# Telewalk: Towards Free and Endless Walking in Room-Scale Virtual Reality

Michael Rietzler
michael.rietzler@uni-ulm.de
Institute of Mediainformatics
Ulm University, Ulm, Germany

Martin Deubzer
martin.deubzer@uni-ulm.de
Institute of Mediainformatics
Ulm University, Ulm, Germany

Thomas Dreja
thomas.dreja@uni-ulm.de
Institute of Mediainformatics
Ulm University, Ulm, Germany

Enrico Rukzio
enrico.rukzio@uni-ulm.de
Institute of Mediainformatics
Ulm University, Ulm, Germany


**Figure 1: The concept of Telewalk: The combination of perceivable curvature and translation gains along with a head based camera control allows to compress any virtual space to a pre-defined real world radius (in our case 1.5m). (Left) illustration of walking paths and (right) plots of the virtual and real path walked in our study application.**

## ABSTRACT

Natural navigation in VR is challenging due to spatial limitations. While Teleportation enables navigation within very small physical spaces and without causing motion sickness symptoms, it may reduce the feeling of presence and spacial awareness. Redirected walking (RDW), in contrast, allows users to naturally walk while staying inside a finite, but still very large, physical space. We present Telewalk, a novel locomotion approach that combines curvature and translation gains known from RDW research in a perceivable way. This combination enables Telewalk to be applied even within a physical space of 3m x 3m. Utilizing the head rotation as input device enables directional changes without any physical turns to keep the user always on an optimal circular path inside the real world while freely walking inside the virtual one. In a user study we found that even though motion sickness susceptible participants reported respective symptoms, Telewalk did result in stronger feelings of presence and immersion and was seen as more natural then Teleportation.


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## CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**.

## KEYWORDS

Redirected Walking; Virtual Reality; Telewalk

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## 1 INTRODUCTION

Navigating inside virtual worlds is challenging to realize, since the scale of the virtual world does not necessarily match the one of the real world. When consuming VR content in a room-scale application, the available real world space does seldom exceed 3m x 3m. The current solution to allow navigation within such a small space is the use of point and teleport, where a user instantly changes their position without actually moving inside the real world. Though this solution is suitable to allow navigation in VR, it still comes with drawbacks, such as the missing feeling of actually moving or the loss of spatial awareness [6]. However, teleportation also has advantages over natural walking that go beyond pure feasibility. Even long distances can be covered in a very short time. For many applications such a technique is a pleasant and comfortable way to move through a virtual world.

An alternative to teleportation is the use of manipulations to trick the user to walk within a given real world space while walking a different path inside the virtual world. Such manipulations are summarized under the term redirected walking (RDW). To design the manipulations of a RDW technique in a way that it is suitable or even unperceivable for users, the required space is still far to big to be realized within a 3m x 3m tracking space.

We propose Telewalk, a novel navigation technique that is based on very strong RDW manipulations to allow infinite and free walking within a 3m x 3m tracking space. Telewalk combines the advantages of RDW and teleportation. The proposed interaction technique has only low demands on the physical space, is based on natural walking (in order to convey a stronger sense of space) and also enables rapid movement within the virtual world. Telewalk essentially works based on three main mechanisms. (1) Perceivable RDW gains: translation gains scale the user's velocity, which leads to a slow pace and smaller steps. As a result, higher curvature gains can be applied, which lead to a smaller radius of the circle, the user walks on. As soon as the user continues to walk faster in the real world, however, an unnaturally fast movement can be achieved. (2) To ensure the user always remains on the optimal path around the tracking space's center, we use the head of the user as input device to allow virtual direction changes without actually turning the body. (3) As a last feature, we included a visual guidance to keep the user aware of the optimal path and direction.

Telewalk also offers great potential for expansion. While the technique presented in this paper is based on a real path around the center of the physical tracking space, it is also possible to define a path that takes into account the individual room geometry including obstacles such as tables and chairs.

