If The Map Fits! Exploring Minimaps as Distractors from Non-Euclidean Spaces in Virtual Reality

Jonas Auda
University of Duisburg-Essen
Essen, Germany
jonas.auda@uni-due.de

Uwe Gruenefeld
University of Duisburg-Essen
Essen, Germany
uwe.gruenefeld@uni-due.de

Stefan Schneegass
University of Duisburg-Essen
Essen, Germany
stefan.schneegass@uni-due.de

(a) Minimap in VR. **(b) Dropping off a ball at a target.** **(c) Comparing room and corridor.**

Figure 1: (a) a participant holds a ball. This ball must be dropped off into a specific container. On the minimap, the correct container is shown (green). (b), the participant drops off the ball into the correct container. (c), a participant standing on the edge of the corridor comparing its depth to the depth of the room. The minimap indicates a larger corridor as observable by the user.

ABSTRACT

With non-Euclidean spaces, Virtual Reality (VR) experiences can more efficiently exploit the available physical space by using overlapping virtual rooms. However, the illusion created by these spaces can be discovered, if the overlap is too large. Thus, in this work, we investigate if users can be distracted from the overlap by showing a minimap that suggests that there is none. When done correctly, more VR space can be mapped into the existing physical space, allowing for more spacious virtual experiences. Through a user study, we found that participants uncovered the overlap of two virtual rooms when it was at 100% or the overlapping room extended even further. Our results show that the additional minimap renders overlapping virtual rooms more believable and can serve as a helpful tool to use physical space more efficiently for natural locomotion in VR.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Empirical studies in HCI**.

CHI '22 Extended Abstracts, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9156-6/22/04…$15.00
https://doi.org/10.1145/3491101.3519621

KEYWORDS

Virtual Reality, Locomotion, Illusions, Non-Euclidean, Distraction, Minimap, Overlap

ACM Reference Format:
Jonas Auda, Uwe Gruenefeld, and Stefan Schneegass. 2022. If The Map Fits! Exploring Minimaps as Distractors from Non-Euclidean Spaces in Virtual Reality. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '22 Extended Abstracts), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3491101.3519621

1 INTRODUCTION

Enabled by Virtual Reality (VR) technology, users can immerse themselves in digital worlds and experience them in great detail. Recent VR technology improvements allow for higher resolutions [16], more precise tracking [2], and low latency [7]. As a result, the immersion into VR increases. With the latest devices being standalone, removing disruptive cables, users can freely move by natural locomotion within the available physical space. Thus, the question arises of how users can explore unlimited virtual worlds which exceed the available physical space.

Previous work investigated different approaches for locomotion in VR. Prior work evaluated how users can move around in VR similar to video games, typically with joysticks, controllers, or gamepads [3]. However, these approaches often result in motion sickness [10]. Therefore, point and teleport locomotion emerged as an alternative approach [6]. However, studies showed that these techniques limit the immersion and potentially result in the disorientation of users [12, 19]. To address these problems, researchers have investigated more natural locomotion approaches, namely redirected walking [1, 14, 17] and non-Euclidean spaces [18, 20]. While redirected walking seems to function best with additional hardware such as electric muscle stimulation [1], non-Euclidean spaces do not rely on any additional hardware components, and thus, can be implemented on any VR device.

Non-Euclidean spaces showed great potential for natural locomotion in VR [18, 20, 21]. Especially the combination with distractions enables interesting approaches to further reduce the need for physical space [5]. Therefore, we ground our research on top of these approaches to answer the following research question: Can a visual distraction and reassurance that suggests the integrity of the experienced VR environment hide its non-Euclidean nature?

