about interpreting these results any further.

Discussion

In the present study, we investigated spatial knowledge acquisition after direct exploration in VR of the virtual city Seahaven. We compared these results to those after learning with an interactive map (König et al., 2019). Taken together, our results suggest that survey knowledge measured in a straight line pointing between houses resulted in better accuracy after direct experience in VR. In contrast, tasks based on cardinal directions or relative orientation yielded better accuracies after map exploration. The better familiarity of houses was weakly correlated with an increase in task accuracy after VR and map exploration as well. Furthermore, our results revealed a significantly better accuracy with time for cognitive reasoning than with spontaneous response independent of the source of exploration. In contrast to map exploration, where we found an alignment to north effect in the 3-second response condition, we found no orientation dependency of task accuracies after direct exploration in VR. Unexpectedly, our results revealed the same pattern for distances after VR and map exploration with a distance effect visible in an accuracy decrease with bigger distances only for judging relative orientations of houses facing directions with a spontaneous response. We found in both groups no significant correlation of task accuracies and the scales of the FRS questionnaire. Overall, our results suggest that spatial knowledge acquisition was influenced by the source of spatial exploration with better accuracy for action relevant relations after direct exploration in VR and better accuracy in tasks that were based on cardinal directions or relative orientation information after map exploration.

Previous research revealed that landmark, route and survey knowledge may evolve by direct experience in real-world (Montello, 1998; Richardson et al., 1999; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982), even though there are large individual differences (Hegarty, Burte, & Boone, 2018; Ishikawa & Montello, 2006; Montello, 1998; Wiener, Büchner, & Hölscher, 2009). Direct experience supports route knowledge in relation to an egocentric reference frame whereas spatial learning with a map heightens survey knowledge in relation to an allocentric reference frame (Frankenstein, Mohler, Bülthoff, & Meilinger, 2012; Meilinger et al., 2013; Meilinger et al., 2015; Montello et al., 2004; Richardson et al., 1999; Shelton & McNamara, 2004; Taylor et al., 1999; Thorndyke & Hayes-Roth, 1982). Due to previous research using the feelSpace augmentation device that gives information about magnetic north (Kaspar et al., 2014; König et al., 2016), we designed the tasks investigated in this study with respect to an allocentric reference frame. The tasks that tested orientation of houses' facing directions towards north or relative orientation between two houses' facing directions directly used knowledge of cardinal directions. The straight line pointing task is supposed to measure survey knowledge (Montello et al., 2004), a map-like representation also called "cognitive map" that integrates knowledge about landmarks and routes adding information about metric spatial relations, which also allows taking shortcuts (Montello, 1998; Siegel & White, 1975). As a map directly provides a fixed coordinate system, survey knowledge is supposed to be preferentially derived from maps (Thorndyke & Hayes-Roth, 1982). But it can also be obtained from direct navigation within an environment (Klatzky et al., 1990; Montello, 1998; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982). Our results revealed better task accuracy in the pointing task after direct exploration in VR compared to the absolute orientation towards the north and relative orientation between two houses. The opposite pattern was found after map exploration. Previous research, evaluating photographs of real-world houses of the city of Osnabrück after at least one year of living in the city, combining direct experience and cartographic information to get to know the environment (König et al., 2017), found the highest task accuracy in the pointing task as well.

Thus, in line with results of spatial knowledge that was acquired by living in a real-world city, our results suggest that survey knowledge was preferentially acquired after direct exploration in virtual reality in contrast to tasks using information about cardinal directions and relative orientation that were preferentially derived with an interactive map.