We implemented Telewalk in several iterations and optimized it based on user feedback. In a user study, we compared our final implementation of Telewalk to the state-of-the-art locomotion approach: Teleportation. The results show that Telewalk leads to a significant increase of presence and was seen as more natural then teleportation. On the other hand, Telewalk also lead to an increase of motion sickness symptoms, most of all to motion sickness susceptible participants. Overall, half of the participants preferred to navigate through a virtual world using telewalk, while the other half preferred teleportation. A further advantage of Telewalk is the exact predictability of the path taken in the real world. This way, the available space can be optimally used and walking on small areas can be realized.

The contributions of the paper are the following:

- The description and implementation of the Telewalk locomotion technique, which allows for continuous movement in space as small as 3x3 meters
- A user study showing that Telewalk can enhance the feelings of presence and immersion
- Implications for future Telewalk implementations and suggestions based on our own experience and participant's feedback

# 2 RELATED WORK

## 2.1 Overview

One of the goals of many virtual reality applications is to provide realistic navigation through the simulated world. Here both of the two main components, the cognitive way-finding and the physical (active or passive) travel [6] need to be available for users. Way-Finding here denotes the spatial-cognitive process of finding a route from one location to another, while travel encompasses the actual movement through the virtual environment. This movement can be carried out in a passive manner (i.e. using a joystick) or active (i.e. moving physically). Latter case is often denoted as locomotion.

Walking is considered to be the most natural way of moving through a virtual world [38], but due to the real world spatial limitations of current virtual reality setups, other locomotion techniques were introduced [35]. Boletsis et. al [2] provide a topology of such techniques, grouping them into four categories (motion-based, roomscale-based, controller-based and teleportation-based). Their categorization is based upon factors like physical or artificial interaction, continuous or non-continuous motion, and limitations of the virtual interaction space.

One common factor amongst most of these locomotion techniques is the occurrence of the so-called simulator or cybersickness with certain users. These are in general considered to be subsets of motion sickness and therefore the symptoms of both are related, including eye strain, headache, sweating, vertigo and nausea [21]. The most accepted theory about the cause of motion sickness is the sensory conflict theory [28]. It states that the body is not able to handle dissimilar information from different sensory systems. When locomotion techniques create such a conflict, due to them presenting different visual stimuli from vestibular ones (e.g. showing visual motion to a standing observer) they can possibly cause motion sickness to occur.

## 2.2 Walking-in-Place

One technique that aims to be realized within a small real world space while moving through the virtual world is the so-called walking-in-place approach [20, 25]. Here users only move their arms, head or legs up and down, while standing on a spot. The system translates said movement into a virtual forward motion. This approach was rated worse compared to actual walking, but better compared to virtual flight [38] or movement based arm-swinging [39].

The walk-in-place (WIP) approach can be enhanced by using a passive or active platform beneath the user, that allows for step movements to be performed more naturally while still staying in one spot. Such treadmills [3, 4] or larger even robotic moving platforms [17] still show less performance compared to real walking [23], as full physical movement increases the efficiency of any navigational search, due to better spatial memory [30].

## 2.3 Teleportation

The approaches mentioned above all cause some form of sensory conflict, as the presented virtual motion does not match the physical motion and can therefore lead to motion sickness symptoms. One locomotion approach that avoids such sensory conflicts is Teleportation – used in nearly all current VR applications. It avoids the conflict by never presenting any kind of motion, instead instantly transporting the user to the target. Teleportation therefore does not suffer from motion sickness [7].

There are however disadvantages to these instant location changes, as they might influence spatial awareness and presence in virtual world negatively [1, 5, 10, 31]. Bowman et al.[6] found that these changes cause spatial disorientation in users, while Christou et al.[9] suggest the overall impact of disorientation on the experience to be negligible, though the potential of missing elements along the route is not.

## 2.4 Redirected Walking

Unlike the WIP or teleportation approaches, redirected walking (RDW) aims to provide unlimited natural walking in VR while still requiring a limited physical space. In order to achieve this, RDW manipulates the users orientation, position or other features. The manipulation of the user's orientation during walking is called curvature gains, presenting the user with a straight virtual path, but manipulating them to walk in a circle in the real world instead [27]. Suma et al. [36] introduced a taxonomy for redirections and reorientations, ranging from subtle, as above, to overt manipulations. Using overt manipulations keeps the discrepancy between virtual and real travel path small enough, so that users may not be able to detect any manipulation. The redirection can occur in different ways, with the two main types being through curvature or translation gains.

