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Bachelor Thesis in Cognitive Science

The Influence of Height-Induced Arousal on a Path Integration Task in Virtual Reality

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Abstract

Path integration is a mechanism of spatial cognition that uses ego-motion to integrate distance and rotation over time. Internal and external cues regarding the ego-motion are processed through attention and frequently updated in the working memory system. If stress and cognitive load interfere with attentional and working memory resources, the ability to reproduce traveled distances is impaired. Height can be used to elicit stress reactions and an increase in cognitive load. Thus, we designed an experiment comparing path integration abilities in high and low height conditions. We expected the error participants make in the reproduction of traveled distances to reflect the influence of height-induced cognitive load. For this task, we used a virtual environment, with two different heights and distances, where landmark information was either provided or not. Participants were immersed in the virtual reality via a head-mounted display, and their walking data was extracted through feet tracker. The resulting errors in reproduced distances could not confirm our hypothesis. A significant effect of distance on the distance error was found, with an overestimation for short distance conditions and an underestimation for long distances. But no main effects of height or landmarks could be found. The time for each trial was influenced by height, with an increase in time if no landmarks were present in high height conditions and for short distances in high height conditions. Furthermore, observable insecurities in walking trajectories were extracted from the tracking data. The lack of an effect of height on the reproduction of distance is probably attributed to the height stimuli not sufficiently increasing cognitive load. The effect of distance on the error is interpreted as participants remembering one mean distance, with respective corrections if the encoded distance was long or short. Further changes are proposed to increase the height impression and guarantee the inclusion of landmark information. The height however affected the time, showing some instability in participants' behavior in high height conditions. Supported by the stable height impression, we conclude that the presence was sufficient in this environment. Therefore, the applicability of this virtual environment is recommended for path integration tasks since it also allows for the integration of bodily cues vital for path integration abilities.

Introduction

For humans and animals, one of the most essential skills to survive has always been the ability to return to shelter, locate our community, and explore productive lands. Being lost can be stressful and even dangerous. To avoid this, we are equipped with a wide variety of navigational systems and spatial cognition. In their daily navigation, humans and animals use several mechanisms of spatial cognition to orient themselves. This constant navigating requires an integration of the perception of the current environment and the spatial working memory. The working memory constantly updates the available spatial information through different mechanisms, as depicted in Figure 1: Spatial updating describes that the position of elements is updated in reference to the individual, which can be used for navigation. In the case of imagined ego-motion by perspective taking a spatial updating of imagined movement occurs. Further, the process of mental rotation concerns the imagined movement of objects. The representation of the individuals' position relative to the point of origin is called path integration. The mechanism of path integration alone is sensitive to error accumulation, which is why it is usually supported by external spatial cues, like landmarks or familiar places (Mallot, 2012). However, in environments without landmark information, path integration is vital in providing navigation.

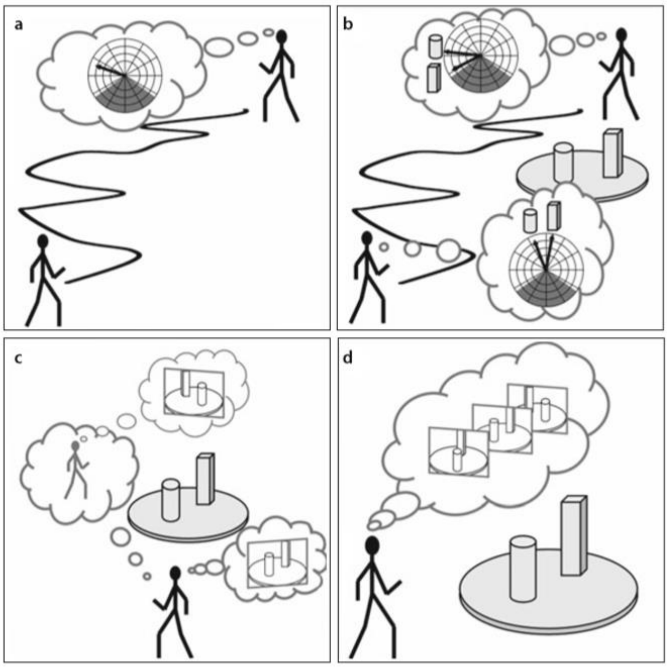

Figure 1: Different mechanisms of working memory in spatial cognition: path integration (a), spatial updating (b), spatial updating of imagined movement (c) and mental rotation (d) (Mallot, 2012).

Animals, for example desert ants, use path integration to find their home after searching for food. During the search, they constantly walk further away from their home. While walking, the distance and orientation are computed from the ants' own walking speed and turning angles and are continuously updated and remembered. This representation of distance and orientation is called a home vector. If the ants want to return home, they walk into the direction of the home vector, again constantly updating, until it reaches zero. This allows the ants to return home on a straight path, as depicted in Figure 2.

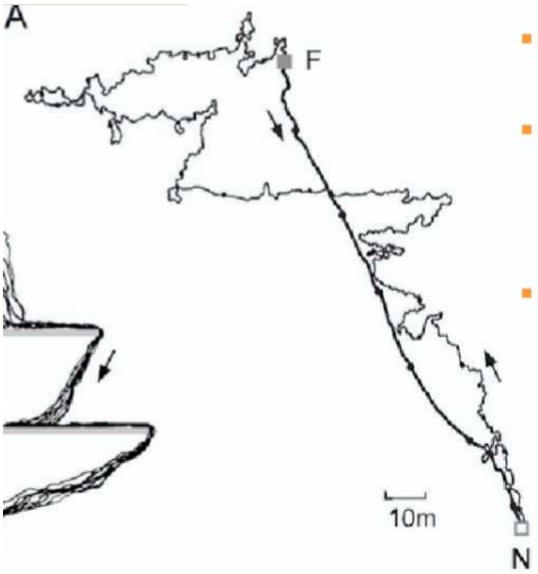

Figure 2: Outbound journey (N -> F) and return path (F -> N) for ants (Mallot, 2012).

The neural substrates of ant path integration are thought to be embedded in the central complex, a brain region that can be found in most insects. This region receives input from speed sensing cells and holds output neurons linked to known steering centers of the insect brain. The ants' current heading is represented in the central complex and must be combined with information about the distance. The current heading is encoded through a head-direction circuit that can use a combination of global compass cues like polarized skylight, landmark information, and rotation estimates. The combination of current heading and traveled distance are integrated over time and stored in the working memory until the ant uses this information to return home. Thus, the central complex forms a neural substrate for the computation of the home vector, and the working memory stores the home vector until it is used (Heinze, Narendra, & Cheung, 2018).

While it is well understood how animals compute path integration, human path integration is still uncertain, with several approaches and ideas seeking to explain it.

The navigational components of distance and rotation have to be computed and integrated over time to allow path integration. The regions thought to track self-motion are the hippocampus as well as parahippocampal and retrosplenial regions. They are active during the encoding and maintenance of input from vestibular, proprioceptive, and motor systems, necessary for path integration. These regions also form the neural substrates for integrating self-motion information into the broader network of spatial navigation (Chrastil, Sherrill, Hasselmo, & Stern, 2016). Further studies (Arnold, Burles, Bray, Levy, & Iaria, 2014) found the engagement of top-down systems that interact with spatial attention (regulated through parietal regions) and working memory systems, shifting the focus away from the hippocampus towards the prefrontal cortex and inferior parietal lobule. These systems are likely used to focus attention on the visual optic flow cues necessary to compute the individual positional changes through the environment. The configuration between attentional and working memory systems varies between individuals, whereas a higher engagement of the memory system correlates with more accurate homing (Arnold et al., 2014).

The varied configurations of these networks might relate to the strategies used to explain human path integration. Two strategies can be differentiated, the continuous strategy and configural strategy (Wiener, Berthoz, & Wolbers, 2011). The continuous strategy resembles the process of animal path integration, with the constant updating of a home vector, through information generated by ego-motion. For the continuous strategy, the home vector should be available at any point and lead to a quicker reaction when asked to indicate the point of origin. This strategy mostly engages visuospatial attention systems for the ongoing updating of the individuals' position and heading. The configural strategy, on the other side, assumes that a path layout is remembered. Accordingly, path segments are stored in the working memory and used to compute a home vector at the end of the outward path. Usually a configural strategy is explained via the encoding-error-model. Thereafter path integration is computed by first sensing the ego-motion, then creating a representation of the route and computing and executing the desired trajectory. A home vector is computed at the end, and errors happen at the sensing and representation steps. The configural strategy is thought to engage posterior parietal regions to store rotations. Using this strategy would increase the reaction times because the home vector has to be computed with the stored information before homing.

To see which strategy seems more likely to be used, several experiments have been carried out using a triangle completion task. The triangle completion task is a standard paradigm to research mechanisms of path integration in humans. It consists of a triangular path, on which participants are asked to walk two of the three legs of the triangle and then point or walk to the starting point. In one experiment, participants were asked to either always update the location of the starting point (continuous) or to remember the shape of the ongoing path (configural) (Wiener et al., 2011). The authors found an influence of instructions on the strategy used, with shorter reaction times in the continuous strategy condition but a better homing accuracy in the configural condition. Therefore a shift in behavior is induced by different instructions regarding the strategy (Wiener et al., 2011). It is very likely that each person engages a different strategy, and this might correlate with the neural configurations of attention and memory, whose engagement in path integration tasks also differ between individuals (Arnold et al., 2014).

The complexity of the path could also have an influence on path integration (Wiener & Mallot, 2006). As normal environments seldomly have simple straight paths, it is useful to look at a more complex setup. In an experiment, the number of path segments was increased for a more complex path. The turning angles were kept the same over all turning points. A textured ground was used to provide a sense of ego-motion through optic flow. This study also investigated the different strategies that might be used: For the continuous strategy a home vector always needs to be cognitively represented and allows quicker reaction times in the triangle completion task, no matter how complex the path is. The pointing accuracy should only be dependent on distance and overall turning angle. For the encoding-error-model (configural strategy) the home vector is computed at the end; therefore, the reaction times and pointing accuracy should increase. The results show that path integration in this setup seems to be independent of path complexity. A negative effect of path complexity on path integration has not been found. Thus, providing no evidence to generally distinguish between the two strategies, so switching between strategies might be possible. It is conceivable that a continuous strategy is mostly used for more complex paths and a configural strategy for shorter simple paths. As most natural paths are long and curved the continuous strategy seems plausible there because the encoding-error-model does not predict curved paths (Wiener & Mallot, 2006).