To answer this question, we employed a minimap as a distractor from non-Euclidean VR environments. Our minimap shows a non-overlapping VR environment, while in fact, it overlaps to a certain degree. We opted for a minimap as it is easy to implement and can be used in any VR experience but at the same time is not fully researched. To explore our approach, we conducted a user study with twelve participants. Our participants traversed virtual rooms using a VR-head-mounted display (HMD), natural walking, and our minimap. We increased the overlap of our rooms in five different levels to uncover the threshold until the overlap was recognized. Our results show that our participants uncovered the overlap of the virtual rooms when it was at 100% or extended even further. Our findings can support designers and developers implementing more convincingly non-Euclidean spaces in VR, and thus, further reduce the physical space needed for natural locomotion.

2 NON-EUCLIDEAN SPACES IN VIRTUAL REALITY

Non-Euclidean spaces – often referred to as *"impossible spaces"* [18] – are virtual worlds that cannot exist in reality as they violate the Euclidean geometry of 3D space. First explorations of such impossible spaces demonstrated that virtual rooms could overlap to a certain degree (e.g., see Figure 2a), and thereby, enlarge the usable virtual space without users noticing [18, 20, 21].

The term *"impossible spaces"* in the context of VR was introduced by Suma et al. in 2012 [18]. In their pioneer work, they maximized the exploration of Virtual Environments (VEs) by natural walking through self-overlapping virtual rooms. As an example, one can consider two rooms in VR connected through a corridor. We can create a virtual overlap of these rooms without the two rooms visually intersecting in VR, but in reality, these rooms share parts or the physical space available depending on how much they overlap virtually. Suma et al. investigated different levels of overlapping virtual rooms (0%-75%). Their evaluation showed that the rooms were judged as being impossible above an overlap of 55.57%.

Warren et al. used a similar approach to investigate how humans gain spatial knowledge [15]. They created two virtual maze environments. One contained wormholes that teleported users between different locations while the other did not. They compared how users build spatial knowledge of these environments after they have traversed them. Warren et al. found that users tend to develop a labeled graph of the environment rather than a global Euclidean map. Such graphs contain approximate local metric information but are geometrically inconsistent. This emphasizes the inability of humans to keep track of the exact Euclidean structure of space, and thus, can be exploited to fit large virtual worlds into limited physical space.

Vasylevska et al. investigated the impact of various layouts of self-overlapping rooms in VR on the perception of users [20]. Different sequences of self-overlapping rooms with a different number of turns, varying door positions, and symmetric or asymmetric walking paths. They designed different layouts of virtual rooms and let participants explore them using natural walking. They found that the overlap of rooms was stronger perceived in right-angled layouts than in curved layouts. Based on the combination of impossible spaces and change blindness, Vasylevska et al. introduced a redirection technique called flexible spaces [21]. Dynamic layout generation enables unrestricted natural walking in large VE through the procedural generation of room layouts that fit into the tracking space. Thereby, they abandoned detailed spatial knowledge and extended the possible overlap up to 100%. To maintain the integrity of Euclidean geometry, Vasylevska et al. exploited change blindness. They changed the layout of the VE depending on the user's position and rotation to prevent the user from noticing.

Ciumedean et al. used a task as a distraction incorporated in the VR narrative to hide its overlapping architecture [5]. Through the distraction, an overlap up to 60% remained undetected. Without the distraction, the overlap was discovered at 40%. To further enhance this, distracting the user is promising. Similar to this approach that used a distracting task [5], we developed a visual distraction and reassurance in form of a minimap. This minimap implies to its users that the VE is non-overlapping, and thus, distracts the user while walking in non-Euclidean VR environments. In the following, we evaluate our approach in a user study.

3 EVALUATION: USING A MINIMAP AS A DISTRACTOR FROM NON-EUCLIDEAN VR

In the following, we introduce how we used a minimap to imply a Euclidean virtual space, although it is not. Therefore, we developed a VR application that consists of two rooms that overlap to a certain extent (see Figure 2a). Our participants traversed these rooms by natural walking. In sum, five consecutive levels with increasingly overlapping rooms. We incentified our participants to use the minimap through a specific task. Through that, we explored how the minimap affects the recognition of the non-Euclidean VR and determined when our participants recognized the mismatch.