Curvature gains are described as a rotational manipulation that is applied during walking. It can be described in the unit degree per meter and can be interpreted as a change of the user's coordinate system while walking. Using curvature gains Steinicke et al. [34] have been able to redirect users onto a circular path with 22m radius without the users being able to detect the manipulation. Another solution, which reduces the required space was suggested by Langbehn et al. [20]. They propose to force the user to walk on already curved paths and additionally apply curvature gains.

Translation gains do not manipulate the orientation, but the velocity during walking. Interrante et al. [16] introduced a system that applies moderate gains onto the users motion, but only in the direction of travel, allowing for a much faster and preferred method for traversing linear corridors. Grechkin et al. [12] used a combination of curvature and translation gains and were able to improve the detection radius down to 12m. It has been shown that translation gains do not influence the detection thresholds of curvature gains, however the velocity of walking during the redirection does [24]. It was also proposed to redirect a user while standing still and turning around. This kind of gains was called rotation gains [18].

While the gains described were examined from the point of view of the perception of manipulation (detection threshold), Rietzler et al. propose to examine gains for their acceptance [29]. They report that curvature gains could be increased up to $20^{\circ}m$instead of the perception threshold (which was reported between $2.6^{\circ}m$ [34] and $4.9^{\circ}m$ [12]).

As long as the users remain on a straight, fixed virtual path, redirection has not to contend with any further factors, but in order to allow for virtual direction changes, further redirection mechanics have to be introduced, to keep users within the physical boundaries. For this problem, Razzaque presented three redirection algorithms that adjust the gains dynamically based on the current position of the user: Steer-to-center, steer-to-orbit, and steer-to-multiple-targets [27]. If the user still collides with the boundaries of the tracking space, a reorientation phase is started in which the user is turned around towards the tracking space's center. In a comparison between these algorithms, steer-to-center was found to be the best performing, while steer-to-orbit is best used for long straight virtual paths [13].

To make all these reorientation phases less obvious distractors were introduced [26, 33]. To avoid interruptions like this, Hodgson et al. [15, 33] presented an algorithm for very large spaces, i. e., 45m 45m. Sometimes though the boundaries cannot be fully avoided and the user needs to be reset. Here Wilson et al. [39] introduce several resetting techniques, that ensure the users' reorient themselves back into the tracked space. Sun et al. [37] propose a technique that utilizes eye-tracking to detect saccadic eye movements in which the user is temporarily blind to apply higher manipulations.

Telewalk uses some results of the presented works. The basic mechanism is based on combining translation and curvature gains. While these are mostly hidden for the user, for Telewalk they are obviously and deliberately used as an interaction technique. Similar to teleportation, the user is always aware that real movement is different from virtual movement. This circumstance allows a stronger compression of the virtual space. Furthermore, a higher virtual walking speed can be achieved in order to overcome greater distances in a shorter time - similar to teleportation. As described in the following, new visualization metaphors will be introduced, which should enable the user to keep control at all times.

# 3 DESIGNING THE TELEWALK

Current VR navigation approaches, which are based on real walking, basically place demands on the real or virtual space. While for example the use of unperceivable gains still requires a huge physical space to be applicable, other approaches, such as the proposed circular paths [20], require a specific path the user walks inside the virtual world. Currently there is no real walking technique that can be applied within small tracking spaces without limiting the VR application or the way a user walks within the virtual world. With Telewalk, we aim at proposing a solution that overcomes these limitations to allow a more natural navigation inside VR applications.

Telewalk is a novel concept for navigation that consists of three parts: (1) Manipulations (RDW gains), (2) a camera control that realizes directional changes based on head rotation instead of physical turns and (3) visual guidance.