Since these systems are often most relevant in situations where an individual may be lost, many studies regarding navigational skills also factor in the role of arousal, cognitive load, and anxiety. The influence of stress on spatial tasks has been examined by Richardson and VanderKaay Tomasulo (Richardson & VanderKaay Tomasulo, 2011). Before performing the spatial task, participants were either instructed to perform a star mirror tracing task (experimental group), which is often used to induce stress, or to watch a nature documentary (control group). Afterward they carried out two spatial tasks: The first task was to navigate through a virtual environment (VE) and remember the location of targets along the way. This needs large scale configural knowledge, only possible through the integration of spatial information over time. For the second task, participants were presented with a map depicting targets. They were instructed to mentally rotate their own position and point to specific targets, as a spatial transfer task. Measured were response time and accuracy, as well as physical stress reactions like heart rate, blood pressure, and cortisol concentration in saliva. The results showed a measurable stress reaction for participants in the experimental versus control group, which also reflected in the participants' ratings regarding their anxiety, frustration, and irritability. Participants in the experimental group were significantly slower in their reaction times for both spatial tasks. The accuracy, however, was approximately the same for the experimental and control conditions. These results show that the memory encoding was not impaired by stress, but memory retrieval was. Slower reaction times can also be attributed to a carryover effect from the initial stress reaction to the star mirror tracing task, a sustained negative affect, or a combination of both (Richardson & VanderKaay Tomasulo, 2011). Altogether it seems like stress interferes with the performance of spatial tasks at the point of information retrieval, leading to longer reaction times.

The experiments conducted by Glasauer and colleagues (Glasauer, Schneider, Grasso, & Ivanenko, 2007) looked at this interference and the influence of cognitive load more closely. They theorized that, in addition to the final distance and turn angle, the representation of time also plays a crucial role in accurate path integration. If the internal timeline is distorted, errors in path integration may occur. As cognitive load has been shown to change the subjective estimation of time, participants were instructed to perform mental arithmetic in different stages of path integration tasks. Path integration computes ego-motion and position without explicit external feedback and therefore requires accurate processing and memorization. The additional mental task influenced the participants' ability to integrate time and significantly changed the distance of reproduced self-motion. The authors assume that the allocation of attention and working memory of the mental task causes an interference effect for time perception and the internal representation of time for movement reproduction. The additional task affects the stored duration of movement and the path integration process itself. This leads to the model of a discrete path integration process, as introduced by the authors. Accordingly, a new distance value is computed and stored in the spatial working memory. The increasing distance during path integration is computed through velocity, duration, or directly through step length. Cognitive load or allocation of attention decreases the frequency of path integration events. If this happens during encoding, the stored distances are shortened, without affecting the velocity. During reproduction, distance is retrieved from memory and compared to an estimate of distance. Mental load during reproduction also affects reproduced distance. This means that perceptual space and time are closely linked, and a disturbance of the internal timeline affects the estimated distance traveled.

Another distinct effect on spatial behavior in animals and humans can be produced by height-induced anxiety. The most common paradigm used to investigate the following effects in animals is the elevated-plus-maze (EPM), which consists of elevated paths in the form of a plus sign. Two arms of the EPM are surrounded by walls, hiding the depth and providing safety. The other two arms are in the open, subjecting the animals to the depth underneath them. The resulting approach-avoidance conflict allows measuring the height induced anxiety on a behavioral level. Avoidance of the open paths is associated with anxiety, while walking on open paths indicates sensation seeking. Little time spent on the open paths and a low frequency of visits correlate with high anxiety in rodents. These findings are not reserved to animal behavior: A virtual reality (VR) study conducted by Biederman et al. (2017) used the same paradigm with human participants, assuming that height induces the same arousal or stress reaction in humans as it does in animals. Participants were presented with a virtual reality environment and instructed to explore. The virtual environment showed an EPM, with two paths being supported by rocks and two open paths high above water, as depicted in Figure 3.

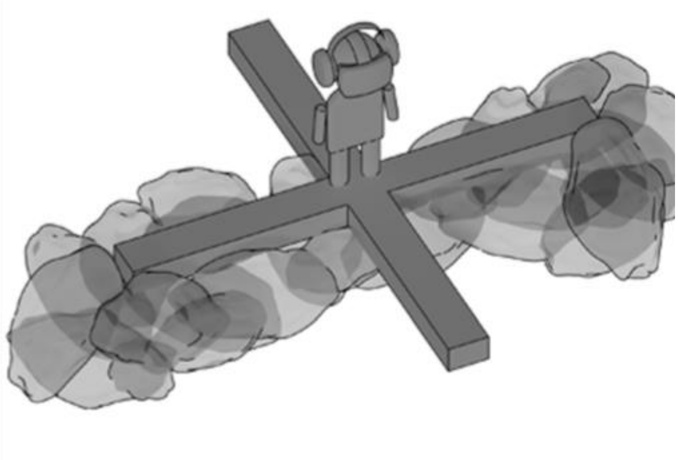

Figure 3: Schematic depiction of the virtual EPM (Biedermann et al., 2017).

The supported paths provide safety, and the open paths above water create a feeling of height. Behavioral components, like the time spent on open paths and the frequency of going to the open versus the closed paths, were measured. The physical indicators of stress, like heart rate, breathing, and skin conductivity were registered as well. Further information was provided by an acrophobia (fear of heights) questionnaire and questionnaires regarding the VR presence (iGroup Presence Questionnaire), side effects (SSQ), social anxiety (LSAS), and general anxiety (STAI), as well as sensation seeking (SSSV). Trait and social anxiety were used to look at sex differences: Female participants showed higher general anxiety, and the age of both sexes correlated with the behavioral measures. Participants reported higher levels of anxiety on the open paths with an increase in anxiety linked to distances further away from the safe arms of the EPM. Participants who scored higher on the acrophobia questionnaire avoided the open paths significantly more than participants with high scores in sensation seeking. There was a high correlation between subjective anxiety ratings and behavior. These were accompanied by indicators of physical stress. Therefore, the EPM proofs to be useful in human studies regarding height-induced anxiety, and the virtual reality approach provides a controlled experimental setup.

Several studies have successfully used virtual reality to research stress in relation to heights. Walking along a virtual balance-beam with an abyss underneath has been shown to initiate physical and cognitive stress reactions (Peterson, Furuichi, & Ferris, 2018). Participants were asked to walk along the balance-beam in two conditions, one where the balance-beam was virtually suspended high above the ground and two control conditions with no height: virtual and real. Measured were heart rate, skin conductance, EEG, reaction time to auditory cues, and how often the participants stepped off the bar. The motion sickness assessment questionnaire and the heights interpretation questionnaire were used for more insight. Highly acrophobic participants were excluded from participation, as not to risk unfinished experiments. To increase the presence, participants walked on a real wooden board, which lay on the ground before them. If they stepped off the balance-beam in the high heights condition, their avatar fell 15 meters in VR. The results show that the experimental setup was successful in activating a stress response: Heartrate and skin conductivity increased in the high heights condition in comparison to a virtual environment with no depth under the participants. The participants' balance was worse in the high heights condition and they stepped off the bar more often. The effect of heights on cognitive load was measured as well: participants were instructed to react to auditory cues. Longer reaction to auditory stimuli and the measured EEG data suggest an increase of cognitive load in the high height condition. Hence, virtual heights evoke measurable stress reactions and cause an increase in cognitive load.

Height further affects people in their body posture, gait, and movements. People who are affected by heights are also more prone to abnormalities in balance control, even when not presented with any depth cues (Boffino et al., 2009). Body sway and postural control also correlate with the subjective assessment of fear of heights. Changes in body swaying and posture control decrease when an acrophobia inducing environment provides static contrasts in the visual surroundings (Wuehr et al., 2014). Another clear effect of fear of heights can be seen in eye and head movements and gait of susceptible people who walked along a balcony of a high building. Participants with a fear of heights avoided looking into the depths and walked slower with more caution. Head movements were reduced as a possible strategy to reduce visual and vestibular stimulation, while eye movements were centered around the path, horizon, and the handrail (Kugler, Huppert, Eckl, Schneider, & Brandt, 2014).

In conclusion, we can draw many connections from height-induced cognitive load and stress to the ability to integrate traveled paths. Since a stress reaction might arise from being lost in an unknown environment, it is crucial to understand its effect on navigation, as this is the situation where navigation is most needed. For spatial navigation, the remembering of landmarks would allow a more stable way to navigate. However, in sparse environments, path integration is the only system to provide orientation, even though it is sensitive to error accumulation. Altogether, the ability to integrate paths relies on the integration of distance and rotation over time in the home vector. For a successful computation of the home vector, the necessary components have to be gathered, combined, and stored continuously. The information regarding the ego-motion and rotation is received through external cues, i.e. textured ground for optic flow, and internal body signals, i.e. vestibular and proprioceptive information. Errors in path integration can occur through incomplete or noisy processing of input signals, faulty integration of signals into the existing representation of distance and direction, and incomplete remembering of the preceding path (Stangl, Kanitscheider, Riemer, Fiete, & Wolbers, 2020). Here the attentional system is vital, as it keeps the focus on external signals and ensures their processing on their receptive levels before integration on higher levels is possible. For constant accessibility, the home vector must be frequently updated and stored in the working memory, with higher involvement of the working memory leading to more accurate homing (Arnold et al., 2014). The integration of time is also crucial for the correct reproduction of a traveled distance. It has been shown that if attention and working memory resources are focused on other mental tasks, the ability to reproduce self-motion decreases significantly (Glasauer et al., 2007). An interference with attention systems or working memory processes would therefore increase errors and negatively affect path integration abilities.

Hence, stress, cognitive load, and other factors known to interfere with memory and attention are especially interesting in path integration tasks. Stress has been shown to negatively influence spatial abilities, as it seems to interfere with the retrieval process of spatial information (Richardson & VanderKaay Tomasulo, 2011). An experiment with virtual heights evoked a measurable physical and psychological stress reaction, as well as an increase in workload (Biedermann et al., 2017; Peterson et al., 2018). These virtual height environments also have a significant effect on participants' movement (Kugler et al., 2014). This shows that virtual environments can evoke physical stress reactions, an increase in cognitive load, and changes in movement when presenting heights. The resulting stress and cognitive load interfere with attention and memory systems, which are vital for path integration. Virtual reality was used in all of these experiments to display realistic and safe heights and has been shown to provide a useful framework for many navigational paradigms (Hardiess, Meilinger, & Mallot, 2015). The studies presented above were successful in showing that virtual heights trigger the same stress responses as real-world heights do, therefore also having a strong presence (Biedermann et al., 2017; Peterson et al., 2018).

As it might be more difficult to subject acrophobic participants to real-world heights, virtual reality provides a good solution. The use of VR technology for scientific studies has increased over the last years due to the realism and practicality of virtual environments. A virtual environment allows control of external factors, as it would not be possible in the real world. Participants can be immersed in the virtual environment through a head-mounted display (HMD) and use joysticks as well as body tracking devices to navigate through the environment. The use of a highly controllable environment, as well as precise motion tracking, provides optimal conditions for an experimental setup, especially regarding spatial cognition (Hardiess et al., 2015). To which extent a person feels situated in the virtual environment rather than the real world is described by the degree of presence. The presence is directly linked to the immersiveness of the VE. Immersion describes how well the environment allows the person to be absorbed in the virtual environment. This is mainly a technical aspect, regarding the interactivity and vividness of the environment (Hardiess et al., 2015). To ensure that the effect of virtual reality is sufficiently close to real-world experiences, presence and immersion should be considered.

