BlindWalkVR: Formative Insights into Blind and Visually Impaired People's VR Locomotion using Commercially Available Approaches

Julian Kreimeier
Nuremberg Institute of Technology
90489 Nuremberg, Germany
julian.kreimeier@ohm-university.eu

Pascal Karg
Nuremberg Institute of Technology
90489 Nuremberg, Germany
kargpa64658@ohm-university.eu

Timo Götzelmann
Nuremberg Institute of Technology
90489 Nuremberg, Germany
timo.goetzelmann@ohm-university.eu

ABSTRACT

Virtual Reality (VR) promises expanded access to spatial information, especially for blind and visually impaired people. Through haptic and acoustic feedback, real world's limitations like the risk of injury or the necessity of a sighted safety assistant can be circumvented. However, the best possible profit of this technology requires interactive locomotion in large virtual environments to overcome real world space limitations. Thus, we present formative insights of blind people's egocentric VR locomotion by comparing four different implementations (i.e., two VR treadmills, trackers on the ankles or joystick based locomotion) in a qualitative and quantitative user study with seven blind and visually impaired participants. Our results reveal novel insights on characteristics of each implementation in terms of usability and practicability and also provide recommendations for further work in this field with the target user group in sight.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **User studies**; **Virtual reality**.

KEYWORDS

Virtual Reality, Locomotion, Accessibility, Blind, Visually Impaired

ACM Reference Format:
Julian Kreimeier, Pascal Karg, and Timo Götzelmann. 2020. BlindWalkVR: Formative Insights into Blind and Visually Impaired People's VR Locomotion using Commercially Available Approaches. In *The 13th PErvasive Technologies Related to Assistive Environments Conference (PETRA '20), June 30-July 3, 2020, Corfu, Greece.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3389189.3389193

1 INTRODUCTION

Most people think of Virtual Reality (VR) as impressive visual-spatial aspects, i.e., the simulation of spatial information through stereoscopic rendering being presented to the users using a head mounted display (HMD). However, VR does also include other sensory feedback, like audio and haptic feedback which comes recently more and more into the focus of research and commercial application. A major benefit of VR is the fact that the sensory perception of the environment is computer simulated, in other words, these objects or rooms do not have to exist in reality or need to be physically constructed. Especially for blind and visually impaired people this is an promising possibility to perceive spatial information and overcome limitations of a real objects. For example, if a blind or visually impaired person wants to explore a new, unknown environment prior to actually visiting, they need a tactile map that needs to be physically produced, sent and stored. Maps that are accordingly large and detailed are often difficult to obtain at all and require a certain storage space. Also, such maps are mostly not interactive and cannot support the user when exploring it by for example audio feedback (e.g., "The object you just touched is the staircase to the second floor."). Such maps or illustrations are mostly allocentric and require the user to change to the egocentric perspective when visiting the real place. Alternatively, one can explore the real place (egocentrically), either on one's own (with the dangers of unwanted harmful collisions) or together with a sighted assistant (who is not always available).

In this context, there are already first approaches that allow the egocentric exploration of a virtual environment (i.e., the 3D scan in scale 1:1 of a real world place [27]), but the type of herein used locomotion (if implemented at all [12]) has not yet been investigated. To overcome real world's space limitation, this locomotion in VR should require as little real locomotion as possible. Certainly there are many implementation possibilities of this virtual locomotion [2–4, 6], but these are aimed at sighted people and are not necessarily all suitable for blind and visually impaired people. Especially, since appropriate software and hardware components are nowadays available as off-the-shelf components, this is an interesting aspect to consider regarding the independence and access to spatial information for blind and visually impaired people.

Thus, we present (to the authors' best knowledge) a first user study which proposes and evaluates different types of VR locomotion which is tested by blind and visually impaired participants. We involved two types of locomotion in a large scale virtual environment, i.e., a walk-in-place approach using a treadmill or VR trackers or a joystick based movement.

In the following sections we consider related work, explain our experiment in detail and present the results of our within-subject user study with seven blind and visually impaired participants. The

PETRA '20, June 30-July 3, 2020, Corfu, Greece

ACM ISBN 978-1-4503-7773-7/20/06…$15.00
https://doi.org/10.1145/3389189.3389193

results are thereafter presented and discussed in detail. Finally, we summarize the main findings of our work and draw implications for further improvements.

2 RELATED WORK

2.1 Egocentric Virtual Reality for Blind and Visually Impaired People

The idea of using VR for blind and visually impaired people is certainly not entirely new (e.g., [7]), but in the scope of this paper we would like to focus on related work that allows users to egocentrically perceive the (virtual) environment while also interactively controlling their movement in it. Regarding related work on the subject of VR for blind and visually impaired people outside this restriction we would like to refer to the detailed related work in [13, 27].

