WIM: Fast Locomotion in Virtual Reality with Spatial Orientation Gain & without Motion Sickness

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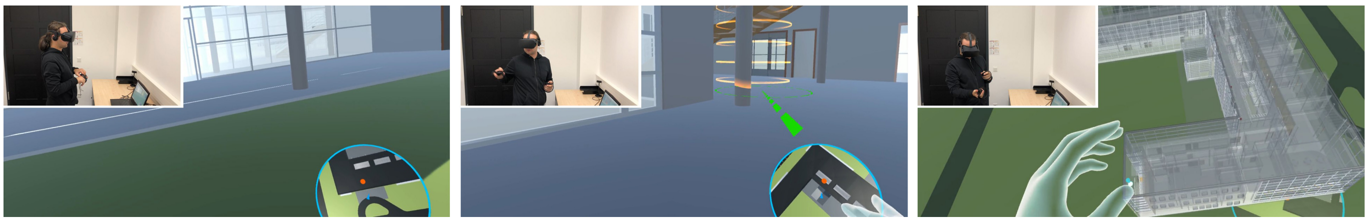

Figure 1. Locomotion techniques. Left: continuous motion using the joystick of the Oculus Touch controller. Center: teleport using a pointing gesture and a button for confirmation. Right: World-in-Miniature (WIM) using a pick&drop gesture for re-locating oneself in a miniature copy of the VE.

ABSTRACT
For locomotion in Virtual Reality (VR), different approaches exist. While continuously moving across the ground through walking techniques or controller input is considered to be most similar compared to the way we move through physical space, this technique causes motion sickness and results in lack of spatial orientation. Teleportation has been shown to result in less motion sickness, while being slower than moving continuously in most virtual environments. World-in-miniature (WIM) allows the user for changing his/her viewpoint through picking and relocating his/her representing icon in a virtual miniature replica of the VR he/she is located in. To see if WIM may be an alternative locomotion technique to continuous motion, we compared the three locomotion techniques contentious motion, teleportation and, WIM (see Fig. 1). We found that WIM outperforms the other two techniques in navigation time for longer distances. Furthermore, it provides best spatial knowledge while causing least motion sickness among the compared methods. We conclude with proposing to provide VR users with a set of locomotion techniques that allows for continuous motion when only moving little, while WIM could be used for moving over longer distances and in environments that are difficult to oversee.

CCS Concepts
•Human-centered computing → Human computer interaction (HCI); Empirical studies in interaction design;

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Author Keywords
Locomotion; Virtual Reality; Motion Sickness.

BACKGROUND & RELATED WORK
Locomotion allows the user for self-propelled movements in virtual environments [7]. Although physically walking in VR is considered to be most natural and immersive [16], it requires too much space, which most physical environments do not provide, and even redirected walking can be barely realized in normal-sized rooms [18]. While walking in place [10, 17, 20] can reduce the space needed for moving through VR, the standing position is not always appropriate, for example, when being in a vehicle [8], to avoid fatigue or physical user collision in multi-user applications. In this work, we hence support seated use cases for VR. Bozgeyikli et al. compared continuous motion in VR with teleportation and physically walking in place. They showed that teleportation-based locomotion reduces motion sickness compared to continuous motion, while continuous motion is faster in environments with obstacles, such as walls, than teleportation and walking in place. In environments without obstacles, no time difference was found between continuous motion and teleportation, while walking in place was the slowest technique. [2]. In 1995 Pausch et al. [14] and Stoakley et al. [19] presented Worlds-in-Miniature (WIM), a hand-held miniature graphical representation of the virtual environment, allowing the user to change the viewpoint and location through moving a virtual representation of oneself in the WIM. The miniature representation of the environment, including the objects contained within, are acting as a proxy for the original objects they represent. Actions performed upon the proxies are performed on the original virtual environment as well. The map dragging technique, which allows the user to use a stylus to drag his icon representation

over a 2D map as a method of transportation, was explored by Bowman et al.in their work on the testbed evaluation of virtual environment interaction techniques [1]. A comparison of 'walk mode' navigation within a 2D versus 3D map of a building using mouse control resulted in no difference in distance estimation but in performance reduction when moving through the 3D map [4]. Since then, several additions where made, such as SSWIM by Wingrave et al.[21], which allows the user to scale and scroll the WIM. Another addition is Step WIM by LaViola et al.[11], where the WIM is on the floor in a CAVE and the user is able to physically walk to his or her destination and then animate the virtual environment to this destination using a foot gesture, therefore not requiring the hands of the user. More recently Elvezio et al. presented their technique, which allows for setting the desired orientation at the destination, before teleportation [5].