Thus, the presented experiment utilizes a virtual environment to look at path integration mechanisms under the impairment of cognitive load. A path integration task under height-induced stress is used. The influence of cognitive load can be observed in the reproduction of a before walked distance in different environments. Therefore, the task consists of one given path in the encoding stage and the participants are asked to return to their point of origin in the reproduction stage. For a successful computation of ego motion, a textured ground and other optic flow cues are provided. Accordingly, a positive effect on path integration abilities should become apparent in conditions with landmark information in the form of random thin poles and palm trees, opposite conditions with only a textured ground. The presentation of landmarks and poles for optic flow is expected to decrease the distance error. To avoid learning and to see whether height influences the internal timeline, different distances are used. A study by Glasauer et al. (2007) found cognitive load to negatively impact the reproduction of traveled distances, and the general effect of height on increasing workload has been shown before (Biedermann et al., 2017; Peterson et al., 2018). Therefore, we expect that participants in a high height environment to obtain larger errors in the reproduced distance. We hypothesized that the condition with a high plank increases the errors in the reproduced direction and distance, represented in the homing and distance error.

The experienced presence in the environment is expected to become apparent in a difference in movement, namely that participants move slower and more insecurely in a high height condition. The subjective height impression should become clear through a height estimation given by participants during the experiment. Therefore, this experiment expects to show the influence of height and height-induced arousal on translation mechanisms of path integration, as well as the effectiveness of VR for path integration experiments. This could provide a basis for further experiments looking at the influence of height-induced arousal and the applicability of VR experiments for path integration mechanisms.

Methods

Participants

The experiment was carried out with eight participants aged between 22-25 years (mean age = 23.37, standard deviation (*SD)* = 1.30). All participants had normal or corrected vision. The participants were students of the University of Tübingen and did not know the experimental hypothesis. They were given informed consent.

Apparatus

The experiment was presented in a virtual reality environment via a head mounted display, namely the HTC Vive Pro (HTC Corporation, 2011-2020). The HMD has a resolution of 1440 x 1600 pixels per eye, leading to 2880 x 1600 pixels (615 PPI) together, with a refresh rate of 90 Hz and a 110° field of view. The HTC base stations allow for a 5m x 5m tracking area (HTC Corporation, 2011-2020). Data was extracted through HTC Vive trackers which were attached to the participants' feet. The virtual reality environment and experimental setup were created with the game engine Unity version 2019.3.3f1 (Unity Technologies, 2020), using freely available assets for the textures and landmark objects. The SteamVR application program interface (API) and the SteamVR Unity Plugin version 2.5 (Valve Corporation, 2020) were used to calibrate the HMD and controller, present the environment, and save data. All programs ran on a PC with Windows 10 Enterprise (64 bit), an AMD Athlon 3000G processor with Radeon Vega Graphics 3.50 GHz, and 7.94 GB RAM.

Stimuli

In the virtual environment, participants were set in a desert, under a blue sky. Participants walked on a plank, with stairs behind them and a return platform in front, both consisting of a stone-like material. In the two height conditions, the plank was either low or higher above the ground. The stairs, the return platform, and return plank were adjusted accordingly. The length of the walking plank towards the platform was varied between two lengths. Measurement units in Unity should correspond to real-world units, meaning one virtual unit equals one meter. The implementation, however, seems to be more ambiguous and should not be fully relied upon. For a better understanding of the virtual units and their translation to real-world measurements, the walked virtual and real distances were compared. The virtual distance in different scene conditions was calculated by subtracting the average z-coordinates at the scenes and stages, namely the return platform from the start platform. The virtual distance reaches a mean of 2.66 Unity units for the short distance and a mean of 3.547 Unity units for the long distance. The actual distance in meters was measured in the real world, at the corresponding points, with a 2.90 meters actual walking distance for the short condition and a 3.60 m walking distance for the long condition. The comparison shows that the virtual units do not match meters exactly, which might be due to unprecise measuring or internal differences in Unity. For better understanding, in the ongoing text, centimeters and meters will be used instead of Unity units.

In the landmark condition, randomly placed landmarks in the form of palm trees and thin grey poles were presented. There were three types of palm trees set on the desert ground, 200 overall, with random rotations to avoid uniformity. The poles were randomly placed on the ground and in the air, with 300 poles appearing in total. The participants' feet and the controller were represented by virtual tracker models, which are included in the SteamVR Unity Plugin. The controller featured a blue beam and a yellow ball if objects could be clicked. Buttons were white with black letters and appeared on the participants' field of view at a certain distance. The buttons moved with the participants' head movement to avoid giving directional information. Shadows were rendered naturally for trees, the walking setup, and the tracker models.

Procedure

Participants were tested in a single session of about 30 minutes (mean minutes = 26.34, *SD* = 4.52). First, they were given informed consent and instructions regarding the procedure. Participants were able to acclimate to the virtual environment during a familiarization trial, set in the experiments desert with a circular walking area. The controller function was explained, and participants were supported in their first steps through the environment, to ensure stability. After the participants felt comfortable enough in their movement through the VE, the experiment started. Participants were reminded of their task and not to use any specific tactics, like counting their steps. One test trial was conducted to verify that the participant understood the procedure. Participants started on the top step of the stairs (Figure 4), where a red dot indicated the position on which they should locate their feet, as shown through the tracker model (Figure 5).

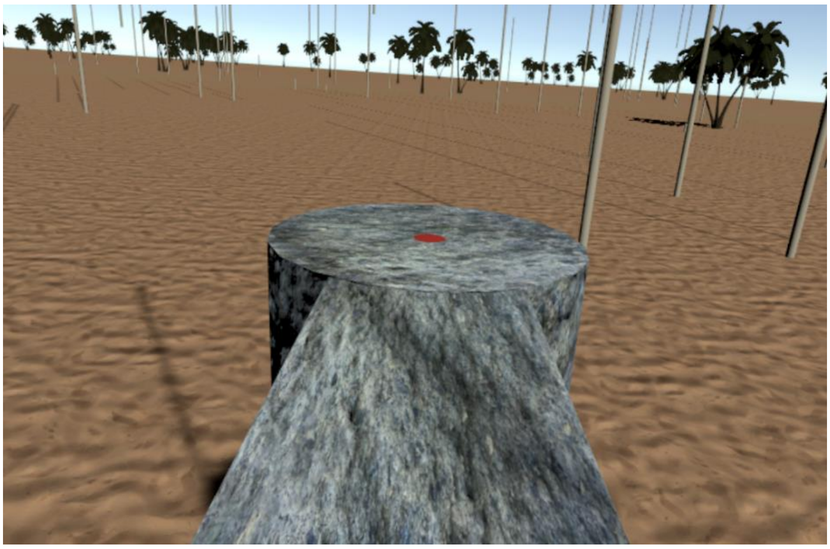

Figure 4: Participants´ point of view at the beginning of a trial in an environment with landmark information.

Figure 5: Position of feet as shown by the tracker model above the red dot indicating the start position.

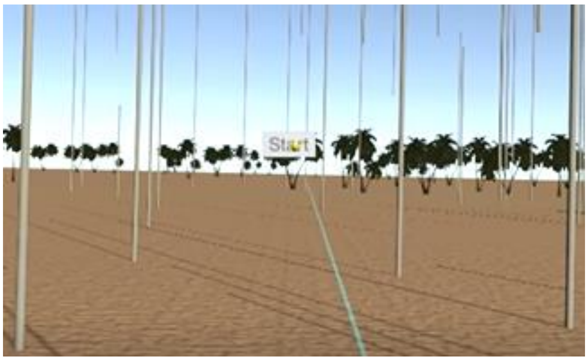

Figure 6: Start button and controller beam in an environment with landmark information.

Looking upward, they could then click on a start button (Figure 5) and walk towards the round platform at the end of the walking plank. As soon as they reached the platform, the plank and stairs disappeared, as well as the landmarks in the landmark condition. There, participants placed their feet on the red dot in the middle of the platform and turned until they believed to face their point of origin. The turning direction was not predefined. Facing their believed point of origin, participants could click on a return button, which appeared in the center of their current viewing direction (Figure 7). On clicking, an endless return path appeared in the direction the participant was facing, as well as an end button and newly randomized landmarks if applicable (Figure 8). Then participants walked along the path until they believed themselves to be at the point of origin and clicked on the end button. This action activated the next trial.

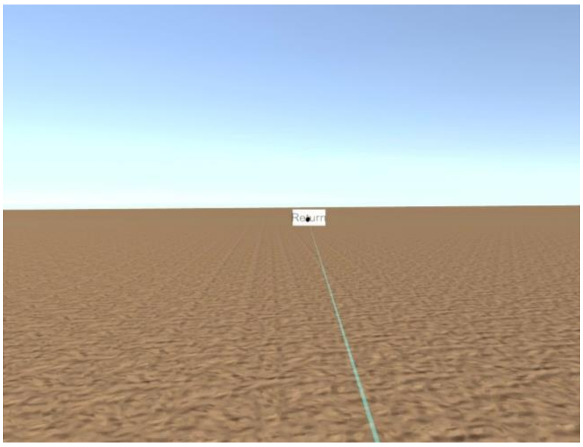

Figure 7: Participant choosing the return way by clicking the return button.

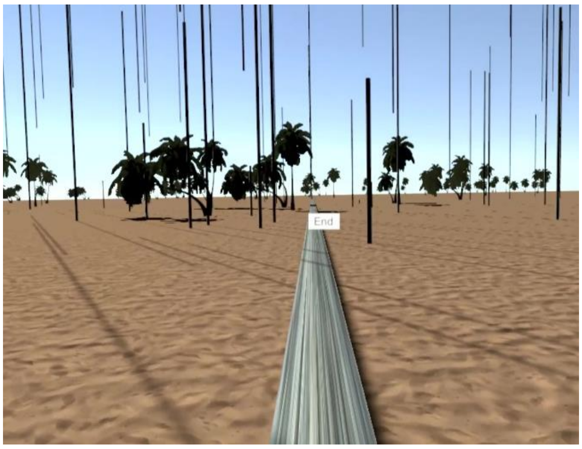

Figure 8: The endless return way in the direction the participant chose, with the end button to click when choosing the end point.

The start platform always appeared at the same place, and depending on what the participant felt comfortable with, they were either led back to the starting point with closed eyes or walked back themselves. At the beginning and towards the end, participants were asked to estimate the height of the walking plank. In the middle they could choose to take a short break on a chair or continue without. After completing the trials, the participants were asked to fill out a questionnaire regarding their demographic data and the experiment. In the end, an explanation of the experimental hypothesis was provided.

Experimental design

The main part of the experiment contained 40 trials and was conducted as a 2x2x2 within participants design with pseudo randomization of the different trial conditions, and each condition occurring five times. The height and length of the walking plank were manipulated as well as the landmark information. The height was set to a high or low condition. In the high condition, the y-value of the feet was 4.5 Unity units, and in the low condition, it was 1 Unity unit. The distance was either long or short, as described before. Landmark information was either provided, namely in form of randomly generated palm trees and poles, or not. As dependent variables, several parameters were measured: the positional data of both feet and the HMD, time, height estimation, and questionnaire data. It should be noted that due to an error in the experiment code, the condition with low height, no landmarks, and a short distance, was only presented four times instead of five times like the other conditions.