The first approach of egocentrically exploring a virtual environment dates back to 2003, when Lecuyer et al. [16] presented a multisensory white cane simulation along a predefined path. The participants perceived force, thermal and audio feedback when exploring a hand modelled virtual proxy of a real world environment and were able to control the locomotion using the white cane's force feedback. Instead of this very big setup, Merabet and Sachnez proposed in 2009 a pure audio VR simulation [18]. In their *AudioDoom* approach the participants could "move in any direction (stepping forward or turning right or left) and interact with the environment in a step-by-step fashion, so as to pass through a corridor or open a door " by "using a keyboard, mouse, or joystick". Tzovaras and et al. [26] presented in the same year a true scale white cane simulation using a force feedback data glove and motion tracking. Although the participants could actually walk inside the tracked area, the "maximum workspace was limited to a "7 m-diameter hemisphere around the tracker transmitter" which clearly limits the walkable space. In 2010 Torres and Gil [25] came up with a sophisticated walkable audio simulation, but such enormous space requirements are for a private person not practicable. Later, Lahav and Mioduser presented an audiohaptic exploration of a real world's VR model using a force feedback joystick [15]. This joystick controlled the players avatar in the virtual world and gave haptic feedback on the very surface the user was in this moment walking on. A similar approach was used by Sanchez to implement an audiohaptic game while controlling the player's avatar using a joystick [23]. In 2013 Maidenbaum suggested a sonification (i.e., mapping geometric distance to sound) approach to interactively explore a labyrinth while "navigation was accomplished using the arrow keys on the keyboard" [17]. Connors et al. also used a keyboard based locomotion when exploring a 2D virtual environment [8]. Picinali et al. presented an audio based exploration of a virtual building while the participants were "provided with a joystick as a navigation control device and a pair of headphones equipped with a head-tracking device" [20]. Guerreiro et al. published an approach of building a sequential cognitive map by virtually walking which is controlled by moving the user's smartphone for locomotion [10, 11]. Kunz et al. suggested real walking in a true scale tracked environment while using a special distance-to-sound mapping for exploring the virtual environment. In her latest work, Orly Lahav used a *Nintendo Wii* controller to enable the exploration of a virtual environment, in this very context to move the participants' perspective and position in space [14]. Most recently, Zhao et al. presented a sophisticated force feedback white cane simulation in a tracked and therefore also limited area [27]. To overcome space limitations in this context, Kreimeier and Götzelmann suggested to use a walk-in-place approach [12].

Thus, it can be classified that the user's avatar in the virtual environment can be controlled either by actually walking (with [26, 27] or without space limitations [12]) or by moving the users' avatar using a joystick [15], keyboard [8, 17] or other motion input [10, 14]. However, it is also known that "blind people can use virtual navigation to quickly learn real-world short routes" [11] with different types of locomotion.

2.1.1 *Types of VR Locomotion.*

As introduced earlier, the visual sensory bandwith exceeds the bandwith of haptics and hearing by far and therefore enables faster and more interactive types of locomotion. For the sake of completeness, these will be listed briefly below, whereby their suitability for blind and visually impaired people must be questioned. This aspect may justify the brevity of this section. The research field of virtual locomotion achieves more and more attention as the hardware and software has become available on the consumer market. There are currently several papers concerning VR locomotion [2–4, 6] which provide a complete and up-to-date overview in this regard. Most often, three main types of (sighted) locomotion are classified as follows: Point and teleport [5, 9], actually walking (either using a walk-in-place approach or redirected walking [1, 21]) or joystick-based locomotion. Boletsis proposed a typology for VR locomotion which defines "motion-based, room scale-based, controller-based and teleportation-based locomotion" [3] and Ruddle et al. [22] indicate that "locomotion devices such as linear treadmills would bring substantial benefits to virtual environment applications where large spaces are navigated". There are even approaches that tackle the sensory illusion of feeling the virtual ground surface [24] or ascending/descending virtual stairs [19].

3 METHODS

To approach the question on if and how which type of locomotion in VR is suitable and interesting for blind and visually impaired people, we conducted a user study. In this within-subject user study we presented a spatial-auditive navigation task to blind and visually impaired participants. The task consisted of walking towards a spatial sound source which disappeared when the user was close enough and reappeared at a random angle in a fixed radius around the user again. Each participant wore a HMD and a headset which provided binaural audio feedback, so the users could hear the fixed sound source in space and a step sound when moving in VR, depending on the users' head orientation.

As independent variable, we define the walk-in-place approach: Two different VR treadmills, a *HTC Vive* tracker based implementation and a joystick controlled locomotion (i.e., the joystick of a *Windows Mixed Reality* controller). These implementations are according to the authors' laboratory experience the most suitable approaches with a possible long-term dissemination potential. As dependent variable, we define the qualitative feedback and quantitative data from the participants. The former is gathered using

(a) (b)

(c) (d)

Figure 1: The *Cyberith Virtualizer* (a) and *Virtuix Omni* (b) VR treadmills which we used, below the respective step detection technology is depicted: Overshoes and optical sensors integrated into the ground plate (c) or IMU sensors on the special shoes (d).

a think-aloud approach and the latter is measured by an ordinal scaled questionnaire. We adopted the questionnaire from the NASA Task Load Index to the context of this user study to evaluating the locomotion interaction.

To understand the locomotion interface primarily from the perspective of blind and visually impaired users, we decided to first focus on the their subjective usability and practicability aspects. Other, more quantitative measures like performance metrics (e.g., travel time and velocity of the locomotion) are certainly also interesting, but we consider them to be subsequent detail optimization.