3.1 Study Design

To investigate the minimap as a distractor in VR, we invited 12 participants to a lab study. Our participants fulfilled a task that requires them to walk through our VR environment with five levels containing increasingly overlapping rooms. Our participants started in a room with 40% overlap (see Table 1). In previous work, participants recognized the overlap at this threshold when no distraction or reassurance was used [5]. Also, our initial overlap is 10% below the threshold reported by Suma et al. [18]. The last room was overlapping 160% of the area of our basis room (see Table 1). Here, an overlap over 100% means that the overlapping room is larger than the overlapped room. We decided on the limit of 160% as it is more than twice as large as thresholds from the literature [18]. We recorded the entire study and encouraged the participants to think aloud while walking. This helped us to uncover when participants perceive the overlapping architecture. We concluded the study with semi-structured interviews.

3.2 Task and Minimap

For our study, we developed a task that required our participants to use the minimap in each level. The objective was to pick up a ball in one room and place it inside a specific container in the other room. The other room contained three containers. Hence, our participants had to look up the correct container on the minimap (see Figure 2b). For each level, this was repeated three times.

3.3 Procedure

First, we welcomed our participants to our lab. The participants filled out our consent form and permitted audio and video recording throughout the study. After that, they were provided with the *Oculus Quest 1* HMD and were situated in a free area of a large and empty room. They put on the HMD and followed the instructions inside the VR app. First, the app informed them of the five levels they should traverse. The VR app reminded them of thinking aloud during the study. Next, the app introduced the objective of the task – picking up blue balls in one room and bringing them to containers in the other room. The participants were told that the minimap indicates the correct container to drop off the ball. After the participants acknowledged the introduction, the app once more reminded them of thinking aloud. Then, the participants entered the VR on Level 1 (40% overlapping rooms). They were picking up the blue ball (see Figure 1a) and dropping them off into the indicated container (see Figure 1b). After a ball was dropped off correctly, the participants were told by the app to walk back to the initial position. After they positioned themselves correctly, they could enter the next level. Between each level, we asked the participants if they noticed anything about the environment to find out if they noticed the overlap without hinting too much towards the illusion. After five levels the app showed an ending screen that told the participants that they can close the app and take off the HMD. After that, we conducted semi-structured interviews. We did not tell the participants that they were facing a non-Euclidean VR environment in advance.

3.4 Apparatus

To explore the influence of our minimap, we developed a VR app in *Unity3D*. The app consisted of two rooms (see Figure 2a). A wall in every room (see Figure 2a, highlighted in green) can be adjusted to manipulate the room size. From each room, the user could enter a corridor that is separated from the rooms by a wall (see Figure 2a, highlighted in blue). In VR, the minimap was floating in front of the participants and followed their movement (see Figure 1a). The minimap showed a red arrow indicating the participant’s position, a blue circle indicating the ball that needs to be picked up, and a green square i.e. the target container (see Figure 2b). To illustrate what the participants were facing during the study, here are two examples.

Table 1: The five Levels with the virtual rooms and their overlap percentage which we used for the evaluation of the minimap in non-Euclidean VR. The last column shows the overall number of participants that uncovered the non-Euclidean VR illusion at the respective level (+ indicates the number of participants that uncovered the illusion at the given level). The base room is shown as a reference of size but was not included in the study.

Level	Overlap/Extent of Base Room	Room Width	# Participants noticed overlap
Room 1	40%	2.10m	0/12 (+0)
Room 2	70%	2.55m	1/12 (+1)
Room 3	100%	3.00m	6/12 (+5)
Room 4	130%	3.45m	8/12 (+2)
Room 5	160%	3.90m	8/12 (+0)
Base Room	0%	1.50m	-

The two maps in Figure 2b show two different VEs. The left minimap shows an environment that does not overlap. As the environment is quadratic, the minimap is quadratic too. The minimap on the right of Figure 2b is stretched on the x-axis indicating a larger VE with no overlap but in fact, the two rooms are overlapping by 50%. That means that the user would traverse back into the physical area of the first room while in VR enters the second room. To reassure that the virtual rooms are non-overlapping, we stretched the map. To have enough space to use our app safely, we prepared an empty room of approximately $5m \times 8m$ at our department. The minimap was always active and could not be disabled by the participants.