Results

Data processing

During the experiment, positional data was extracted from the HTC Vive tracker and the HMD. Positional data was saved every second, and when participants stopped and clicked between the different stages in each trial, the exact time and position were saved. The positional data consists of x, y, z values, and shows the movement of the participants head and feet in the allocated space (Figure 9). The location of the walking plank in the VE means that participants started out on a more negative z-value, which decreased during walking. On the x-axis, participants were placed on zero, meaning a negative or positive change in value coincides with walking more to the left or right. The y-value describes the vertical movement and is dependent on the height condition. The positional data of the tracker at the participants' feet was averaged between both feet. The questionnaire data and height estimations were recorded on paper. All data was processed with Excel (Microsoft Corporation, 2020) and RStudio (RStudio Team, 2020). To analyze the influence of the different conditions on the ability to reproduce the traveled distance, we compute the distance error. Another measure is the homing error, which takes the sideways deviation into account as well. See Figure 10 for a visualization of both errors. The error measures were compared using an analysis of variance (ANOVA) with assumed sphericity. A significance level of $p < .05$ was used for all statistical analyses. All means are given with the standard deviation (*SD*).

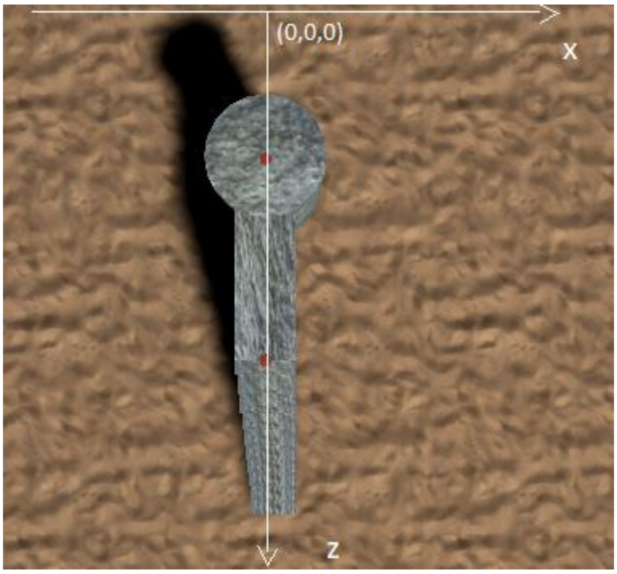

Figure 9: The walking plank as represented in the coordinates of the VE.

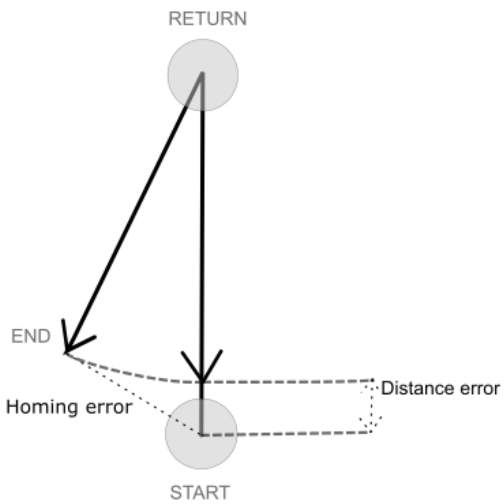

Figure 10: Depiction of distance and homing error with formulas.

Distance error

The distance error is the difference between the absolute walked outward way and return way and was calculated as follows: $\sqrt{(x_{end} - x_{start})^2 + (z_{end} - z_{start})^2}$ This can show by how much participants over- or underestimated the distance in the encoding stage. The ANOVA presents a main effect for distance ($F(1,7) = 28.09$, $p = .001$, $\eta^2 = .80$) on distance error, as depicted in Figure 11. No other effects are significant (height $F(1,7) = 1.95$, $p = .205$, $\eta^2 = .22$). The ANOVA yields values slightly above our significance level for the factor landmarks on low height and long distance, but the effect size is relatively large ($F(1,7) = 5.46$, $p = .052$, $\eta^2 = .44$). Looking further at the distance error, we see that participants had a general undershoot in the long distance condition (mean distance error = -0.327 m) and an overshoot in the short distance condition (mean distance error = 0.142 m). This means that participants underestimated the return distance after walking a long distance by a mean of 12.24% (preset distance = 3.547 m, mean reproduced distance = 3.221 m, mean absolute distance error = 0.434 m, *SD* = 0.312) of the actual walking distance. And they overestimated the return distance if they walked a short distance before by a mean of 9.89% (preset distance = 2.66 m, mean reproduced distance = 2.8 m, mean absolute distance error = 0.263 m, *SD* = 0.225). Without taking the different distances into account, the mean reproduced distance was 3.016 m (*SD* = 0.508), and the mean preset distance is 3.104 m. Looking at the variance of distance errors for the high and low height condition shows no significant difference ($t = -0.343$, $df = 13.979$, $p = .737$), see lines in Figure 11.

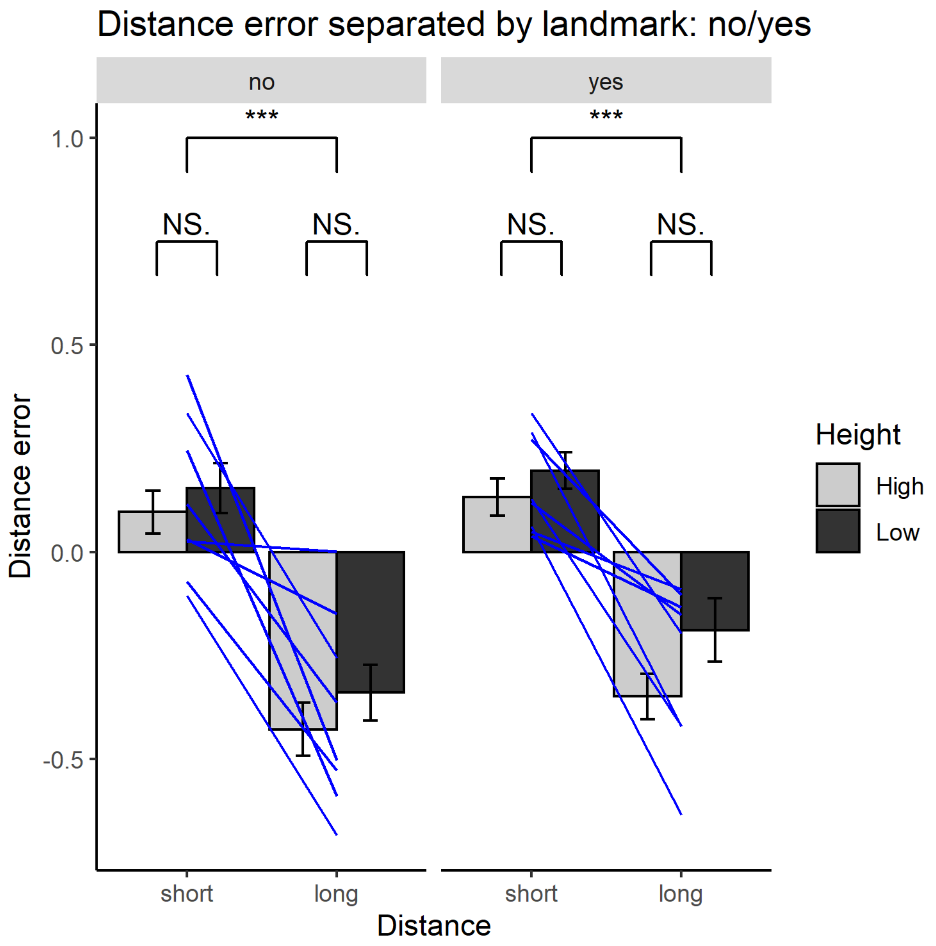

Figure 11: Distance error by landmark, distance, and height with significances. Three asterisks indicate p < .001. Not significant (NS.) means p > .05. The blue lines show participants individual errors. Error bars show the standard error of mean (SEM).

Homing error

The homing error displays how much the start and end point lay apart and was calculated as follows:

$$\sqrt{(x_{start} - x_{return})^2 + (z_{start} - z_{return})^2} - \sqrt{(x_{return} - x_{end})^2 + (z_{return} - z_{end})^2}$$

This takes the error of the direction as well as the distance error into account. The ANOVA shows main effects for distance (*F(1,7) = 10.91, p = .013*). No other effects are significant. The individual homing errors, depicted in Figure 12 as blue lines, show a greater variance than in the distance error, with even some reverse tendencies. The homing error takes the angle error into account, meaning the error in the direction participants chose as a return direction. Since participants could deviate to both sides, the absolute values were used. These angle errors were altogether very small (mean = 2.28°, *SD* = 3.45°), with no significant effects visible in an ANOVA. The maximal angle error (max = 31.474°) occurred where the maximal homing error was made (max = 1.846 m).

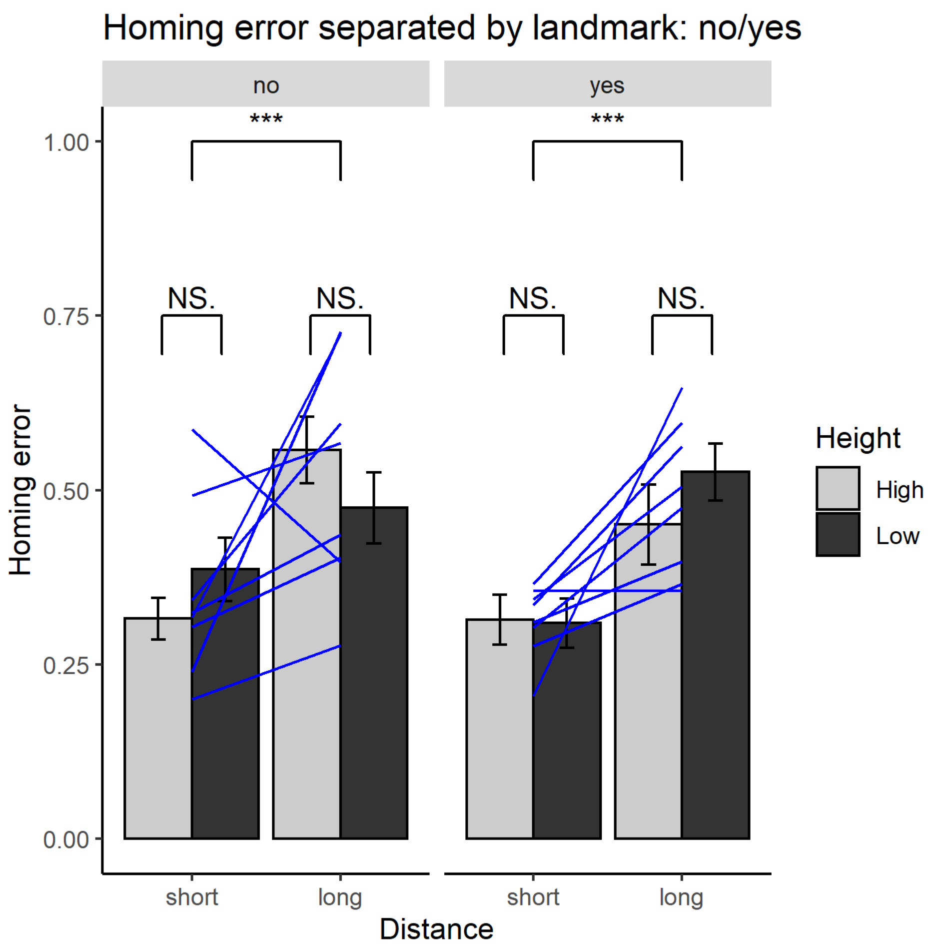

Figure 12: Homing error by landmark, distance, and height with significances. Three asterisks indicate p < .001. Not significant (NS.) means p > .05. The blue lines show participants individual errors. Error bars are the standard error of mean (SEM).