Spatial orientation in VR is known to be more difficult than orientation in the real world. It is, for example, a well know phenomenon that people underestimate egocentric distances in head-mounted display virtual environments compared to estimates done in the real world [12, 13]. Spatial orientation has been investigated for different map visualizations [4] and for landmark-based navigation [3]. Moreover, it is widely accepted that spatial orientation is gained while moving through space [9]. Therefore, the effect of different movement styles (or locomotion techniques) on the gain of spatial knowledge is worth investigating.

WIM is a promising candidate for gaining spatial knowledge as it provides an overview of the environment and a clear understanding of landmark location versus the position of oneself (through one's representing icon) [14, 19]. Gaining spatial knowledge is only one essential aspect when looking at locomotion techniques for VR. Moreover, the time to reach a landmark and not causing motion sickness are two more major parameters that need to be taken into account when evaluating locomotion techniques. Finally, ease of use is a standard usability requirement of interaction techniques, which should be guaranteed. This paper contributes through comparing WIM, continuous motion, and teleportation regarding their effect on motion sickness, spatial knowledge gain, time needed to reach landmarks as well as ease of use.

METHOD

To investigate if WIM fulfills locomotion technique expectations, we compare it against two commonly used techniques: continuously moving the viewpoint in VR (referred here as continuous motion) and teleportation. We evaluated the techniques in a controlled experiment to collect quantitative data about *performance*, *perceived mental effort*, and *motion sickness* as well as qualitative and quantitative data about the gain of *spatial knowledge*. *Performance* provides insights in how fast users can reach a location. *Mental effort* indicates which locomotion technique is easier to use. As *motion sickness* is a known negative side effect of locomotion, we aim understanding what technique causes least *motion sickness*. Finally, we aim to get insights what locomotion technique supports or prevents gaining *spatial knowledge* and for what reason.

Experiment Design, Measures & Task

Our study had a 3x3x3 within subject design with the independent variables *locomotion technique* (continuous motion, teleport, WIM), *environment* (park, city, building), and *landmark distance* (5m, 15m, 45m). The *environments* were chosen to cover different levels of difficulty as previous work has been shown that locomotion performance depends on environment difficulty [2]. *Park* is the easiest one providing a good view on the next target location, and it allows for easy access. In the *city*, target locations, while still having easy access, are not always visible, as walls may occlude them. In the *building*, again, walls may occlude locations, but also reaching targets is more difficult as it may require to pass doors or take stairs. In summary, difficulty increases in the city (compared to the park) through landmark occlusion and in the building through landmark occlusion as well as through an increase of access difficulty having doors and stairs. Target locations are arranged in 3 *distances* (5m, 15m, 45m) to form paths. The *distances* were chosen to allow for creating paths that fit in a building, as well as increasing difficulty across the *environments*. Each path contains 9 landmarks, three of each *distance*, and we arranged them in random order. The task was to follow a path by reaching the landmarks one after another. 3 paths per *environment* were presented, one for each *locomotion technique*. Hence, participants completed 9 paths and passed 81 landmarks during the experiment (9 landmarks x 9 paths).

The dependent variables were *performance*, *perceived effort*, *motion sickness*, and *spatial knowledge*. *Performance* was measured as *task completion time* (TCT) and recorded in log files. *Perceived effort* (for each locomotion technique and each environment) was measured using the SMEQ scale, because it is known to be very sensitive with small sample sizes [15]. *Motion sickness* was recorded using the motion sickness assessment questionnaire (MSAQ) [6]. We used a semi-structured questionnaire to gather qualitative data about what specific aspects support or prevent gaining spatial knowledge.