We mainly hope to find the most intuitive and precise implementation of VR locomotion, but suspect that the *Omni* treadmill will probably perform better than the *Virtualizer* treadmill in terms of precision due to its sensor technology. Both will be most probably surpassed by the joystick controlled approach, as this is entails the least physical effort. This approach could also perform better in terms of intuitive use and the users feeling of safety, maybe even better than the VR tracker based locomotion, which involves more physical interaction. Also, the treadmills might most likely also need the most physical effort. However, these are certainly only hypotheses at first, which we would like to investigate through the data collected from the participants and to also understand their perspective on VR locomotion.

3.1 Participants

Seven volunteers from nearby blind and self-help associations volunteered to participate in our user study, see Tab. 1 for detailed information. Thereof 4 are female and 3 male, the mean age is 38.7 ± 13.3 years. For each participant we also recorded demographic and visual acuity related data. To compress the contents of the table, 'Modern IT' summarizes smartphone, PC (screen reader) and braille display. 'DRON' means Disease of the retina and/or optic nerve not known in detail by the participant and 'RP' is the abbreviation of retinopathia pigmentosa while 'ONA' stands for optic nerve atrophy. All of them knew basic VR, whereas participant 4 and 6 already had experience with a VR treadmill [12]. However, no participant knew all types of locomotion being presented in this user study.

3.2 Procedure

Before the actual experiment began, the participants were given a detailed explanation of the purpose of the user study and all questions were answered in advance until they declared ready to start. The data shown in Tab. 1 were then collected and the experiment began with the randomly selected first type of locomotion.

Here, the participants were told how this type of VR locomotion works in detail and how walking in VR works best. At first, they could move arbitrarily to familiarize with the device while step sounds made the distance covered audible. Having familiarized with this device, the experimenters set the audio source active. This audio source was placed in a random direction at a fixed radius around the participant. Whenever the players avatar touched it, the audio source would disappear and reappear in a corresponding new position. Provided with such a spatially fixed audio source and spatial audio rendering, the participants could test this type of VR locomotion until they stated to have finished testing. This process took maximum approx. 5-10 minutes with any participant.

Thereafter, each participant filled an NASA-TLX adapted questionnaire (see Tab. 2) with assistance from the experimenters. They also noted a think aloud answer concerning the participant's conclusion of the locomotion implementation. Having completed this and answered any question that may have arisen, one of the remaining devices was randomly selected and the same procedure was carried out, Finally, the participants had tested all types of locomotion and were asked for an overall conclusion of all tested implementations of locomotion.

3.3 Questionnaire

To measure the usability of each locomotion implementation, we used a 10 point Likert-scale questionnaire investigating the feeling of security, speed, precision, intuitive use, mental, and physical workload which we derived from the well established *NASA-TLX* questionnaire, see Tab. 2. This followed consultation with blind and visually impaired people from previous user studies, so the original questionnaire would contain some questions that were unfavourable from their point of view whereas other relevant questions would be missing.

3.4 Virtual Environment

To implement the different types of locomotion, we used the *Unity* VR engine and off-the-shelf software and hardware components.

Table 1: Overview of participants' relevant data.

Participant	Sex	Age	Onset of blindness	Impairment	Residual Vision	Used Tech Assistance	VR Experience
#1	f	26	congenitally	DRON	0%	Cane and modern IT	none
#2	f	22	early	DRON	0-2.75%	Cane and modern IT	none
#3	f	58	early	DRON	roughly light/dark	Cane and modern IT	minor
#4	m	30	congenitally	ONA	1-2%	Cane and modern IT	minor [12]
#5	m	51	congenitally	DRON	roughly light/dark	Cane and modern IT	none
#6	f	32	congenitally	DRON	0%	Cane and modern IT	minor [12]
#7	m	52	congenitally	RP	0-1%	Cane and modern IT	little

Table 2: The context-adapted NASA-TLX questionnaire which we applied in our user study.

Question	Level of measurement
How safe did you feel using this type of locomotion?	1 (low) - 10 (high)
How fast did you move in VR?	1 (too slow) - 10 (too fast)
How precise were you able to move in VR?	1 (low) - 10 (high)
How intuitive felt this type of interaction?	1 (low) - 10 (high)
How mentally demanding felt the interaction?	1 (low) - 10 (high)
How physically demanding felt the interaction?	1 (low) - 10 (high)
What is your bottom line of this type of locomotion?	Qualitative feedback

Several computers and VR glasses or headsets were used so that the participants could test all implementations one after the other without waiting time for adjusting each VR setup. This certainly does not provide entirely identical conditions for all experiments, but since the focus of the user study is on locomotion and spatial audio rendering serves only for the purpose of spatial understanding, we consider this negligible.