## 3.1 Overview of the Challenges

The required real world space of a RDW technique most of all depends on the strength of the gains that are applied. These gains have their limits, since too high gains would lead to cybersickness, disorientation and would at some point no longer be pleasant for the user. In a preliminary work we propose a maximum of acceptance for curvature gains at a level of around $20°m$ [29]. This reduces the required physical space to around 6x6m for walking a straight path. But there is an additional challenge when implementing RDW: the technique that ensures the user keeps within the available real world space. Most tests on RDW were done on walking a short straight line. Curvature gains, for example, keep the user walking on a circle with a certain radius, but as soon as the user turns around, these gains would have to be increased or decreased to keep the user within the available space. Since such turns are unpredictable, the actual implementation of a RDW approach would require additional space and variable gains.

## 3.2 Curvature and Translation Gains

The first problem we tried to solve with Telewalk was the limitation of gains. Depending on the source, it was suggested to use gains of a maximum of $2.6\ °m$[34] or $4.9°m$[12] because users will be aware of the manipulation. Problematic with the use of such gains is the enormous space requirement which is 44m x 44m (for $2.6°m$) or 23m x 23m (for $4.9°m$) to realize only a constant forward motion – if the user changes the direction, this space requirement would increase even further. The suggested maximum gain considering acceptance instead of detection still requires around 6m x 6m for infinitely straight walking [29]. To realize walking on a space of 3x3m, gains of around $38°m$ are required. To further further increase the acceptance of higher gains, Telewalk is designed to use curvature gains in combination with translation gains (as suggested by Grechkin et al. [12]). It has been observed that walking at reduced speed leads to fewer detection rates for curvature gains [24]. We assumed that with higher translation gains the walking speed would decrease and thus the acceptance of higher gains would increase. While Grechkin et al. evaluated the influence of low translation gains (scaling the velocity by a factor of 1.4) we applied much higher gains with a maximum scale of 5. Since such high translation gains proved to be confusing when being designed as a constant, we decided to design them dependent on the current velocity a user walks. The higher the pace the higher the applied gains. With this mechanism we aimed at forcing the user to walk slowly, as small steps are sufficient to cover greater distances.

For the concrete implementation of Telewalk we take the available tracking space, fit the biggest circle and use its diameter to calculate the required curvature gain ($G_c$) as follows:

$$G_c \quad \frac{360}{\pi \cdot d} \tag{1}$$

The first implementation of translation gains considered the current velocity of the user or the translation between two frames respectively and scaled this translation according to the current gain. We found this scaling to be causing motion sickness, since when applying the translation gain on the translation vector between two frames, the bouncing of the head while walking is scaled as well. In case of the maximum (being scaled by the factor 5), bouncing 3cm to the left and right would lead to bouncing 15cm. This was reported to be uncomfortable by several test users. We therefore decided to apply the translation gain not as a scaling factor for the actual translation, but as an additional translation into the current optimal direction the user should walk given their current position inside the tracking space. This optimal direction ($V_o$) can be computed as the normalized orthogonal vector of the one between user and tracking space center and can be imagined as the tangent of the circle the user should walk on.

Test users additionally reported that the use of the current velocity let the gain alternate very strongly. We therefore decided to use the velocity calculated by the user's translation in the last second. The result was a slowly increasing but still responsive gain when starting to walk. The concrete implementation used this distance minus 0.2m (to exclude motions of the head while standing still), divided by 0.2 and clamped to a value between 0 and 1. The result is than multiplied with the defined maximum gain (which was in our case the constant of 5).

The maximum gain is therefore applied at a velocity of 1.44 km/h or higher. With a velocity of 0.72 km/h or lower the applied gain is 1 (no manipulation). With a velocity between 0.72 km/h and 1.44 km/h the gain linearly increases from 1 to 5.

The final implementation to calculate the current translation gain ($G_t$), with $v$ being the velocity within the last second, was as follows:

$$G_t \quad \frac{\|v\|-0.2}{0.2} \cdot 5 \cdot \|v\| \cdot \overrightarrow{P_c - P_u}^{\perp} \tag{2}$$

with $P_u$ being the position of the user; $P_c$ being the center of the tracking space and $\|v\|$ being the magnitude of the translation of the user within the last second and $\frac{\|v\|-0.2}{0.2}$ being clamped between 0 and 1; All calculations are done in 2D space.