Additional to the source of spatial exploration also, the design of the performed task has to be considered as an influential factor (Montello et al., 2004). Pointing tasks in spatial research generally test pointing from a specific location to another specified location. Besides this general structure, there exist a large variety of different designs. They reach from pointing tasks in rooms to large-scale environments and virtual environments, from imagining the learned layout to embodied real-world test conditions with real sensory input while tested in aligned, misaligned or disoriented conditions and everything in between (e.g. McNamara, 2002; McNamara, Rump, & Werner, 2003; Montello et al., 2004; Mou & McNamara, 2002; Shelton & McNamara, 1997; Waller & Hodgson, 2006). In recent research, Zhang et al. (2014) investigated the development of “cognitive maps” after map and desktop VR learning with two different pointing tasks adapted from previous research (Holmes & Sholl, 2005; Mou, McNamara, Valiquette, & Rump, 2004; Waller & Hodgson, 2006). They used a scene and orientation-dependent pointing (SOP) task, which was based on egocentric embodied scene and orientation information and a judgment of relative direction (JRD) task, which was supposed to be based more on remembered knowledge of allocentric relations between landmarks. Their results indicated that after spatial learning in VR, which was based on an egocentric reference frame, performance in the SOP task was better. In contrast, after map learning of the VR environment, providing an allocentric reference frame, the performance was better in the JRD task. For spatial knowledge acquisition in our present study, participants either explored the large-scale virtual city with an immersive HTC Vive headset or an interactive city map, which provided screenshots of the views of task-important houses. Participants spent the same amount of time (three repeated 30-minute sessions) in both exploration conditions, and we strictly investigated the same pointing design after using the different sources for exploration. Our pointing task was performed outside the VR and displayed screenshots of the tested houses in a 2 AFC design, where participants had to choose the correct arrow on a target house pointing back to a previously shown prime house. With this design, we stayed within the visual domain for testing. This allowed using identical test conditions after VR and map learning. In agreement with Zhang et al. (2014), we found a better pointing accuracy with our pointing task after exploration directly in VR. We suggest that even though the pointing stimuli did not provide scene and orientation information further to the screenshots taken in VR, the display of these visual images triggered the remembered visual scene information available while exploring the virtual environment. As the map exploration solely provided the screenshots of the houses and the city map from a bird's eye view, no additional embodied information was learned. Additionally, solving the tasks after map exploration came with a switch in required perspective from bird’s eye perspective in the map view to ego perspective in the tasks, which is known to cause a reduction in performance (McNamara, Sluzenski, & Rump, 2008; Meilinger et al., 2013; Shelton & McNamara, 2004). Our results suggest that the accuracy in our pointing task was supported by remembered scene and orientation information after exploration in VR, which led to better accuracy than after map exploration.

Performance of tested spatial tasks is often measured by accuracy or by reaction time (Montello et al., 2004). Measuring reaction time tests how quick an answer can be given directly. But also in most studies investigating accuracy, spontaneous responses are required. In contrast, we used two response conditions in the present study. Here, participants had to respond either within three seconds, testing spontaneous response or had infinite time for a response for cognitive reasoning. These two response times were chosen based on dual-process theories (Evans, 1984; Evans, 2008; Finuncane, Alhakami, Slovic, & Johnson, 2000;

Kahneman et al., 2002). Response decisions within three seconds can be understood as "System 1" processes that require rapid and intuitive cognitive processes. However, infinite time to respond allows for time-consuming slow, deductive and analytic cognitive reasoning by "System 2" processes. Our results revealed after VR as well as map exploration a better accuracy with time for cognitive reasoning. Kahneman et al. (2002) suggested that "System 2" processes with more proficiency descend and improve "System 1" processes. Thus, our results indicate that acquired spatial knowledge yielded measurable results with time for cognitive reasoning, whereas with a spontaneous response, more familiarity is required.

In real-world spatial navigation studies, orientation specificity and distance between tested objects were found to be differential factors after direct experience in the environment and map use. Orientation specificity is measured as an alignment effect that is visible in a better accuracy when learned, and retrieved orientations were aligned. This was consistently found after spatial learning that provided a fixed reference frame like cardinal directions of a map or environmental features (Brunyé, Burte, Houck, & Taylor, 2015; Frankenstein et al., 2012; McNamara, 2003; McNamara et al., 2003; Montello et al., 2004). After direct experience in the environment, which might lead to multiple local reference frames (Meilinger, 2008; Meilinger et al., 2015, 2006; Montello et al., 2004) an alignment effect was much less consistently found (Burte & Hegarty, 2014; Presson & Hazelrigg, 1984). In agreement, our results revealed no alignment effect of tested house orientations towards north after direct experience in the virtual city. Even though participants were astonishingly good at estimating north after VR exploration, they were not able to use this knowledge to improve task accuracies. In contrast, we found an alignment effect towards the north after map exploration (König et al., 2019). Thus, our results are in line with a differential effect of orientation specificity after direct experience and map exploration.

Investigating the influence of distance between tested houses, previous research indicated that when getting to know a large-scale environment by direct experience smaller distances between tested objects improved task performance (distance effect), whereas after learning with a map no distance effect was found (Frankenstein et al., 2012; Loomis et al., 1993; Meilinger et al., 2015). In contrast, our results revealed the same pattern of distance dependency after direct city exploration in VR and with a map. In both groups, with time for cognitive reasoning to respond, task accuracies were not influenced by the distance between tested houses whereas with spontaneous responses, we found a significant negative correlation between accuracy and distance in the relative orientation task but not in the pointing task. The spatial extent of our virtual city, which allowed for distances between houses up to 400 (virtual) meters, is relatively large for a virtual environment. However, it might not be large enough to yield the same effects as in a real-world city. Thus, our results revealed a comparable pattern for the influence of distance onto task accuracy after VR and map exploration with only a distance effect in the relative orientation task with spontaneous responses.