For the *Cyberith Virtualizer* and the *Windows Mixed Reality* joystick we used a *Lenovo P51* notebook running *Unity*, the *SteamVR* plugin and the appropriate *Cyberith* plugin in combination with an *Acer AH100* HMD and *Logitech G933* headphones. The second treadmill *Virtuix Omni* was connected to a common desktop gaming computer running *Unity* and a *HTC Vive* HMD with a so-called *Deluxe Audio Strap* providing headphones. The *HTC Vive* tracker based approach used a common workstation computer running as well *Unity* and a *HTC Vive* with a so-called *Deluxe Audio Strap*. In all scenarios, the participants perceived spatial audio feedback using the *Resonance Audio* plugin.

Due to the different locomotion devices, the speed and accuracy of locomotion could only be compared to a limited extent. However, we matched the step size or speed as far as possible using the experimenters preference of realism.

The capsule collider of the avatar of the user had a radius of 0.5 m, just like the sound source object. The latter was automatically placed at a random angle in a 5 m radius around the users position, see Fig. 2.

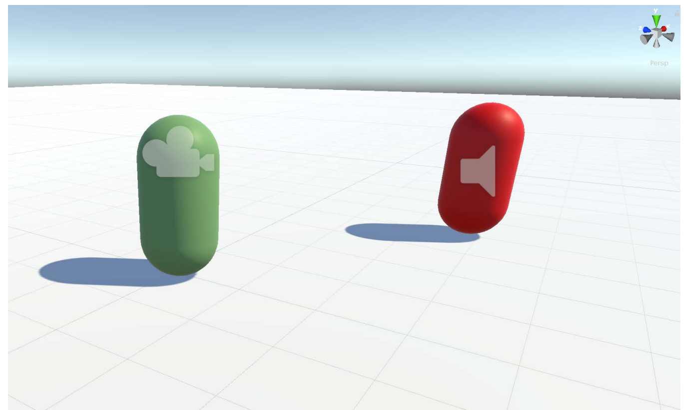
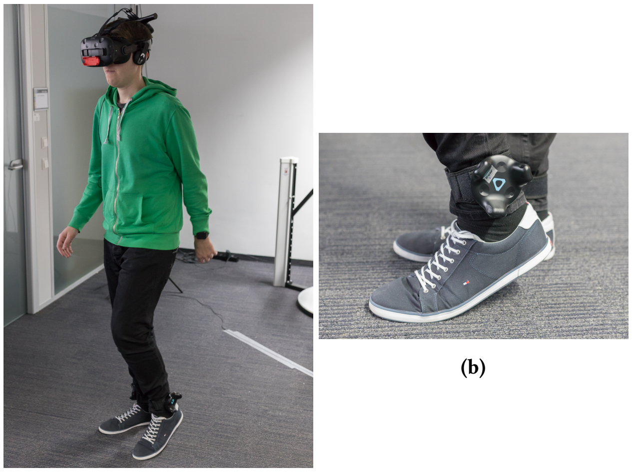


Figure 2: Implementation of the experiment in VR: The green capsule represents the user and is controlled by the actual locomotion implementation. When touching a red capsule (i.e., the audio source), the latter disappears and reappears in a new location around the user. The direction and distance from the green to the red capsule are audible by means of spatial hearing regarding the participants' head.

3.4.1 Cyberith Virtualizer. This treadmill detects the user's motion by the vertically adjustable and rotating harness in combination with the optical sensors in the ground plate, see Fig.1a and Fig.1c. Thus, the speed (i.e., the frequency of feet sliding over the sensors) and the direction (i.e., the position of the ring facing along the user's body) can be read into *Unity*. However, the manufacturer's SDK only provides a 'speed controller' variable to adjust the locomotion in VR.We left this to its standard value of 1 and also decided against the possibility of vibrating the base plate, as we thought this might unsettle the participants.

3.4.2 Virtuix Omni. This treadmill detects motion using IMU (inertial measurement unit) sensors which are mounted on each of the user's feet which slide along the parabola-shaped ground plate, see Fig.1b and Fig.1d. As with the *Cyberith Virtualizer*, the harness' height can be adjusted but is not flexible. In contrast, it can be opened on one side to enter or exit the device. As with the *Cyberith Virtualizer*, the direction and speed of locomotion is computed internally and can be only read using an *Unity* prefab from the



(a) (b)

Figure 3: The tracker based locomotion (a) with VR trackers mounted to the user's feet (b).

(a) (b)

Figure 4: The joystick based locomotion using an *Acer AH100 Windows Mixed Reality* HMD and a *Logitech G933 headset* (a), the user's input regarding speed and direction of locomotion is adjusted by tilting the left controller's joystick (b).

manufacturer. Here, we also left the movement parameters to their default values, as preliminary test proved these to be reasonable and comparable to the *Virtualizer*.

3.4.3 HTC Vive VR tracker based. To mount the *HTC Vive* VR trackers to the participants' ankle, we used *Govark* straps and the trackers were pointing sideways away from the user's ankle, see Fig. 3a and Fig. 3b. The participants had to alternately raise and lower their feet and we mapped the sagittal rotation speed of each tracker to a forward motion. As this rotation is physiologically linked to the lifting and lowering of each foot, the virtual step length respectively locomotion speed could be controlled by the amount and frequency of feet movement. The forward direction was determined by the cross product between the vector between the two feet and the upward vector which is known from the *SteamVR Lighthouse* setup. This implementation is certainly subject of further improvements which we plan to show later, but it fulfills the authors' purpose of a feasibility study with blind and visually impaired users in this first interaction test.