## 3.3 Using the Head as Controller

The second problem we tackled was the directional changes a user performs to walk freely inside the virtual world. We implemented the *steer to center* as well as the *steer to orbit* approaches as suggested by Hodgson and Bachmann [14]. Since our approach relies on applying very high gains, the suggested approaches proved to be inapplicable for Telewalk, since they resulted in very high deviations of the curvature gains within a short time and too often required reset strategies since we aimed at implementing Telewalk within a 3m x 3m space. Test users stated that these deviations of the applied gains made it impossible to navigate and lead to strong feelings of motion sickness. We therefore required to find an approach that allowed constant curvature gains while still allowing the user to turn around inside the virtual space. This is why we used the head as input device to realize turning without any actual physical turn.

Directional changes are usually realized by rotating the virtual camera. In case of a VR application, camera rotation is triggered by rotating the head. If the full body is turned (e.g. to change the direction of walking) this directional change is still realized by a rotation of the camera, since the head rotates in line with the body. To allow body turns without any physical turn we needed to divide these kinds of camera rotation two parts: Looking around and turning around. In our implementation, the head triggers both of these actions. While the head rotation itself is mapped one to one on the virtual camera, rotating the head over a defined maximum triggers an additional virtual body turn, which is realized by rotating the virtual world around the the camera.

For the concrete implementation, we defined a region of $\pm 10°$ from the optimal path (the tangent of the circle the user walks on) to be ignored for directional changes. For the region between $\pm 10°$

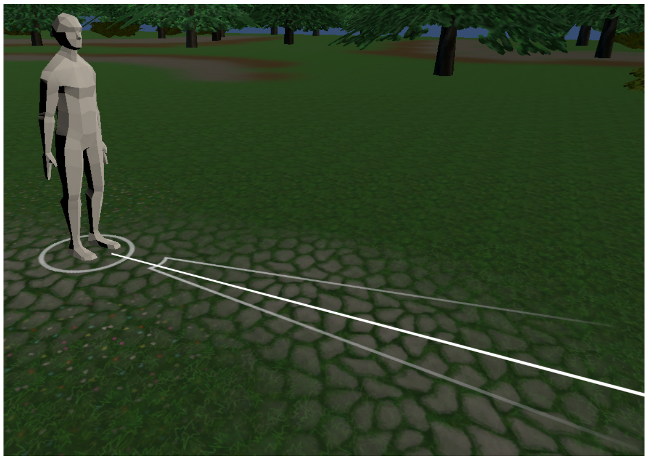

**Figure 2: The visualization of the optimal path including the spot with the optimal distance to the tracking center and the two lines indicating the optimal direction. The user's viewing direction is visualized by a single line.**

and $\pm 35^{\circ}$ we applied a linear increasing rotation (similar to turning a joystick to the left or right to control a character). The maximum rotation per second was defined as $80^{\circ}$. If the user exceeded the $35^{\circ}$ from the optimal path, the virtual character was rotated by the maximum of $80^{\circ}$/s.

### 3.4 Visualizing the Optimal Path

Without any visual guide, this approach turned out to be uncontrollable, since the user was unaware of the optimal direction. We therefore decided to include a visual guiding system indicating the region in which no rotation is applied. It consists of the current gaze direction in form of a needle like a compass as well as a visualization of the optimal direction as two lines as triangle displayed in front of the use. Both were displayed on ground-level in front of the user (see 2). Though this visualization helped users to keep well oriented, they still tended to walk too far or too close to the tracking center. While walking to far obviously leads to leaving the tracking space, walking too close leads to very fast changes of the optimal direction since the circle the user walks on becomes smaller. We have therefore decided to separate the position of the optimal direction indicator from the position of the user. The starting point of the needle was always fixed at the point which intersects the circle of the optimal distance with the line between the circle center and the current user position. Thus the line served as an additional visual aid to follow the optimal path.

### 3.5 Turning the Telewalk On and Off

To ensure, the user always remains on the optimal path around the center of the tracking space, we turned the Telewalk off as soon as the user's distance to the optimal position passed 30cm. In this case the users could walk without any manipulations as long as they reentered the optimal position. We also included a button that could be pressed to manually turn the Telewalk on and off. If a user for example reaches a region of interest, they could deactivate the Telewalk to examine the region more closely. The visualization of the optimal position remained visible at the position where Telewalk was turned off, but the optimal direction was set to invisible until it was reactivated.