Navigation is a multimodal activity that requires embodied interaction of the navigator with the environment. This is in line with theories of embodied and enacted cognition, which understand cognition as an embodied activity that includes mind, body and environment (Engel et al., 2013; Noë, 2004; O'Regan & Noë, 2001; Varela, Thompson, & Rosch, 1991; Wilson, 2002). Spatial navigation continuously requires multimodal sensory input about the visual, motor, proprioceptive and vestibular changes. Thus, getting more insight into natural navigation with the help of VR requires a design in close analogy to natural conditions. Therefore, we aimed in our study at providing a large virtual environment with great detail of visual information with a fully immersive head-mounted setup to support immersion and a close to real-world experience. However, spatial updating also depends on vestibular and kinesthetic information (Chance, Gaunet, Beall, & Loomis, 1998; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Loomis et al., 1993; Riecke, Cunningham, & Bülthoff, 2007;

Wang & Spelke, 2000). The performance of spatial tasks was shown to improve with active exploration and natural movement in the environment (Klatzky et al., 1998; Mou & McNamara, 2002; Waller et al., 2004). Thus, one crucial point in navigation experiments in virtual environments is to investigate the influence of aspects of directional movements during VR exploration. Ruddle and colleagues (Ruddle & Lessels, 2006; Ruddle & Lessels, 2009; Ruddle, Volkova, & Bülthoff, 2011) found that translational movement was more important than pure body turns for improved accuracy in spatial tasks (e.g. cognitive maps measured by direction and straight-line distance estimations or search tasks) with virtual environment exploration. In contrast, Riecke et al. (2010) adapting Ruddle's design found that full-body rotations already resulted in comparable performance levels as full walking. This is supported by real-world studies, which discovered a better accuracy in direction estimations with physical body turns than imagined turns (Mou et al., 2004; Presson & Montello, 1994; Rieser, 1989). As free-space walking requires considerably more space, improved tracking systems and increased safety management (Riecke et al., 2010), we realized movements in our setup with joystick translations and bodily rotations on a swivel chair. For a fully immersive embodied experience in VR, free-space walking would be desirable to include all movement aspects as close to real-world sensory experience. Nevertheless, adding movement to spatial navigation research in virtual environments reduces the gap between classical lab and real-world conditions and makes it possible to investigate embodied aspects of spatial cognition.

Investigating brain areas that are involved in spatial navigation (Bellmund, Gärdenfors, Moser, & Doeller, 2018; Doeller, Barry, & Burgess, 2010; A. Ekstrom, 2010; Epstein, Patai, Julian, & Spiers, 2017; Gramann et al., 2010; Maguire, Nannery, & Spiers, 2006; Spiers & Maguire, 2007; Zhang, Copara, & Ekstrom, 2012) faces the problem that investigations of physiological processes on humans are mainly performed with fMRI, PET, MEG, or EEG. For the former three methods, human participants have to lie or sit still and passively view a virtual environment. Thus, the results of brain activation during navigation often derive from VR experiments without physical movements. Recording brain activity during spatial navigation in a virtual environment with full mobility would be a desirable solution for future research. Specifically for straight-line walking, reliable and validated implementations are already available (Gwin, Gramann, Makeig, & Ferris, 2011; Oliveira, Schlink, Hairston, König, & Ferris, 2016). Of course, recording in a natural environment allows the investigation of much more complex movement patterns and their influences on cognitive processes (Reiser, Wascher, & Arnau, 2019). Recent research including natural movement, indicate that the lack of physical movement in simple virtual environments leads to quantitatively and qualitatively different physiological processes (Bohbot, Copara, Gotman, & Ekstrom, 2017; Ehinger et al., 2014). Ehinger et al. (2014) investigated brain activity with mobile EEG during a spatial path integration task to get insight into brain activity during real-world navigation. They found significant differences in alpha activity in cortical clusters in respect to passive or active movement conditions, thus the availability of vestibular and kinesthetic input. Taken together, investigations in VR are of high importance for spatial navigation research and investigations of brain activity in humans. Further research is needed to determine the sweet spot for studies of spatial cognition of ecological validity and experimental control on the broad range of simple laboratory setups and virtual reality setups of different degrees of sophistication.

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