Positional data

Looking at the positional data over time can illustrate the participants' walking behavior. Because the positional data could only be saved every second, the separation of data into individual steps was unclear and likely to miss steps. It was therefore not possible to calculate step length reliably. Looking at the mean positions of the trackers for a specific axis reveals, that on average, the participants' chosen end point was shifted on the x-axis by -.103 m from the start point. This means participants made rotational errors more towards their right side, across all conditions.

Examining the movement data of a single participant can show how insecure a participant walked in a specific condition or trial. In Figure 13-16, we see the exemplary walking trajectories of the first participant for different conditions. The light grey crosses show the exact position of each tracker and the bold data points represent the mean between both feet tracker. The mean function is plotted in a dotted line. The opaque purple dots depict the start and return platform and are not to scale. A wider spread suggests higher insecurity while walking, and data points that are closer to each other indicate longer times spend at that stage. The mean function only indicates the approximate walking trajectory. Exact data points for each tracker are depicted in light grey, and a wider range can show a more insecure gait. The trial depicted in Figure 13, shows a condition with low height, no landmarks, and a short distance. There the first participant had their largest distance error with an overshoot of 1.073 m. We can see that there are more data points towards the end, indicating that the participant walked slower. Comparing the individual tracker positions to the mean between both tracker positions can show us that in this trial, tracker two deviated on the x-axis by an average of .019 m (*SD* = .078) from the mean. Altogether there are 17 data points, meaning the trial took 17 seconds to complete. In Figure 14, we can see the walking trajectory of participant one with the biggest undershoot distance error of -0.775 m. In Figure 16 the walking trajectory for a high height condition of participant one is depicted: we can again see more data points in either direction and a wider spread in individual tracker points.

The exact position of the HMD was observed to check for swaying in the participants' gait, see Figure 15. Contrasting the head movement with the walking trajectory (Figure 15 and Figure 13) shows a similar movement, with a slightly wider range of data points for the HMD on the x-axis. This can show a bigger range of motion for the head, with participants maybe tilting their heads towards one side.

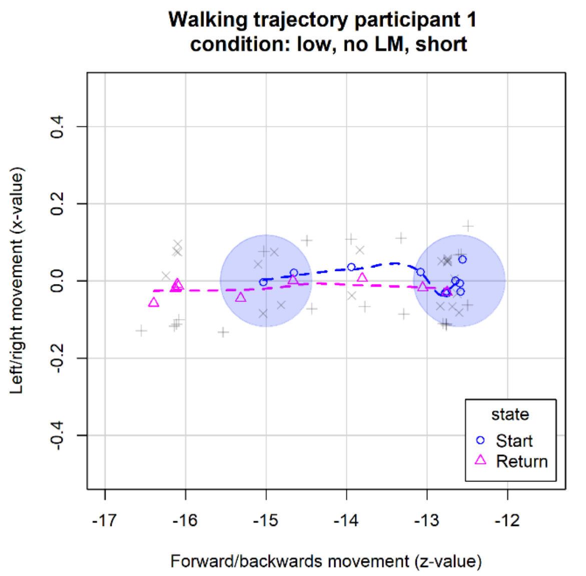

Figure 13: Walking trajectory of the first participant with the largest overshoot distance error. The environment had low heights, no landmarks, and a short distance.

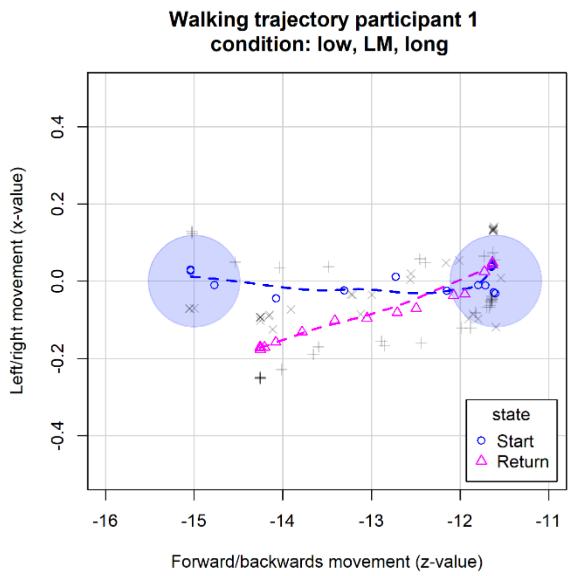

Figure 14: Walking trajectory of the first participant with the largest undershoot distance error. The environment had low heights, landmarks, and a long distance.

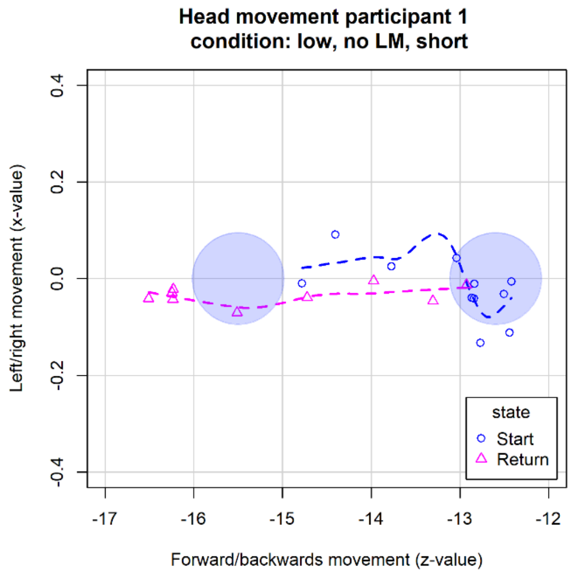

Figure 15: Head movement of the first participant with the largest overshoot distance error. The environment had low heights, no landmarks, and a short distance.

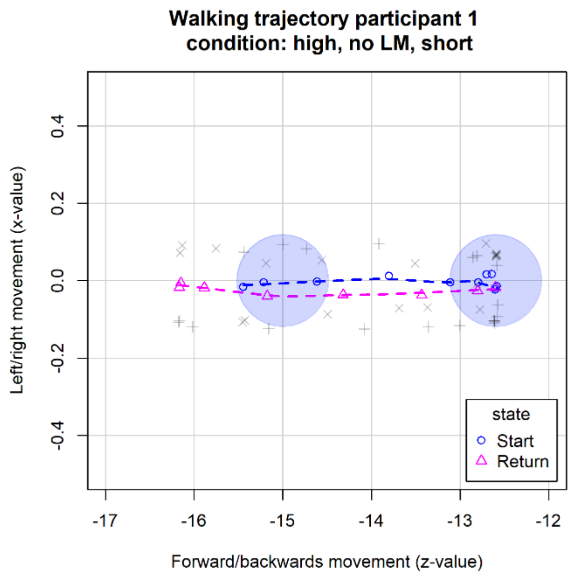

Figure 16: Walking trajectory of the first participant in a condition with high heights, no landmarks and a short distance.

Time

The exact time of each participants' click was recorded, and therefore the intermediate time periods can be used to describe how long the different stages in each condition took. The time difference per trial was calculated by subtracting the time at the start point from the end point. Analyzing the time differences with an ANOVA for the different conditions, we see a main effect for height on time ($F(1,7) = 15.94$, $p = .005$) and a main effect of distance on time ($F(1,7) = 13.37$, $p = .008$), we also see a slight interaction between height and landmarks ($F(1,7) = 6.04$, $p = .044$). See Figure 17 for main effects. There is also an interaction between height and distance, explaining the main effect of distance (Figure 18). For short distances, participants took significantly less time if the height was low. The interaction between height and landmarks describes a negative effect of low height in time if no landmarks are provided (Figure 19). Participants' overall mean time was 22.7 seconds per trial with a *SD* = 4.116. There are no significant differences in the time participants spent on the return platform before choosing the return direction (mean = 8.271 s, *SD* = 2.889). In the time participants took from the return platform until choosing the end point, we can see some small differences for height (mean time high = 10.174 s, *SD* high = 4.08, mean time low = 9.415 s, *SD* low = 3.386, difference between high and low = .76 s). These are not significantly different but show some tendencies and larger differences than the other factors (difference between mean landmark conditions = .31 s, difference between mean distance condition = .34 s). The mean velocity from the start to the return platform was 0.747 m/s and from the return platform to the end point 0.309 m/s. For the high height conditions, the velocity was reduced to 0.695 m/s (start to return) and 0.296 m/s (return to end).

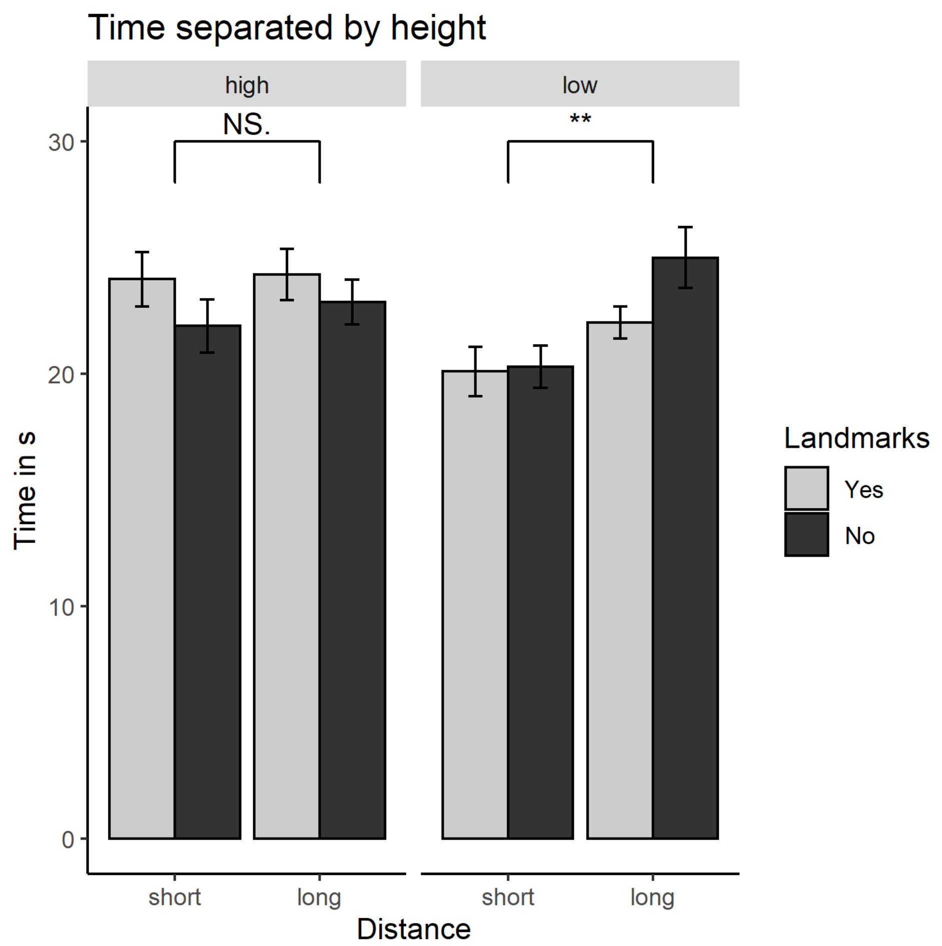

Figure 17: Mean time of trials by height, distance, and landmark. A significance level of two asterisks represents p = .001 and non-significances (NS.) equal p > .05. Error bars are given in SEM.