Participants

We recruited 18 participants (8 females). They had different experiences with VR, which varied particularly between those that with experience in using VR HMDs in general (13 participants), Oculus Rift + Touch (4 participants) in particular or joysticks (15 participants). Participants had an average age of 30.2 years ($SD = 11.4$).

Apparatus

The experiment was conducted on a VR capable notebook (MSI GT72VR 6RE Dominator Pro) using Oculus Rift and Oculus Touch as output and input devices respectively. The test environment was created in Unity3D[1].

To clearly communicate the task procedure, each landmark that should be accessed next was presented as orange colored ascending rings, and the color changed to green over 3 seconds, when the participant entered the landmark's activation range. Thereafter the landmark visualization disappeared and the next landmark was visualized. The time between the appearance of the landmark and when the participant reached it was measured

[1] Unity3D, https://unity3d.com/

as task completion time (TCT) and stored along with the distance to the previous landmark (calculated as shortest path via Unity NavMesh) in a database using SQLite[2].

Our pilot studies showed that target searching was much harder in the *teleportation* and *continuous motion* conditions than when using *WIM*. To ensure difficulty fairness across the conditions and as minimaps are commonly used in games to give environmental overview, we added a minimap in the bottom right corner in these two conditions, as shown in Fig. 1.

For locomotion the techniques *continuous motion*, *teleportation*, and *world-in-miniature* (WIM) were implemented. For *continuous motion*, the two joysticks on the Oculus Touch controllers were used. The movement was controlled by the joystick on the left controller, while the joystick on the right controller allowed for additional left/right rotation.

During *teleport*, teleportation was started/stopped with double tapping the index finger on the left Oculus Touch controller. Teleport activation is indicated through a straight dashed line originated from the right hand and drawn into the direction where the user is pointing at. The destination where the user would teleport to was marked by a dashed circle on the ground. If teleportation would have placed the user in the landmark's activation range, the line, as well as the circle, would be colored green, otherwise it was colored orange. To confirm the teleportation, the left joystick would have been pressed, if the destination was valid, the user was then teleported to its position. This was done in order to maximize the accuracy at long distances, since it makes the aim more steady while triggering the teleportation.

During *WIM*, the user could open a miniature version of the environment on top his/her right palm. We mapped this to a hand gesture rotating the palm upwards, which caused the right hand model to disappear and the miniature environment to appear instead. This was maintained as long as the gesture lasted. The user's own position as well as positions of interest (landmarks in this case) were marked by inverted cones pointing towards it. For distinctness, the user's marker was – similarly to the user's virtual hands and the user marker on the minimap – colored turquoise, while the landmarks were orange. As long as the miniature environment was visible, the user was able to change his/her virtual position by picking his/her own marker up and dropping it at the desired destination. Upon the location change, a raycast was performed from the tip of the cone downwards onto the miniature world. The resulting position was corrected to fit the bounds of the participant's representing icon, if possible. If the destination was invalid, e.g. outside or below the environment, the location change was aborted. The picking gesture was done with the thumb of the left hand on either the X button, the Y button or the thumb rest, while pressing the index finger trigger.

Procedure

After filling in a demographic questionnaire and a training phase for each of the three *locomotion techniques*, participants were asked to follow a given path through navigating to 9 landmarks as fast as possible. During the tasks, the participants were sitting at a desk, wearing the Oculus HMD and holding Oculus Touch controllers in their hands. We counterbalanced the order of the *locomotion techniques*. Within each *technique*, we randomized the order of the 3 *environments*. Within each *environment*, the 9 location landmarks, 3 of each *distance*, were presented in random order. After completing a condition, the participants filled in the SMEQ and in the MSAQ. After completing all 3 conditions for each *locomotion technique*, participants rated the potential of gaining *spatial knowledge* using that technique and answered qualitative questions explaining what aspects supported and what aspects prevented them in gaining *spatial knowledge*.