In the user study we noticed, though, that this feature was seldom used and that participants constantly walked using the Telewalk, and without turning it off.

### 3.6 Paths beyond optimal circles

In this work, the optimal path was realized as a perfect circle around the center of the tracking space. However, it is also possible to realize this path as long as the start and end points are equal. For example, you could define a path that makes optimal use of the room geometry and considers obstacles such as furniture. Since such paths do not have a constant curvature like a circle, it would be necessary to adjust the curvature gain to be applied as well as the visualization of the optimal running direction to the current curvature. This approach would make it possible to use Telewalk in rooms where not even 3m x 3m free space is available. On the other hand, in larger rooms it would be possible to have an overall longer path available. This would reduce the average required curvature gain.

## 4 STUDY

To get insights on the performance of the Telewalk navigation approach, we designed a small virtual environment that included several points of interest the participants could navigate through. We tested and compared two navigation approaches: Telewalk and Teleport, being the most commonly used navigation approach in VR for room-scale applications.

### 4.1 Participants

We recruited 18 participants (2 female, 1 non-binary) with a mean age of 25, ranging from 19 to 29. Most of them were students or employees of our university since we recruited on campus. The participants stated to spend 4 hours per week consuming VR content in mean, varying between 0 and 10 hours. Additionally we used the motion sickness susceptibility questionnaire (MSSQ) [11] to get insights on the general sensitivity of our participants towards motion sickness in general. We only used the MSB score (the one concerning the participants experiences over the last ten years). The mean score over all participants was at around 4.3 ranging from 0 to 7.9. Our sample therefore included both, motion sickness susceptible and non-susceptible participants.

### 4.2 Method and Procedure

Our study was designed as within-subject having the locomotion approach as independent variables leading to two conditions: (1) Telewalk and (2) Teleport. We compared both approaches concerning several attributes that were considered relevant for a navigation approach in VR. Our metrics follow the suggested quality metrics of Bowman et al. [6]. They propose that an effective navigation technique should implement the following attributes: (1) speed, (2) accuracy, (3) spatial awareness, (4) ease of learning, (5) ease of use, (6) information gathering and (7) presence. We used self-reports to measure the respective attributes, since we aimed at measuring the perceived quality of the respective locomotion approaches. Most of the named attributes were assessed via single questions using a five point Likert scale titled as *absolutely disagree*, *slightly disagree*, *neutral*, *slightly agree* and *absolutely agree*. The questions were formulated as follows:

(1) "*The speed with which I traveled through the virtual world was appropriate*", (2) "*I could navigate with a high accuracy*", (3) "*I never lost track of my position and orientation within the virtual environment*", (4) "*I could easily learn how to move inside the virtual world*", (5) "*The navigation technique was too complex*", (6) "*I could obtain information from the environment during travel*". In addition to these items, we included two further Likert scale questions: "*The way I moved through the virtual world felt natural*" and "*I had the feeling of truly moving through the virtual world*", which targeted at providing insights on additional features a locomotion technique should implement according to [38]. Since the Telewalk approach uses very high RDW gains which could lead to symptoms of motion sickness, we also included the simulator sickness questionnaire (SSQ) [19]. To get insights on the performance of Telewalk compared to Teleport regarding presence, we included the SUS presence questionnaire [32]. Additionally we included the E$^2$I questionnaire [22] to measure immersion and enjoyment.

In a post questionnaire that the participants answered after both conditions, we asked the participants to state which navigation approach they did prefer and asked them to write down general feedback of the navigation approaches as well as to state for which kind of application they would prefer Teleportation or Telewalk.

The order of the two conditions was counterbalanced over all participants.