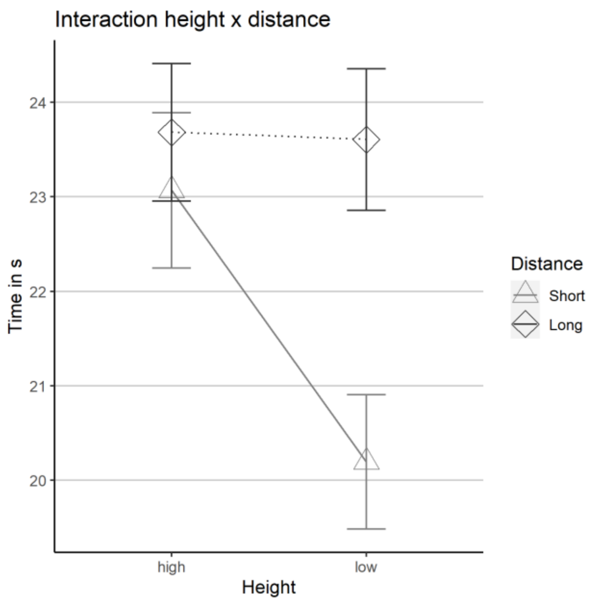

Figure 18: Interaction of height and distance.

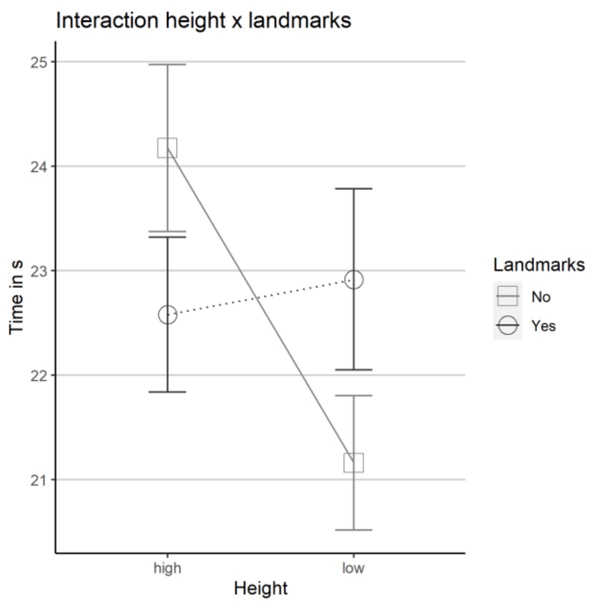

Figure 19: Interaction of height and landmarks.

Height estimation

During the experiment, participants were asked to estimate the height of the walking plank four times: in the first trials, in high and low conditions, and towards the last trials for high and low. Participants clearly differentiated high from low, as can be seen in Figure 20 with significant differences between high and low on both estimation times (start: $t = 3.576$, $df = 8.86$, $p = .006$; end: $t = 3.389$, $df = 9.09$, $p = .008$). Furthermore the height impression did not change much from the start to the end of the experiment, as can be seen in the mean height estimations in Figure 20: there is no significant difference between the start and end estimation for both heights (high: $t = 0.408$, $df = 13.842$, $p = .689$; low: $t = 0.015$, $df = 13.97$, $p = .988$).

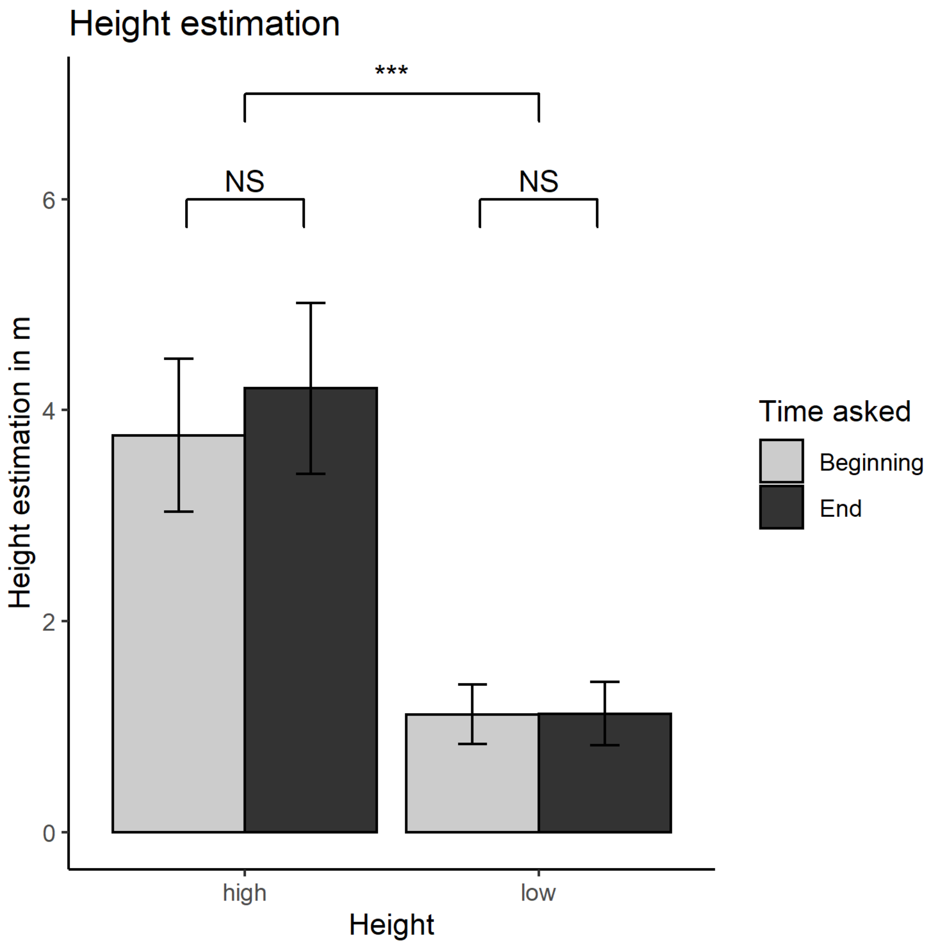

Figure 20: Height estimation by height and time participants were asked. Three asterisks indicate p > .001 and no significanses (NS.) equal p > .05. Error bars are given as SEM.

Questionnaire data

After the experiment was completed, participants were asked to fill out a short questionnaire with questions regarding the virtual environment and their experience during the experiment. See Figure 21 for depiction of all answers. Participant one reported that they have a fear of heights. Two participants wanted help returning to the start platform throughout the experiment. All participants felt unsteady or some amount of vertigo at the beginning but became used to it and only one participant felt uncomfortable. No participant, however, felt too uncomfortable and wanted to stop the experiment. Two participants noted that it was more straining to walk in the virtual environment and took the opportunity to have a short break. Seven participants stated that the height and environment felt very realistic and affected them in some way. Only the thin poles and return path material were named as less realistic. Five participants said that they used a conscious or unconscious tactic, for example turning in a swift motion to keep the right direction or using the symmetry of the desert sand pattern as a guide. Most reported to have used their walking rhythm as a largely unconscious indicator of distance and found it hard not to do so when becoming aware of this. Some technical glitches were reported. For example, a palm tree appeared close to the walking plank and obscured the walkway with its shadow, which irritated the participants.

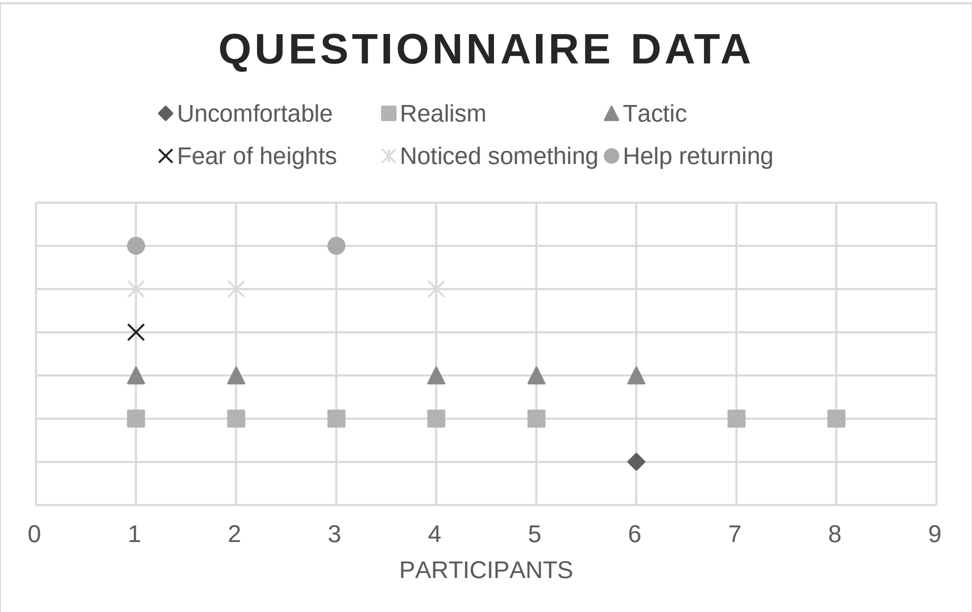

Figure 21: Participants answers to questionnaire questions in yes/no format.

Discussion

For a better understanding of path integration abilities, this experiment investigated the possible error source of cognitive load. The environment featured high height stimuli as a stress-inducing factor, to impair attention and memory resources. By utilizing this method, we expected a high height environment to increase path integration errors. However, the results could not confirm our hypothesis, as the expected main effects of height on reproduced distances and directions were not found. There was a main effect of distance on distance error, where the long walking plank led to a general undershoot, and the short plank to an overshoot in the reproduced distance. The presentation of landmarks had no significant effect on distance or homing error. Even so, landmark information interacted with height in the time participants took for each trial. There was also an interaction of height and distance in time. Participants' movement data could illustrate the distance errors and insecurities in walking behavior for individual trials. The height estimation shows a difference between estimates in high and low height conditions and no significant decrease from the beginning to the end of the experiment. Additionally, the questionnaire data provided further descriptive insight regarding the participants' experience and the immersive quality of the VE.