[2]SQLite, https://www.sqlite.org/

RESULTS

We used three-way repeated measures analysis of variances (ANOVAs) to determine significant effects of the independent variables *locomotion technique*, *environment*, and *landmark distance* on *TCT*. While *TCT* was measured for each *landmark distance*, all other measures were only recorded after a path with 9 landmarks was completed. The SMEQ scale allows for using two-ay ANOVAs to analyse *Mental effort* [22]. Kruskal-Wallis H Test was used to indicate significant effects on the ordinal data*motion sickness*, and Post-hoc analysis with Mann-Whitney U tests were conducted with a Bonferroni correction applied, resulting in a significance level set at .017. *Spatial knowledge* was also qualitatively analyzed using open coding to classify aspects that support or prevent gaining knowledge. The classified aspects were then aggregated through deleting redundancies and summarized through highlighting the most relevant ones.

Mental effort: Descriptive statistics led to following values for *environment*: $park\_mean = 3.30$ ($SD = 2.94$), $city\_mean = 3.90$ ($SD = 3.17$), $building\_mean = 4.92$ ($SD = 3.05$) and for *locomotion technique*: $continuousmotion\_mean = 3.94$ ($SD = 3.37$), $teleport\_mean = 3.94$ ($SD = 3.18$), $WIM\_mean = 4.24$ ($SD = 2.79$). Mental effort was perceived significantly different for *environment* ($F_{2,153} = 3.778, p = .025$) but neither for *locomotion technique* ($F_{2,153} = .166, p = .847$) nor for the interaction between the variables *environment*technique* ($F_{4,153} = .067, p = .992$). Bonferroni corrected pair-wise t-tests revealed a significant difference between *building* and *park* ($p = .022$) but not between any other *environment* using the significance level of $p <= .05$.

Motion sickness: While Kruskal-Wallis H test did not indicate a statistically significant difference in *motion sickness* score between the different *environments* χ^2 = 1.433, p = 0.488010, with a mean motion sickness score of 23.97 for *park*, 28.56 for *city* and 29.97 for *building*, a Kruskal-Wallis H test showed that there was a statistically significant difference in *motion sickness* score between the different *locomotion techniques*, χ^2 = 9.137, p = 0.010, with a mean motion sickness score of 36.17 for *motion*, 25.61 for *teleport* and 20.72 for *WIM*. Mann-Whitney U tests showed that *WIM* caused in significantly less *motion sickness* than *motion* ($U = 68, p = .002$), while nor a significant difference could was found between *motion* and *teleport* ($U = 100, p = .051$) neither for *teleport* and *WIM* ($U = 134, p = .389$).

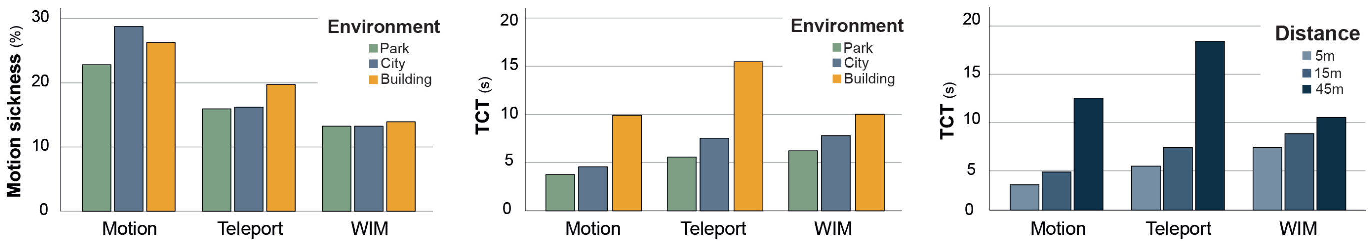

Figure 2. Motion sickness per locomotion technique (left), TCT over environment (middle), TCT over landmark distance (right).