3.5 Participants

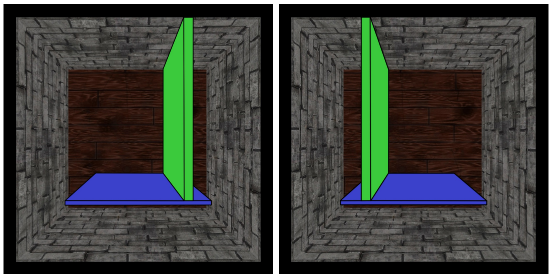
We recruited 12 participants (9 male, 3 female, 0 other) with a mean age of 30 years ($SD = 7.50$, $Med = 28$ $IQR = 5.50$). We asked the participants to rate their previous experience with 3D games and VR on a 5-Point-Likert Scale. They reported having good experience with 3D games ($Med = 5$) and some experience with VR ($Med = 3$).

3.6 Results

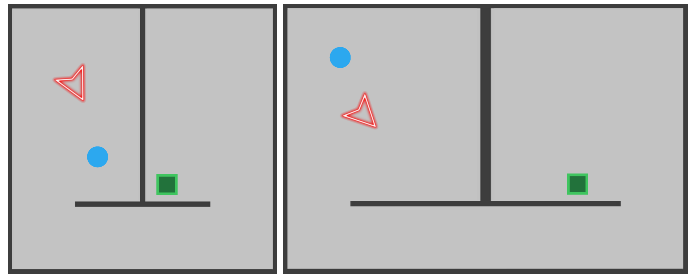
In the following, we present the results of our investigation of the impact of the minimap as a distractor from non-Euclidean VR environments along with qualitative feedback. Therefore, we used thematic analysis to group the feedback of the participants. Two researchers coded statements independently then employed an affinity diagram [8] of the open codes and organized the codes into groups, which were then further refined into themes using an online whiteboard[1].

Illusion Threshold with a Minimap. Eight out of our 12 participants stated that they uncovered the overlap within the environment. One while traversing the rooms with 70% overlap, five while traversing the rooms with 100% overlap, and the remaining two while traversing rooms with 130% overlap. Hence, the illusion was

[1]Miro. https://miro.com, last retrieved March 8, 2022



(a) Virtually Overlapping Rooms.



(b) Minimap for a 0% overlapping environment and a 50% overlapping environment.

Figure 2: (a) Top view on the two rooms: The green walls are adjusted to create rooms that are overlapping. A user that traverses from the left room through the corridor (blue wall) into the right room would in reality walk in a smaller area than the rooms suggest. (b) Two minimaps that are used in VR to navigate the environment. The red arrow indicates the position of the user, the blue circle indicates the position of the ball which the user has to pick up. The green rectangle depicts the position of the container in which the user should place the ball to fulfill the task.

uncovered on average when rooms overlapped at around 100% (M = 103.75%, SD = 17.98, Med = 100, IQR = 7.5). An overview is shown in Table 1. Figure 3 shows an example of the path on the minimap next to the real walking path taken by one participant traversing Level 4 that consists of two rooms with an overlap of 130%. We conducted a Cochran Q test to statistically compare the nominal data (overlap detected/not detected) of the different rooms. The test revealed significant differences ($Q = 22$, $df = 4$, $p < 0.001$). A post hoc pairwise McNemar with Bonferroni correction revealed a significant difference between Room 1 and Room 4 ($\chi^2(2,12) = 6.125$, $df = 1$, $p = 0.013$, $r = 1.250$). Four participants did not mention that they noticed anything suspicious throughout the study. Taking these participants into account to calculate a lower bound, the results indicate that the threshold until the illusion can be uncovered is higher (M = 122.50%, SD = 30.31, Med = 115, IQR = 60). Here, we assumed an overlap of 160% (max. overlap in this study) for the additional participants to calculate our results.