3.4.4 Windows Mixed Reality joystick. For joystick controlled motion, we used the *Acer AH100 Windows Mixed Reality* VR HMD, see Fig.4a. It comes with two controllers and uses optical inside-out tracking. The users were able to control the speed and the direction of VR locomotion by tilting the joystick on the left controller, which resulted in a corresponding movement with respect to the current orientation of the controller, see Fig.4b. As with the other implementations, the participants could move their head and body decoupled from this.

4 RESULTS AND DISCUSSION

The following section presents the quantitative and qualitative results of our user study. By randomizing the order of the tested devices per participant, learning effects that might interfere with the results can be prevented.

4.1 Quantitative Data

The color coded boxplots in Fig.5 show the distribution of each rating in our questionnaire (see Tab. 2) for all participants. Ideally, the red, green and light blue values are at its maximum of 10, the yellow at 5 and the dark blue and purple at its minimum of 0. This means the user feels perfectly safe with a most intuitive and precise type of locomotion while moving not too slow and not too fast with as little mental and physical workload as possible.

The following discussion is supplemented by parametric or non-parametric statistical tests indicating a significant difference, the Shapiro-Wilk normality test was used to test for decisive normal distribution. Depending on its results, either a Student's T-Test or a Wilcoxon's signed-rank test will be applied.

When looking the rating on the users' feeling of safety, the *joystick controlled locomotion* outperforms clearly all other devices as all participants gave this device the highest possible value of 10. This is followed in descending order by the *Virtualizer* treadmill, the *tracker* based locomotion and the *Omni* treadmill. The safety ratings on the *joystick controlled locomotion* are even statistically significant higher than those of the *tracker* based approach ($V=10$, $p=0.048$). This corresponds with our assumption that a movement with as little physical interaction as possible is perceived as the safest. Due to the special design and the mechanical play inside the ring of the *Omni* treadmill, this device performs somewhat worse than the other *Virtualizer* treadmill. The *tracker* based locomotion, however, has the lowest median value, which is probably due to the potential movement and therefore collision in real space.

When it comes to the rating on speed, *Omni* and *Virtualizer* values scatter more around the ideal value of 5 (i.e., not too slow and not too fast) than the remaining devices. This is most probably due to the applied technology which detects the real world steps and the users' subjective perception. The *tracker* based locomotion was oftentimes rated as too fast or too sensitive, which underlines the optimization potential of our yet basic step detection algorithm. The *Virtualizer's* optical sensor based step detection leads to rating values which are scattering even more, both towards a 'too fast' and 'too slow' rating. *Omni* and *joystick controlled locomotion* perform best, which is probably because of the former being a fully-developed commercial product and the latter allowing a much more precise input and thus control of speed and direction.

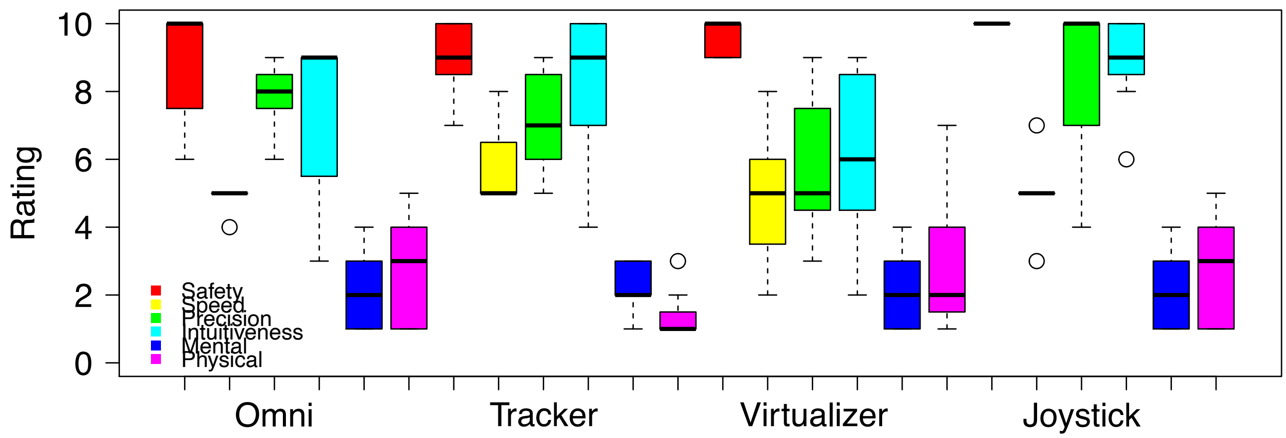


Figure 5: Box plots for questionnaire results regarding the four different implementations of locomotion.

Regarding the users' rating of the precision of the locomotion, the *joystick controlled locomotion* achieved the highest median value and overall highest values. *Omni*, *tracker* and *Virtualizer* follow in descending order. This distribution might be justified by the different input architectures: The simple movement of a joystick is much more precise and easier to control than capturing and interpreting the user's hole body when walking. With the latter, various inaccuracies in the mechanical construction and the software readout of the respective sensors apply. This underlines our previous assumption, the *Omni* ratings are statistically significant higher than those of the *Virtualizer* (t=2.3664, df=6, p=0.028), which felt less precise than the *joystick controlled locomotion* (t=-1.9718, df=6, p=0.048). Again, this is might be explained by the different sensor technologies to capture the users motion input.