Our hypothesis was that the height would draw cognitive resources away from path integration, leading to an increase in errors for high height environments. Errors can occur in the processing of external and internal cues, in the integration of such cues, and in the remembering of before traveled paths. However, the lack of a main effect of height on distance and homing error indicates that height does not impair path integration abilities on any of these stages. Additionally, there were no differences in the variance of distance errors for the two height conditions, which indicates stable effects. If enough resources were drawn away from the main task during high height conditions to lead to stronger errors, an effect of height on reproduced distance would probably become visible. The reproduced distance, however, was only influenced by the preset distance of the walking plank during the encoding state. The main effect of the manipulated distance on the distance and homing error presents itself in an undershoot for the long distance conditions and an overshoot for the short distance condition. The respective errors amount to 10-12% of the traveled distances. With stable distance errors of about 10% in each direction, the mean reproduced distance reflects the mean preset distance almost exactly. This means, that the distance errors can also be looked at as deviations from a mean distance towards the actual distances. The preset distances differ by 0.89 m from each other. Therefore, if the deviation from the mean distance would have been doubled, the preset distances would have been reproduced correctly. The individual errors in the distance and homing error reflect the direction of the overall effect, with only one reverse effect in the homing error. In the environment with landmark information, we expected a positive effect on the ability to reproduce the path, as spatial systems use external cues to update and correct internal distance representations. However, the results present no significant effect of landmark information on distance and homing error. The individual homing errors varied more in the condition without landmark information, indicating a less stable integration of direction. In the distance error, the variance seems similar in both landmark conditions, indicating that landmark information has less influence on reproduced distances. The ANOVA shows a tendency of landmark information to influence the distance error for long distances and low heights, as we can see in the respective effect sizes. This tendency is not present in the homing error, where the overall variance was wider, especially for the conditions without landmark information. This means that participants' path integration abilities did not significantly increase when additional visual optic flow and distance cues were provided. Path integration abilities were also not impaired in the high height environment. Only the preset distance influenced the errors in the reproduced distance. The errors participants made are clearly reflected in the individual walking trajectories and general positional data.

The individual data of both feet trackers and the HMD was saved each second and can display participants walking trajectories. For a rough comparison of positional data, we can look at the mean tracker positions in each condition. Overall, these mainly reflect the before calculated errors. But the mean tracker position on the x-axis at the end point shows a clear tendency of participants to end more often towards the right. The exact positional data has been computed for individual walking trajectory plots, as exemplary visualizations for the calculated errors. Especially the single data points and the return path can demonstrate the distance errors and even some walking behavior. The individual distance and homing error values are visible in the walking trajectory plots of participant one and can visually confirm the calculated over- and underestimation of distances. Even the small angle errors can be detected. The plots can show that in the trial where their distance error was the highest, participant one had an accumulation of data points towards the end. As positional data was saved every second, several data points translate to several seconds spent at this position. An accumulation of data points could indicate higher insecurity in choosing the end point, which then led to the higher error. In the walking plot for a trial with the smallest distance error, we can see no accumulation towards the end, which we interpreted as more confident walking and choosing of the end point. The trackers' single positions can be compared to the average tracker position each second and thus roughly show how wide the data points were spread, therefore serving as an indicator for gait. Single tracker positions, which were further apart, could illustrate that participants preferred a wider stance for stability. Individual data points also slightly reflect velocity changes and insecurities. The data from the HMD coincides with the tracker movement, showing a wider range of motion as participants looked around. The positional data includes time as another indicator of walking behavior, providing further information regarding participants' insecurity in specific conditions.

The time participants took for each trial can give indicators regarding the participants' path integration processes. We also looked at the velocity as an important cue for walking behavior. There is no difference in the time participants spent on the return platform before choosing the return direction. This could indicate that here, height did not interfere with the retrieval of the encoded direction. The mean velocity was higher during the encoding stage and lower during the reproduction stage, where participants chose their end point. In high height conditions the velocity was slightly below the average for both stages, indicating some influence of height on walking speed. Analyzing the time across all conditions reveals main effects of height and distance and an interaction between height and landmarks, as well as between height and distance. The interaction between height and landmarks describes a negative effect of low height on time if no landmarks are available. This means that in no landmark environments, it took participants longer to complete a trial when they walked on a high plank than on a low plank. For environments with landmark information, the time was about the same for both heights. The interaction between height and distance shows a negative effect of low height on time if the distance is short. Thereafter, participants took more time to complete a trial in short distance conditions if the plank was high. On average participants needed more time to complete a trial in the long distance condition than in the short distance condition, as would be expected. Altogether, participants seem affected in their walking time by height, significantly so in combination with other factors. This can only be caused by a realistic height depiction.

Any discussion of effects in VR experiments has to be accompanied by the questions regarding the immersive qualities of the VE and the presence participants experienced. If the environment did not evoke presence, it can be hard to argue for the transfer of any effects to real-world situations. One observable indicator for presence is a strong reaction to stimuli or features in the VE. Regarding this, we looked at whether participants wanted help to return to the start platform as well as participants' reports on their experience of height. Across the whole experiment, participants were consistent in their estimate of the presented heights. The estimated height reflects the height given in Unity units. This demonstrates that the impression of the presented height stimuli was as expected and did not change over the course of the experiment. Six participants were able to walk back by themselves to the start point after a few trials, and two wanted to be led back with closed eyes, so as not to experience being virtually suspended in mid-air. This again provides evidence for a stable height impression. In the questionnaire, all participants stated that they experienced the environment to be realistic, with the palm trees, the desert, and the rendering of the shadows being named as very lifelike. The only feature taking away from the realism were the thin floating poles and the rendered texture of the return path. One participant reported to have noticed a symmetry in the ground texture. The rendering of the ground material led to slightly visible straight lines in the ground when looking towards the horizon. In general, participants responded very well to the VE, with no strong reactions of discomfort.

Altogether, this experiment provides a wide range of measures regarding path integration abilities and walking behavior. Errors in path integration are reflected in distance and homing errors and walking behavior can be derived from positional data and time. Further insight is given by height estimation and questionnaire data. The main effects of distance and homing error show that the height was not sufficient in affecting path integration abilities. This can probably be attributed to the height stimuli not being strong enough. A more pronounced height impression could elicit the desired effect. A height condition with the elevation being several meters above ground and only a thin balance beam was used in other studies (Peterson et al., 2018). One experiment presented water below open walking planks (Biedermann et al., 2017). To give additional sensory feedback, participants in some experiments walked on a real wooden balance beam and a falling simulation was presented when they stepped off it to establish the height as real (Peterson et al., 2018). To validate height as a stress inducing factor and as the cause of increased cognitive load, additional measures can be taken. The cognitive load during an experiment was measured by having participants react to other unrelated stimuli, such as an auditory cue (Peterson et al., 2018). Higher reaction times indicate an increase in cognitive load. Stress reactions in previous experiments were often physically measured through heart rate, blood pressure, and cortisol levels in saliva (Biedermann et al., 2017; Peterson et al., 2018). These measures provide evidence for a physical reaction being caused by higher heights in comparison to the lower control conditions and can thus support the claim that height affects working memory and attention. The height presented in our experiment was probably not strong enough to elicit this effect and influence the reproduced distance.

The reproduced distance was only influenced by the manipulation of distance, where we presented a long and short path during the encoding stage. The main effect of distance on both distance and homing error can be explained as participants storing one mean traveled distance over time in their working memory. In their experiment, Glasauer et al. (2007) explained the errors in distance reproduction as being caused by a distortion in the internal timeline through cognitive load. According to Glasauer et al. (2007) the traveled distance is continuously calculated through passed time, velocity, or step length. If attention is focused on other tasks during the encoding stage, the authors found that reproduced distances are shortened without affecting the velocity. Cognitive load during the reproduction stage is seen to disturb the ongoing comparison of the remembered traveled distance and the reproduced distance. Since our results show a consistent error in distances, independent from the cognitive load inducing factors, we cannot explain our effects accordingly. We also had a consistent height condition during the encoding and reproduction stages, leading to no difference in impairment between stages. Altogether, the cognitive load seems to have been too weak to impair the path integration abilities in any stage of both height conditions. The effect of distance on the errors can thus be due to a false comparison of the before traveled distance to the distance to be reproduced, or a false remembering of the before traveled distance. Since we used new randomly generated landmark information in each encoding and reproduction stage, there were no external cues that could be used to compare encoded to reproduced distances. The overall tendency towards the mean distance can be interpreted as participants storing one main distance in their working memory, which they only slightly corrected with information from the immediately before walked distance. This is supported by the fact that we have distance errors in the form of respective over- and underestimations for short and long distances, but still a significant difference between the reproduced distances of the two conditions. If participants did not adapt their distance, the reproduced distances would be the same for both distance conditions. The adaptations were in the right direction, as the over- and undershoot errors represent, regressing towards the mean distance. The errors can thus be attributed to a false remembrance of the before traveled distance as one mean distance and an insufficient correction. However, the correction reflects the right direction, meaning some integration of traveled distance occurred. The only available source for correcting the walked distance are bodily cues: the internal timeline, step length, and velocity. Counting steps was discouraged, but afterwards participants reported to have used their walking rhythm as an indicator of distances. This most likely allowed participants to correct their reproduced distance according to the previously walked distance, which they experienced as being either shorter or longer than the remembered overall distance. Without the use of actual step counting or landmarks for spatial updating, the reproduction was prone to error accumulation. The traveled distance was most likely computed through internal ego-motion cues. Supporting the claim that participants mostly used bodily cues to reproduce the traveled distance is the lack of a main effect of landmark information.

The randomly placed landmark information was designed to mainly function as distance and optic flow cues, as it disappeared when participants reached the return platform. Newly generated landmarks appeared for the return way. Landmark information had no significant effect but exhibited some interesting tendencies. The lack of a stronger effect could be because the desert texture and walking plank itself provided enough ego-motion information, or because the palm trees and poles were not used as external motion cues. Both would lead to no significant differences in landmark versus no landmark environments. Other experiments found eye movement to be reduced for acrophobic participants in high height environments, with a focus on the path immediately in front of them (Kugler et al., 2014). It might be plausible that in the presented experiment, participants were more focused on the plank before them than on their surroundings, not computing the additional optic flow cues. The participants most likely used only the desert texture and walking plank as optic flow cues to indicate distance. Further distance cues were probably derived from internal information regarding the ego-motion. If the walking plank were longer, it would be more necessary for participants to rely on external cues for distance information. For the relative short paths, no external updating information was needed, as path integration with only bodily cues was sufficient.

During path integration, internal and external distance cues are constantly combined and updated. Therefore, errors can occur in several stages. A recent study was able to subdivide path integration errors into different categories (Stangl et al., 2020). In the conducted experiment, young and old adults performed a complex path integration task with several stops. The authors developed an error model as a continuous updating system, taking velocity estimates as input to attribute errors to their sources and make predictions. Possible error categories were the false remembering of movement before, noise in the incremental updates, and noisy integration. Their results show that errors in path integration are mainly caused by the accumulating noise from the velocity input to the path integration system. Therefore, the biggest part of path integration errors is attributed to unbiased noise. We would expect our errors to be of the same nature, due to no main effect of landmarks. This attributes all errors to internal continuous updating systems, where unbiased noise impairs path integration abilities. Nevertheless, studies regarding the path integration strategies assume that for short straight paths, a configural strategy is most likely to be used (Wiener et al., 2011). In the configural strategy, path segments are remembered, and the home vector is only computed at the reproduction stage. A continuous updating strategy, with the ongoing integration of walked distance and directional information, is only used for more complex and curved paths (Wiener et al., 2011). Considering these findings, we cannot differentiate between path integration and a simple remembrance and comparison of distances in the experiments task. Since the experiment we conducted only featured a simple path to be reproduced it may be possible that a strategy more resembling the configural strategy was used. The effect of distance on distance errors could reflect this as well: under- and overestimations can be caused by a faulty comparison of encoded path segments to the reproduced distances. This also does not allow us to conclusively match our errors to a specific path integration source, as path integration error models assume continuous updating.