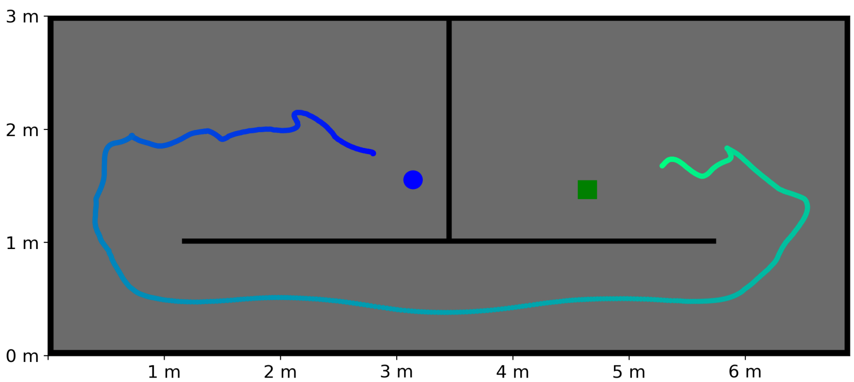
Illusion Break Through the Minimap. We asked the participants how they have noticed the illusion. Two participants reported that they uncovered the illusion by observing their movement on the minimap. They noticed that the red arrow that was indicating the participants' position was moving faster on the minimap while the participants were walking through the corridor that connects the rooms. The increased speed of the cursor results from the fact that the minimap is stretched when two rooms overlap. This is necessary to show the participants a map with rooms arranged side-by-side while, in fact, the rooms overlap. Consequently, the participants' cursor moves faster in the corridor to match the movement of the participants in reality (see Figure 3b). One of these participants added: *"[. . .] the corridor here is shorter, or I'm moving faster, than when I'm in the room"*. Eight participants reported that they used the minimap to locate the ball they needed to pick up and where to drop it off. Two participants were frequently looking at the minimap while moving. Further, nine participants were not aware that the minimap grew wider with each room. Further, three participants did notice the illusion after overlaps at or above 100%. Only one participant found the minimap slightly bothersome while moving through the rooms because it was only needed when locking up the item or the drop-off container location and added: *"I thought, why should I look at it [the minimap], it's clear where I need to go [. . .], the level is not that complicated"*.

Illusion Break Through the Environment. Six out of those participants reported recognizing that the number of steps needed to walk from one room into the other did not match their expectations with regards to the length of the corridor. As one participant stated that *"The corridor here is shorter [. . .] than when I'm in the room"*, and another mentioned, that *"The room is bigger than it should have been after that corridor"*. Also, participants confirmed their suspicions by standing right on the edge of the corridor. From there they could see that the room is as deep (or even deeper, depending on the current overlap) as the corridor is long (see Figure 1c).

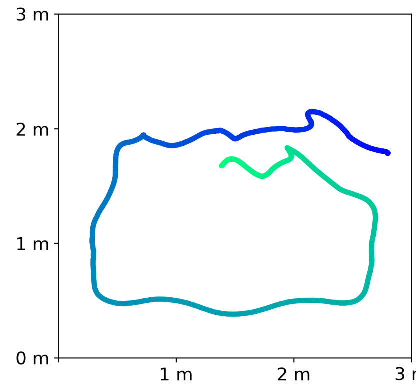
4 DISCUSSION

In the following, we discuss the results and derive recommendations for overlapping VEs.

Illusion Threshold with a Minimap. We found that, on average, the participants uncovered the overlap when it was more than twice as large as Suma et al.'s *"Impossible Spaces"* who used a similar setting [18]. In their evaluation, they did deliberative let the participants know that there is an overlap. This poses a limitation to our work. Future evaluations could further investigate this, by comparing the perception of users who know about the non-Euclidean environment and users who do not. Nonetheless, we found that the uncovering can happen in mainly two different ways – through the minimap itself or the VE. We believe that the minimap provides a useful distraction but is dependent on the given scenario. Further distracting users could block their ability to detect the mismatch between map and environment. For example, Ciumedean et al. embedded a distracting task into the VR narrative. Through the distraction an overlap up to 60% remained undetected [5]. This promises, that a combination of distractors e.g. challenging tasks or visual navigation aids like the minimap could enable larger overlaps, but future evaluations are needed.