With regard to the impression of an intuitive use of VR locomotion, the *joystick controlled locomotion* outperformed all other devices as the movement of the human hand and fingers is an everyday well-trained motion. Also, this motion input is less physically demanding than moving one's feet. The *tracker* based approach took the second place, probably because mimicking the well trained bipedalism did feel intuitive, but with the restriction of not moving in the real world. Among both treadmills on the last places, the *Omni* performs somewhat better because it has a sensor system on the user's feet, which captures a natural walking movement more precise than optical trackers embedded in the *Virtualizer's* ground plate. The *Virtualizer's* ratings are significantly lower than with the joystick based locomotion (t=-2.2818, df=6, p=0.031) which statistically underlines this characteristic and our initial assumption.

The mental workload in both the *Omni* and *Virtualizer* treadmill and the *joystick controlled locomotion* was rated equally, which shows that basically all devices were easy to use, but differ in terms of subjective impressions. The *tracker* based approach, however, scatters a little more towards a higher mental workload as the users might use additional load to just walk on the spot and not move in real space.

The overall physical workload reaches the highest values with the *Virtualizer*, as the sensors in the ground plate require the user to perform an energy-intensive feet sliding on the ground plate. *Omni* and *joystick controlled locomotion* are easier to use, since the user's input is less physically demanding (i.e., just moving one's hand and finger instead of sliding one's feet on the ground). The *tracker* based approach was assigned the least physical workload, probably because this approach mimics the intuitive human bipedalism which is physiologically well trained. The *Omni's* ratings are significantly higher than those of the *tracker* based approach (V=10, p=0.049) or *joystick controlled locomotion* (V=10, p=0.049). The same characteristic applies to the *Virtualizer* (V=15, p=0.027 and V=15, p=0.029). Overall, the physical workload data underlines our straightforward hypothesis that a larger degree of physical movement (even if it's well trained in everyday life) entails greater physical effort.

4.2 Qualitative Data

4.2.1 Regarding the Treadmills. When it comes to treadmill-based locomotion, most participants said that interaction felt somewhat unnatural because of too much cognitive workload (participant 5) and imprecision in terms of software and hardware (participants 3 and 4). Also, the storage space and acquisition cost problems of this somewhat bulky and expensive devices were questioned, these aspects do impede a possible dissemination of such technology (participants 1 and 4). However, between the two used devices some interesting differences in details were found: Participant 1 preferred entering the *Omni* device compared to the *Virtualizer* one, as this is possible from the side and not from above. Also, participant 3 would rather go for the *Omni* by "subjective feeling". However, both participants 1 and 5 made a remark on the disturbing loud noise when walking in it. Participant 5 described walking in the *Omni* treadmill less intuitive than in the *Virtualizer* because the harness has design dependent mechanical play within the harness, whereas participant 6 mentioned that "walking in it feel real, that's OK". For participant 7 the *Omni* felt "more precise than the other treadmill".

Overall, most participants preferred the *Omni* treadmill over the Virtualizer one, as its IMU based step detection felt more precise and reliable than with the *Virtualizer* which makes use of optical sensors in the ground plate. Yet no participant was completely satisfied with the step recognition and evaluation. For sighted people, "exact step recognition only plays a subordinate role in the visual context, but for blind and visually impaired people it does!" said participant 4. With regard to safety, the robust mechanical design and thus 'safe zone' of both devices was found to be positive. Additionally, one might include haptic information on the virtual ground on which the user is walking on (participants 1 and 7), but in this context a significant more precise step detection is crucial (participants 3 and 4) so that "each virtual step matches the real step" (participant 6).

4.2.2 Regarding the Tracker Based Locomotion. The *tracler* based locomotion received mixed reviews from the participants. One the one side, it is "much easier to use than a treadmill and therefore best controllable" (participant 3), with improvements even a possible alternative to a treadmill (participant 4). On the other side, the *tracker* based locomotion needs a more precise step and forward direction detection (participants 1-4 and 7) which should be less sensitive (participant 5). Therefore, participant 4 suggested to use IMU sensors as with the *Omni* treadmill that would ideally match every real world step to a virtual step. Thus, he could significantly reduce the amount of cognitive load since he had not to mentally map real world steps to virtual world ones (participant 5). However, participant 5 also commended the possibility to adjust the virtual step length by the degree of feet movement. Participant 4 suggested to define a more restricted type of real world motion which is mapped to the virtual locomotion and participant 1 proposed to "use a carpet tile as a floor indicator in order not to move unconsciously in the real world".

Nevertheless, walking using the VR trackers felt "overall best, closest to 'normal' walking". Participant 7 concluded that "placing the motion detection sensors as close as possible to the user's body increases the step detection performance" and would recommend this type of locomotion in the long run.