The errors in the reproduced path can be further illustrated by the extracted positional data. The feet tracker data and HMD data were used to compute individual walking trajectories, mean positions, and walking speed. The individual walking trajectories reflect higher insecurity in walking paths with distinct errors, as the accumulation of data points towards the end with a wider range demonstrates. The occurrence of more data points at a certain stage indicates that the participant walked slower, and a less straight walking trajectory indicates instability while walking. Such behavior was observed through the positional data in trials with larger errors, leading to the interpretation that larger errors coincided with participants walking more insecurely. The effect of distance on the errors can be found in this behavior: participants tried to correct their reproduced distance by remembering the immediately before walked distance. The comparison of the encoded distance to the currently reproduced distance leads to a longer time spent before deciding on an end point. A more confident walking behavior was observed for walking trajectories with small distance errors, through fewer data points accumulating before the chosen end point. The data from the HMD reflects the same pattern as the feet tracker data, with a slightly wider range of data points, indicating that participants possibly tilted their heads. Considering that the HMD cables had to be held by another person during the experiment, this could purely be influenced by the presence of the other person or the HMD itself. Recent studies found the head movement to be uncorrelated with path integration abilities altogether (Stangl et al., 2020). Therefore, it can be questioned if this measure should be included in future experiments. Looking at the mean tracker position, we found that participants overall ended more on their right side. The participants' general deflection towards the right might have been subconsciously influenced by the person walking next to them while holding the cables. This might have had a general effect on participants' movement and should therefore be kept in mind. The observed movement could however, as noted above, reflect insecure walking behavior through longer time spent before choosing an end point, especially in trials with larger errors.

Other measures of walking behavior are the overall velocity and the velocity for each path. One participant stated after the experiment that they walked fast because they felt unsteady, showing that not only slow walking can be an indicator of insecurity. However, generally, slow walking is associated with participants feeling more insecure (Kugler et al., 2014). The participants' velocity while walking the path from the start to the return platform was higher than the velocity from the return platform to the end, as participants were likely more confident in walking towards the given platform and more unsure about choosing the end point themselves. In the high height conditions, participants walked slower than the average velocity for both ways. This can show us that, on average, participants were affected by the height in their walking speed in equal measure during the encoding and reproduction stage. A decreased velocity can indicate less confidence and more cautious walking behavior, which would be expected for real heights as well. More cautious walking behavior for certain conditions can also be indicated by the time taken for each trial.

Time can illustrate that height affected participants' walking behavior in conjunction with other factors. We can see some effects of height on participants' behavior as the velocity decreased below the overall average in high height conditions during the encoding and reproduction phase. In combination with landmarks and short distances, high heights led to slower walking, which indicates higher levels of insecurity. That participants took longer with high height in landmark sparse surroundings might be because the lack of external distance information led to a more unstable computation of distance. Without external updating information, only bodily cues could be used. This seems to result in more insecurity in high height conditions, which can indicate that less attentional resources were available. More mental resources must then be focused on body cues, and the ensuing insecurity prolongs the walking time. The shorter distance took participants longer in high height conditions due to more careful walking behavior. This indicates that height had a bigger impact if the walking plank was shorter, causing the participants to take roughly as much time as they did for long distances. The stronger effect of the height conditions in the short distance condition could be due to a change in velocity. For the longer path, participants might have started out more cautiously in the high height condition but then gained confidence and increased their velocity, leading the overall trial time to average out to about the same time as for low heights. The time difference becomes especially apparent in the very short amount of time it took participants to walk the short path at a low elevation. For the short path at a low height, no processing time was needed, as neither the path nor height imposed any effort on walking. The height could have made it necessary to take more time even for the short path, as participants were more careful in their walking behavior. In the interactions, we can clearly see that height has some of the expected effect on participants' behavior. This is only possible if the given height stimuli are experienced as real elevations.

Participants were asked to give their estimate of the presented virtual height at the beginning and the end of the experiment in both height conditions. The estimated heights reflect the height in Unity units, and the perceived height did not change between the first and the last trials in either high or low conditions. This strongly suggests that participants experienced the height differences as we would expect them to, according to the measurements given by Unity. Another factor for strong presence would be the participants' reaction when stepping off the walking plank, namely a negative reaction and avoidance behavior. In the questionnaire, participants reported the environment to have been realistic. This addresses the first of the two main technical aspects of immersion: vividness and interactivity (Hardiess et al., 2015). The second, interactivity, was achieved through the synchronous motion of the tracker and controller models in VR with the participants' own movement. The feet trackers seemed sufficient in giving an interactive experience. Even with some tendency of the tracker to shift during the experiment, it was possible to elicit a sense of presence in the environment and compute walking trajectories with the tracker data. Participants reported that the trackers did not disturb their natural movement and were comfortable to wear. The use of VR with positional tracking devices for path integration mechanisms has proven useful in our experiment as well as another recent path integration experiment (Stangl et al., 2020).

Considering these findings, some changes for the experimental design and the environment are proposed. Future experiments could adjust the experimental design to elicit more pronounced effects while keeping the general VR setup. Regarding the lack of a main effect of height on the distance error, a thinner walking plank, higher heights, and falling simulations are possible modifications for further experiments. To establish the virtual experience of elevation, a falling simulation could be added. For this, participants are given an avatar that virtually falls for a short period of time when participants step off the plank. If participants were to test this simulation during a test trial, it would establish the height as a more realistic threat to be avoided. Another way to increase the sense of height in our setup would be to use higher elevation and a thinner walking plank, which can draw more attentional resources towards the walking process. Additionally, a real wooden plank on the ground can support the realism, as participants are provided with another sensory indicator of limited space to walk on and the possibility of stepping beside it. With a more pronounced height experience, acrophobia questionnaires should be used before the experiment to exclude highly acrophobic participants. These questionnaires might also allow differentiation between the degrees of acrophobia, which could be another interesting factor for analysis. Physical reactions can support the claim of height as the stress-inducing factor, and reaction time to external stimuli can be used as evidence for increased workload. Also, the height manipulation can be different for encoding and reproduction stages. This could allow to further disentangle specific error sources. In addition to height, further studies could also use mental tasks to increase cognitive load, this would however diminish the attributability of height as a leading factor. Having participants react to external stimuli could provide evidence for increased workload, as well as measured physical reactions to heights. These changes could be incrementally adapted until the expected effect of height becomes visible, according to theory.

Because of the short, straight paths, landmark information was probably not needed as an external indicator of distance. Another way of providing reliable landmark information would be to display mountains or other features at the horizon, giving a more stable indicator for distance and ego-motion. The effect of landmark information could be further investigated by using eye-tracking data to show that the participants' attention was focused on the landmark information and in which condition. In a more complex setup of paths, the effect of landmark information should also become more apparent, as for the given single paths the internal bodily cues seem to be sufficient. A more complex setup can be provided by an actual triangle completion task or, more generally, by presenting longer paths or curved ones with more than one turning point.

On a technical level, some additions could provide further evidence for the investigated effects. The HMD made it necessary that a person walked next to the participant to hold the cables. This probably influenced the mean end position of participants and should be avoided, as it may influence other measures as well. Additionally, the availability of continuous movement data could greatly increase the options for analysis to include gait and step length. Given continuous data, it would be helpful to develop a model that can compare and evaluate the single positional data points to get a more cohesive picture of influences on walking behavior. For a complete understanding of walking behavior, a mean trajectory of all participants can be computed and used as a baseline for comparisons, as has been done in other studies with walking trajectories (Hicheur, Pham, Arechavaleta, Laumond, & Berthoz, 2007).

For a comparison of individual walking behavior, the deviation of individual trajectories to the mean could then be computed and analyzed for significant deviations. This should also account for time, as a strong indicator of insecurity.

Regarding presence in the VE, the presented environment was sufficient in providing a stable and realistic experience. Further measures for presence would be the participants' reaction to a virtual falling simulation. This can also establish a realistic elevation and increase the immersion. One change to provide even higher interactivity could be presenting an avatar body to move with the participants' own body. Real world feedback, like walking on a wooden plank, would support the presence as well. The feet trackers were sufficient for extracting positional data and providing interactivity. They could therefore be used in further experiments to measure walking behavior, keeping in mind the ambiguous relationship between units in Unity and actual meters. Further changes in the virtual environment include a less symmetrical ground texture and floating particles as naturalistic optic flow cues. Overall, participants reacted positively to the immersive qualities of the experimental environment, probably making no major changes necessary. The stable height impression, reported realism, and some effect of the presented height speak to the effectiveness of the experimental environment as well.

In conclusion, the expected effect of height as a resource allocating factor was not found in the errors participants made, some effect was however visible in interaction effects regarding time and in the walking behavior. The factor height had no significant effect on errors in reproduced distance. This can be attributed to the height stimuli not being pronounced enough. Higher elevation, falling simulations, and additional measures for physical stress reactions and mental load are proposed changes. These alterations should reveal main effects and make further investigation of the impairment of cognitive load possible. The main effect of distance is visible in over- and undershoot errors for short and long distances, respectively. The cause for this effect is theorized to consist in participants storing one mean distance, which is corrected by integrating bodily distance cues from the immediately before traveled distance. The use of longer, more complex paths is recommended to make it more necessary for the path integration system to include external cues. This would probably lead to a more distinct effect of landmark information as well. The positional data provide a wide range of measures for behavior: illustrating the distance and homing error, as well as depicting insecure walking behavior where larger errors were made.

The overall velocity supports the claim that height led to more careful walking behavior. The recording of continuous data is recommended for further analysis of step length and gait. Analyzing the time participants took for each trial revealed some interaction effects between height and landmarks, as well as between height and distance. These interactions can be interpreted as participants displaying more cautious walking behavior on high walking planks in combination with no landmarks and short distances. This indicates that the height was experienced as realistic enough to provoke some change in behavior. The height estimation further supports the claim that the presented height was experienced as expected. This concludes that the presence in the given experiment was strong enough to provide a stable height impression and to affect behavior. The benefit of added body-based indicators of ego-motion in VR is a likely enhancement for investigations into this topic. Therefore, the presented framework should be considered for future path integration experiments.

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Eigenständigkeitserklärung

Hiermit versichere ich, dass ich die vorliegende Bachelorarbeit selbständig verfasst, keine anderen als die angegebenen Hilfsmittel und Quellen benutzt habe und alle wörtlich oder sinngemäß aus anderen Werken übernommenen Aussagen als solche gekennzeichnet sind. Diese Bachelorarbeit war weder vollständig noch in wesentlichen Teilen Gegenstand eines anderen Prüfungsverfahrens und wurde weder vollständig noch in wesentlichen Teilen bereits veröffentlicht. Das in Dateiform eingereichte Exemplar stimmt mit den eingereichten gebundenen Exemplaren überein.

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