Performance: Descriptive statistics led to following *TCT* values for *environment*: $park\_mean = 5.19$ ($SD = 3.04$), $city\_mean = 6.64$ ($SD = 5.41$), $building\_mean = 11.79$ ($SD = 15.05$), for *locomotion technique*: $continuousmotion\_mean = 6.08$ ($SD = 10.12$), $teleport\_mean = 9.52$ ($SD = 12.21$), $WIM\_mean = 8.02$ ($SD = 5.63$), and for *landmark distance*: $5m\_mean = 4.57$ ($SD = 3.63$), $15m\_mean = 6.13$ ($SD = 5.92$), $45m\_mean = 12.92$ ($SD = 14.20$), see Fig. 2. *TCT* was significant affected by *environment* ($F_{2,486} = 33.932, p < .001$), *locomotion technique* ($F_{2,486} = 8.423, p < .001$), and *landmark distance* ($F_{2,486} = 55.536, p < .001$) as well as by the interaction effect of *environment*technique* ($F_{4,486} = 2.820, p = .025$), *environment*distance* ($F_{4,486} = 10.816, p < .001$), and *distance*technique* ($F_{4,486} = 7.326, p < .001$). For *environment*, Bonferroni corrected pair-wise t-tests revealed a significant difference between *building* and *park* ($p < .001$) as well as between *building* and *city* ($p < .001$), but not between *park* and *city* ($p > .05$). For *locomotion technique*, Bonferroni corrected pair-wise t-tests revealed a significant difference between *motion* and *teleport* ($p < .001$), but not between any other *technique* ($p > .05$). For *landmark distance*, Bonferroni corrected pair-wise t-tests revealed a significant difference between *5m* and *45m* ($p < .001$) as well as between *15m* and *45m* ($p < .001$), but not between *5m* and *15m* ($p > .05$).

Spatial knowledge: Qualitative data showed that all but one participants found the overview given through the *WIM* map helped gaining *spatial knowledge*. Interestingly, during the other two conditions, the mini-map we had provided for motion and teleport to ensure a fair condition design was often (*continuous motion*: by 3 participants, *teleport*: by 6 participants) named to be used for getting an overview of the terrain and to gain *spatial knowledge*. Beside using a mini-map, participants looked around and used location changes to discover the environment during the *continuous motion* and *teleport* conditions. Motion sickness was mentioned twice to limit spatial orientation during the *motion* condition. Participants also mentioned that the *WIM* map better helped in gaining *spatial knowledge* compared with the mini-map provided in the other two conditions, as it gives more detailed information and allows for perspective changes. Finally, two participants indicated the first-person perspective used in the *continuous motion* and *teleport* condition would actually hinder getting an overview of the terrain, while a bird view, such as provided by *WIM*, was promoted as *spatial knowledge* helper.

DISCUSSION

Our findings extend on those of Bozgeyikli et al. [2] who found that continuous motion and teleportation being equally fast in environments without obstacles, such as walls, while teleportation gets significantly slower as soon as obstacles occur. While Bozgeyikli et al. used only obstacles like walls, we also introduced doors and level changes (stairs). Such difficulty increase was perceived significantly harder than having only walls, which led to slowest locomotion time in buildings. Moreover, indoor navigation was found significantly harder than navigating in the park. We further found that the distance between landmarks is very important for the performance of locomotion techniques, and WIM was the only technique with stable velocity over distances from 5 to 45m. Ways having distances of 45 and more meters are very common in all kinds of movement scenarios. Hence, we think that the fact that WIM outperforms continuous motion as well as teleportation at 45m distances is a core finding of this paper.

WIM being a promising locomotion candidate can even be strengthened through the feedback on the gain of spatial knowledge it provides. Such overview gain might be compensated through minimaps, but WIM was still favored over a minimap due to the great detail of information is shows and as interaction with WIM is much richer, e.g. supports perspective changes. Finally and very importantly for locomotion techniques in VR, WIM reduces motion sickness compared to continuous motion, while not being mentally harder than one of the two common techniques.

CONCLUSION

Navigating in VR has two major issues: motion sickness and the loss of spatial orientation. In this paper, we promote WIM to be a promising locomotion technique for VR, and to support our argumentation, we compared WIM with two common locomotion techniques: continuous motion and teleportation.

We found that WIM not only outperforms the other two techniques in velocity for distances from 45m. It also provides best spatial knowledge while causing least motion sickness. We conclude with proposing WIM to move through VR. For short moves, continuous motion may still be provided as its issue of motion sickness can avoided with switching to WIM. Finally, choosing the right locomotion in VR highly depends on scenario and use case. In some cases, despite WIM outperforming in terms of spatial knowledge and motion sickness, one might still prefer a first-person view locomotion method due to immersion/gameplay mechanic/realism/sense of scale.

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