4.2.3 Regarding the Joystick Controlled Locomotion. When looking a the *joystick controlled locomotion*, most participants appreciated the "simplicity and practicality" (participant 1) of this approach. Participant 3 felt "significantly more agile" because the "(non-)movement of the legs affects the precision of the hands, so the orientation of the controller is perpendicular to the shoulders which is a good reference. The movement's speed and direction can be thus better controlled than with the treadmills". Participant 4 stated that "this is something a visually impaired or trained blind person definitely can use". Participant 6 considered this approach to be "the most practicable, least space consuming and easiest concept". Also, participant 5 said he liked the multiple possible ways of interactively controlling the locomotion and described this approach as a "neat gadget". However, participant 5 and 6 thought at first that tilting the *joystick* sideways would also rotate their point of view in VR, not make them walk sideways. After max. 5 minutes of testing they understood the system without any problems, but found it easier if one maintained a fixed position in real space and would turn in VR with the *joystick* instead of beeing able to walk sideways. Participant 4 suggested to test this in a more sophisticated audio-spatial virtual environment and participant 5 suggested to also convey different virtual floors surfaces via haptic or audio feedback. Participant 1 found the *joystick based locomotion* "not essentially less intuitive than the other types of locomotion, but the most accessible" and "if you once understood it, it works as well as the trackers". Participant 2 thought about "exploring unknown buildings while sitting the sofa at home" using this type of VR locomotion. Participant 7 also evaluated the ratio between effort and usability with the *joystick* implementation best, but the movement speed felt too slow and one would "developed only a reduced sense of space compared to actually walking using the VR trackers".

4.3 Lessons Learned

In the following we would like to summarize the main findings in a condensed form in order to facilitate further developments in this research field.

- The static *joystick* was determined as the safest device to use, and *tracker* the least safe because of possible collision in real space.
- The *Omni* and *joystick controlled locomotion* perform best in terms of speed.
- The *joystick controlled locomotion* topped the precision and intuitive user ratings.
- The cognitive load was nearly equal across all four approaches.
- The physical demand was higher with the treadmills than the other approaches.
- The quotative findings prefer *joystick* and *tracker* controlled locomotion, but also underline the potential for improvement in terms of step detection precision in all devices.
- The findings should be confirmed in a larger user study, but do open up novel perspective on blind peoples' VR locomotion for sighted developers.

5 CONCLUSION AND FUTURE WORK

This paper details the first user study to compare four types of VR locomotion (two *treadmills*, *trackers* on the ankles, and a *joystick*) to support egocentric VR locomotion with seven blind and visually impaired participants. Using a within-subjects approach, our study presented a navigation task, in which the participants were asked to move towards spatial sound sources with each hardware implementation. Quantitative results showed that the *joystick* controlled locomotion was determined as the safest device to use, and *trackers* on the ankles the least safest because of possible real world collisions. Also, the *Virtuix Omni* treadmill and *joystick controlled locomotion* performed best in terms of speed, the latter even topped the precision and intuitiveness user ratings. The cognitive load was about equal across all four implementations, whereas the physical demand was higher with the *treadmills* than with other devices.

The participants' qualitative feedback further contextualized these quotative findings, for example, as the the *treadmill*-based locomotion felt unnatural, space demanding, and less precise, whereas the *joystick* implementation was appreciated for "simplicity and practicality".

In the long run VR locomotion does offer promising opportunities for blind users: For example, to realistically explore an unknown environment beforehand. Our formative work is a first step in enabling this goal. By sharing this novel insights gleaned from the evaluation of existing commercially available VR locomotion approaches, we wish to support future researchers and practitioners in developing technologies with the target user group in sight.

ACKNOWLEDGMENTS

We thank all volunteers for their participation in the user study and their valuable feedback.

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*. ACM, 431.

[2] Ian Bishop and Muhammad Rizwan Abid. 2018. Survey of Locomotion Systems in Virtual Reality. In *Proceedings of the 2Nd International Conference on Information System and Data Mining (ICISDM '18)*. ACM, 151–154. https://doi.org/10.1145/3206098.3206108

[3] Costas Boletsis. 2017. The new era of virtual reality locomotion: a systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction* 1, 4 (2017), 24.

[4] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*. ACM, 205–216.

[5] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2019. Locomotion in virtual reality for room scale tracked areas. *International Journal of Human-Computer Studies* 122 (2019), 38–49.

[6] Fabio Buttussi and Luca Chittaro. 2019. Locomotion in Place in Virtual Reality: A Comparative Evaluation of Joystick, Teleport, and Leaning. *IEEE transactions on visualization and computer graphics* (2019).

[7] Chetz Colwell, Helen Petrie, Diana Kornbrot, Andrew Hardwick, and Stephen Furner. 1998. Haptic Virtual Reality for Blind Computer Users. In *Proceedings of the Third International ACM Conference on Assistive Technologies* (1998) *(Assets '98)*. ACM, 92–99. https://doi.org/10.1145/274497.274515

[8] Erin C Connors, Elizabeth R Chrastil, Jaime Sánchez, and Lotfi B Merabet. 2014. Virtual environments for the transfer of navigation skills in the blind: a comparison of directed instruction vs. video game based learning approaches. *Frontiers in human neuroscience* 8 (2014), 223.