(a) The virtual walking path of one participant plotted on the minimap suggesting a Euclidean VE.



(b) The walking path the participant took in reality.

Figure 3: An exemplary walking path in VR and the physical counterpart. The two rooms overlapped by 130%. Color depicts walking time starting from blue to green.

Illusion Break Through the Minimap. We found that the participants uncovered the illusion through the minimap. Suggesting a non-Euclidean environment with a 2D Euclidean surface results in a stretched map similar to a map of a globe where certain areas appear larger than they are. When traversing the stretched parts of the map, the cursor indicating the position of the user moves faster. This can be recognized by the participants and therefore has implications on the design of future non-Euclidean VR environments. For example, a designer of such worlds might consider this when using such navigation aids. For example, the map cloud be shown while the user is standing but is hidden while walking. Further, our minimap was stationary. Other types of minimaps that move with the user might better hide cues that hint towards the non-Euclidean geometry of VR environments. Such maps could be restricted to show only parts of the area around the user, not the entire environment. Here, cues on the side could help the user to navigate towards a destination outside the visible area similar to off-screen visualization techniques [4, 9]. Further, the task we used to encourage participants to use the minimap could have influenced the results. As participants were forced to use the minimap to solve the task, they might tend to uncover the overlap through the map. If there is no need to use the map the participants might recognize the overlap faster through observing the environment. This interplay between environment, minimap, and objective (i.e., the task) should be carefully considered when overlapping architectures are used.

Illusion Break Through the Environment. Participants uncovered the non-Euclidean nature of the VR through the environment. The reduced number of steps hinted towards a violation of the Euclidean geometry in VR. This was also observed by Suma et al. [18]. Also, observing certain features in the VR environment helped the participants to uncover the illusion. For example, participants observed the length of the corridor and the depth of the rooms. When the overlap was too large, they could clearly observe the violation. This indicates that our participants had to distribute their attention between the minimap and the VE. They could see the next target on the minimap but for navigation and collision avoidance they had to focus on the environment. We conclude that our minimap does not distract its users too much while walking, and thus, they are still able to perceive the VE and possible violations. Future VR environments could be built to make such observations less likely. For example, using distractions like tasks for the user in VR from the field of redirected walking [11] to further hide illusion or employ distractions [5].

Recommendations and Future Work. Our results point out that the minimap can help to distract from overlapping VR environments but is important to keep limitations in mind. VR designers and developers could incorporate a Euclidean map into their apps to extend the space for natural locomotion. This can be done entirely in software and therefore can work on any VR-HMD. Also, the minimap can be combined with existing methods like redirected walking [17], EMS [1], or task-driven distractors [5] to form a holistic solution that enhances natural locomotion experiences in VR. As each of these methods has its limitations and thresholds, combining or adapting them dynamically could bring real value to future locomotion experiences. Therefore, we suggest investigating such combinations in the future. We uncovered such a limitation of our minimap. The minimap led participants to uncover the overlapping rooms. Therefore, we suggest that the minimap is dependent on the scenario and could serve as additional means to hide overlapping VEs. Further research could investigate new designs of maps that manipulate the perception of VR users. For example, a user-centered map that shows only parts of the area around the user or maps that distort the environment and thereby suggesting a non-overlapping architecture. Future work could get inspiration from the field of map projections and distortion e.g. Mercator projections that project a globe onto a plane to obtain a 2D map [13].