[9] 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*. ACM, 147.

[10] Joao Guerreiro, Dragan Ahmetovic, Kris Kitani, and Chieko Asakawa. 2017. Virtual Navigation for Blind People: Building Sequential Representations of the Real-World. https://doi.org/10.1145/3132525.3132545

[11] Joáo Guerreiro, Daisuke Sato, Dragan Ahmetovic, Eshed Ohn-Bar, Kris M Kitani, and Chieko Asakawa. 2019. Virtual Navigation for Blind People: Transferring Route Knowledge to the Real-World. *International Journal of Human-Computer Studies* (2019), 102369.

[12] Julian Kreimeier and Timo Götzelmann. 2019. First Steps Towards Walk-In-Place Locomotion and Haptic Feedback in Virtual Reality for Visually Impaired. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, LBW2214.

[13] Orly Lahav. 2014. Virtual reality as orientation and mobility aid for blind people. 8, 2 (2014), 95–107. https://doi.org/10.1108/JAT-08-2013-0020

[14] Orly Lahav, Hadas Gedalevitz, Steven Battersby, David Brown, Lindsay Evett, and Patrick Merritt. 2018. Virtual environment navigation with look-around mode to explore new real spaces by people who are blind. 40, 9 (2018), 1072–1084. https://doi.org/10.1080/09638288.2017.1286391

[15] Orly Lahav and David Mioduser. 2011. Blind persons' acquisition of spatial cognitive mapping and orientation skills supported by virtual environment. 4, 3 (2011), 231–238. https://doi.org/10.1515/IJDHD.2005.4.3.231

[16] Anatole Lécuyer, Pascal Mobuchon, Christine Mégard, Jérôme Perret, Claude Andriot, and Jean-Pierre Colinot. 2003. *HOMERE: a Multimodal System for Visually Impaired People to Explore Virtual Environments*. Vol. 2003. https://doi.org/10.1109/VR.2003.1191147

[17] Shachar Maidenbaum, Shelly Levy-Tzedek, Daniel-Robert Chebat, and Amir Amedi. 2013. Increasing Accessibility to the Blind of Virtual Environments, Using a Virtual Mobility Aid Based On the "EyeCane": Feasibility Study. 8, 8 (2013), e72555. https://doi.org/10.1371/journal.pone.0072555

[18] Lotfi Merabet and Jaime Sánchez. 2009. Audio-based navigation using virtual environments: combining technology and neuroscience. 2, 3 (2009), 128–137.

[19] R. Nagao, K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose. 2018. Ascending and Descending in Virtual Reality: Simple and Safe System Using Passive Haptics. 24, 4 (2018), 1584–1593. https://doi.org/10.1109/TVCG.2018.2793038

[20] Lorenzo Picinali, Amandine Afonso, Michel Denis, and Brian F. G. Katz. 2014. Exploration of architectural spaces by blind people using auditory virtual reality for the construction of spatial knowledge. 72, 4 (2014), 393–407. https://doi.org/10.1016/j.ijhcs.2013.12.008

[21] Sharif Razzaque, Zachariah Kohn, and Mary C Whitton. 2001. Redirected walking. In *Proceedings of EUROGRAPHICS*, Vol. 9. Citeseer, 105–106.

[22] Roy A. Ruddle, Ekaterina Volkova, and Heinrich H. BÃijlthoff. 2011. Walking Improves Your Cognitive Map in Environments That Are Large-scale and Large in Extent. 18, 2 (2011), 10:1–10:20. https://doi.org/10.1145/1970378.1970384

[23] Jaime Sanchez. 2012. Development of Navigation Skills Through Audio Haptic Videogaming in Learners Who are Blind. 14 (2012), 102–110. https://doi.org/10.1016/j.procs.2012.10.012

[24] Hyungki Son, Hyunjae Gil, Sangkyu Byeon, Sang-Youn Kim, and Jin Ryong Kim. 2018. RealWalk: Feeling Ground Surfaces While Walking in Virtual Reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18)*. ACM, D400:1–D400:4. https://doi.org/10.1145/3170427.3186474

[25] M. A. Torres-Gil, O. Casanova-Gonzalez, and J. L. Gonzalez-Mora. 2010. Applications of Virtual Reality for Visually Impaired People. 9, 2 (2010), 184–193. http://dl.acm.org/citation.cfm?id=1852403.1852412

[26] Dimitrios Tzovaras, Konstantinos Moustakas, Georgios Nikolakis, and Michael G. Strintzis. 2009. Interactive mixed reality white cane simulation for the training of the blind and the visually impaired. 13, 1 (2009), 51–58. https://doi.org/10.1007/s00779-007-0171-2

[27] Yuhang Zhao, Cynthia L. Bennett, Hrvoje Benko, Edward Cutrell, Christian Holz, Meredith Ringel Morris, and Mike Sinclair. 2018. Enabling People with Visual Impairments to Navigate Virtual Reality with a Haptic and Auditory Cane Simulation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, 116:1–116:14. https://doi.org/10.1145/3173574.3173690