Limitations. As we had no control condition to compare the effectiveness of our minimap, we had to solely rely on findings from the literature. Previous research suggests that an overlap of up to 50% remains uncovered by user [18]. When using task-driven distraction the overlap can be increased up to 60% [5], or up to 100% using procedural layout generation and change blindness [21]. Many different approaches can be used to hide an overlapping architecture. Therefore, we suggest that a minimap posed a new possible distraction but needs further investigation to determine its full distraction effectiveness and limitations. We can assume that fewer people would have noticed the overlap in a between-subject design. Our participants were continuously introduced to overlap changes during traversing the different levels which could serve as a reference point to them.

5 CONCLUSION

We conclude that our work is a step towards confining the physical space needed for natural walking in VR. In our approach, we used a distraction in form of a minimap. This minimap suggests that the virtual, self-overlapping environment is non-overlapping. This helped to hide overlaps up to 100%, and thus, further decreases the physical space needed for large VEs. In the future, VR systems or apps could incorporate such distractions to create more sophisticated and immersion preserving natural locomotion experiences. A minimap can be implemented solely in software and can be used on any VR device. We pointed out several benefits and drawbacks when a minimap is used as a distractor from overlapping VEs. Therefore, we argue that future research is needed to fully consider the interplay between VR user, VR environment, and the underlying objective or task. Further, future research could combine our findings with other approaches, such as redirected walking or task-driven distractions to create infinite virtual worlds that can be explored using natural walking.

REFERENCES

[1] Jonas Auda, Max Pascher, and Stefan Schneegass. 2019. Around the (Virtual) World: Infinite Walking in Virtual Reality Using Electrical Muscle Stimulation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/3290605.3300661

[2] L. Baker, J. Ventura, S. Zollmann, S. Mills, and T. Langlotz. 2020. SPLAT: Spherical Localization and Tracking in Large Spaces. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 809–817. https://doi.org/10.1109/VR46266.2020.00105

[3] Florian Borsum, Max Pascher, Jonas Auda, Stefan Schneegass, Gregor Lux, and Jens Gerken. 2021. Stay on Course in VR: Comparing the Precision of Movement betweenGamepad, Armswinger, and Treadmill. In *Mensch und Computer 2021 - Tagungsband* (2021-09-05). Gesellschaft für Informatik e.V. https://doi.org/10.1145/3473856.3473880

[4] Stefano Burigat, Luca Chittaro, and Silvia Gabrielli. 2006. Visualizing Locations of Off-Screen Objects on Mobile Devices: A Comparative Evaluation of Three Approaches. In *Proceedings of the 8th Conference on Human-Computer Interaction with Mobile Devices and Services* (Helsinki, Finland) *(MobileHCI '06)*. Association for Computing Machinery, New York, NY, USA, 239–246. https://doi.org/10.1145/1152215.1152266

[5] Claudiu-Bogdan Ciumedean, Cristian Patras, Mantas Cibulskis, Norbert Váradi, and Niels C. Nilsson. 2020. Mission Impossible Spaces: Using Challenge-Based Distractors to Reduce Noticeability of Self-Overlapping Virtual Architecture. In *Symposium on Spatial User Interaction* (Virtual Event, Canada) *(SUI '20)*. Association for Computing Machinery, New York, NY, USA, Article 6, 4 pages. https://doi.org/10.1145/3385959.3418453

[6] Markus Funk, Florian Müller, Marco Fendrich, Megan Shene, Moritz Kolvenbach, Niclas Dobbertin, Sebastian Günther, and Max Mühlhäuser. 2019. Assessing the Accuracy of Point & Teleport Locomotion with Orientation Indication for Virtual Reality Using Curved Trajectories. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300377

[7] R. Gruen, E. Ofek, A. Steed, R. Gal, M. Sinclair, and M. Gonzalez-Franco. 2020. Measuring System Visual Latency through Cognitive Latency on Video See-Through AR devices. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 791–799. https://doi.org/10.1109/VR46266.2020.00103

[8] Gunnar Harboe and Elaine M. Huang. 2015. Real-World Affinity Diagramming Practices: Bridging the Paper-Digital Gap. In *Proc. 33rd Annual ACM Conf. Human Factors in Computing Systems*. ACM, 95–104. https://doi.org/10.1145/2702123.2702561

[9] Niels Henze, Benjamin Poppinga, and Susanne Boll. 2010. Experiments in the Wild: Public Evaluation of off-Screen Visualizations in the Android Market. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (Reykjavik, Iceland) *(NordiCHI '10)*. Association for Computing Machinery, New York, NY, USA, 675–678. https://doi.org/10.1145/1868914.1869002

[10] Eike Langbehn, Paul Lubos, and Frank Steinicke. 2018. Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking. In *Proceedings of the Virtual Reality International Conference - Laval Virtual* (Laval, France) *(VRIC '18)*. Association for Computing Machinery, New York, NY, USA, Article 4, 9 pages. https://doi.org/10.1145/3234253.3234291

[11] Eike Langbehn and Frank Steinicke. 2019. Space Walk: A Combination of Subtle Redirected Walking Techniques Integrated with Gameplay and Narration. In *ACM SIGGRAPH 2019 Emerging Technologies* (Los Angeles, California) *(SIGGRAPH '19)*. Association for Computing Machinery, New York, NY, USA, Article 24, 2 pages. https://doi.org/10.1145/3305367.3327976

[12] Florian Mathis, Xuesong Zhang, Mark McGill, Adalberto L. Simeone, and Mohamed Khamis. 2020. Assessing Social Text Placement in Mixed Reality TV. In *ACM International Conference on Interactive Media Experiences* (Cornella, Barcelona, Spain) *(IMX)*. ACM, New York, NY, USA, 205–211. https://doi.org/10.1145/3391614.3399402

[13] Karen A. Mulcahy and Keith C. Clarke. 2001. Symbolization of Map Projection Distortion: A Review. *Cartography and Geographic Information Science* 28, 3 (2001), 167–182. https://doi.org/10.1559/152304001782153044 arXiv:https://doi.org/10.1559/152304001782153044

[14] Sharif Razzaque. 2005. *Redirected Walking*. Ph.D. Dissertation. USA. Advisor(s) Brooks, Fredrick P. AAI3190299.

[15] D. Rothman and William Warren. 2010. Wormholes in virtual reality and the geometry of cognitive maps. *Journal of Vision - J VISION* 6, 143–143. https://doi.org/10.1167/6.6.143

[16] J. Spjut, B. Boudaoud, J. Kim, T. Greer, R. Albert, M. Stengel, K. Akşit, and D. Luebke. 2020. Toward Standardized Classification of Foveated Displays. *IEEE Transactions on Visualization and Computer Graphics* 26, 5 (2020), 2126–2134. https://doi.org/10.1109/TVCG.2020.2973053

[17] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. 2010. Estimation of Detection Thresholds for Redirected Walking Techniques. *IEEE Transactions on Visualization and Computer Graphics* 16, 1 (2010), 17–27. https://doi.org/10.1109/TVCG.2009.62

[18] Evan A. Suma, Zachary Lipps, Samantha Finkelstein, David M. Krum, and Mark Bolas. 2012. Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture. *IEEE Transactions on Visualization and Computer Graphics* 18, 4 (April 2012), 555–564. https://doi.org/10.1109/TVCG.2012.47

[19] Martin Usoh, Kevin Arthur, Mary C. Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks. 1999. Walking > Walking-in-Place > Flying, in Virtual Environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99)*. ACM Press/Addison-Wesley Publishing Co., USA, 359–364. https://doi.org/10.1145/311535.311589

[20] K. Vasylevska and H. Kaufmann. 2017. Towards efficient spatial compression in self-overlapping virtual environments. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*. 12–21. https://doi.org/10.1109/3DUI.2017.7893312

[21] K. Vasylevska, H. Kaufmann, M. Bolas, and E. A. Suma. 2013. Flexible spaces: Dynamic layout generation for infinite walking in virtual environments. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*. 39–42. https://doi.org/10.1109/3DUI.2013.6550194