## 4.3 Study Application

We designed the virtual environment in a way it provided both, longer walking distances without special events that captured the participants' attention as well as shorter distances. The path the participant needed to navigate through further included two passages where a high accuracy was needed (two small bridges that had to be crossed). On the way through the environment seven attractions or obstacles were presented. It was a fantasy world where the participants could find for example a wizard, a knight or a giant. The places where such creatures were displayed invited for closer exploration, which should lead to users moving beyond the intended locomotion mode during both Teleportation and Telewalk.

## 4.4 Results

The analysis described in the following was done using a Wilcoxon signed rank test for dependent variables. The results are interpreted as significant with p values below the 5% level and as highly significant with p-values below 1%. Boxplots of the results of the presence, immersion and enjoyment as well as the SSQ scores are presented in figure 3. The single item questions are presented as diverging stacked bar chart in figure 4.

A Wilcoxon signed-rank test showed that Telewalk and Teleport did elicit a highly significant change regarding the **SUS presence** score (Z = -3.11, p = .002, r = .52), with Telewalk resulting in more presence. Telewalk lead also to a significantly higher immersion (Z = -2.54, p = .011, r = .42). The $E^2I$ enjoyment scores, though, did not show a significant difference (Z = -.80, p = .422, r = .13).

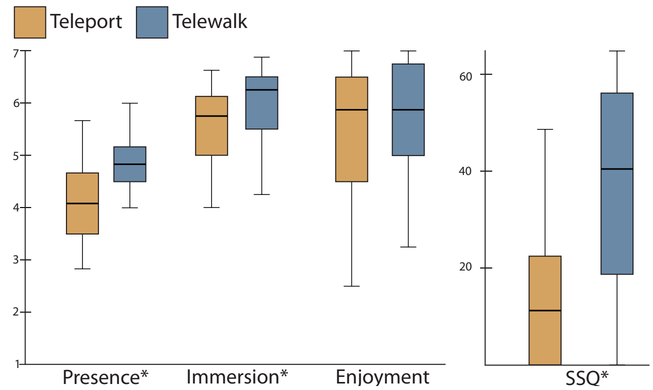


**Figure 3: Boxplots of presence (SUS), immersion and enjoyment (E$^2$I) and simulator sickness (SSQ) scores. The marked comparisons were significant on the 5% level.**

Regarding the SSQ scores, again a highly significant difference was found (Z = -3.41, p = .001, r = .57), with Telewalk being used for navigation resulting in stronger symptoms of simulator sickness. We also compared Telewalk and Teleport by the ratings of the single item questions as described in the method section using Wilcoxon's signed rank test. While Telewalk was rated as significantly more complex (Z = -2.11, p = .035, r = .35), it provided on the other hand a significant higher feeling of truly moving through the virtual world (Z = -2.33, p = .020, r = .39) and felt significantly more natural (Z = -2.01, p = .041, r = .34) and allowed to obtain more information from the surrounding (Z = -2.11, p = .038, r = .35). The remaining items, being whether the speed was seen as sufficient (Z = -.59, p = .557, r = .10), the perceived accuracy (Z = -1.00, p = .318, r = .17) and ease of learning (Z = -1.00, p = .317, r = .17), were not significantly differing between Telewalk and Teleport. The results are illustrated in figure 4.

To get insights if we could predict the feeling of motion sickness in the Telewalk condition using the MSSQ scores, we performed a Spearman correlation on the MSSQ and SSQ scores of the Telewalk condition. There was a positive correlation between MSSQ and SSW scores, which was statistically significant ($r_s$ = .548, p = .045).

## 4.5 Final Rating and Textual Feedback

After both conditions were rated by the participants, they were asked to fill a last questionnaire containing one answer in which the participants were asked to state which locomotion approach they preferred. Both, Telewalk and Teleport were chosen 9 times as favorite locomotion approach. The additional textual feedback for both locomotion approaches gave further insights on these ratings.

Those who rated telewalk as preferred locomotion approach commended the naturalness and ability to closely examine the surrounding. Even some of those who preferred teleport reported that the feeling of walking through the virtual world "was a great experience". On the other side, Telewalk was criticized most of all for the head controller that was not smooth enough and too fast for some of the participants. One participant (who preferred the Teleport condition) stated that "Telewalk was actually way better for immersion [...] and one was actually able to walk for an extended

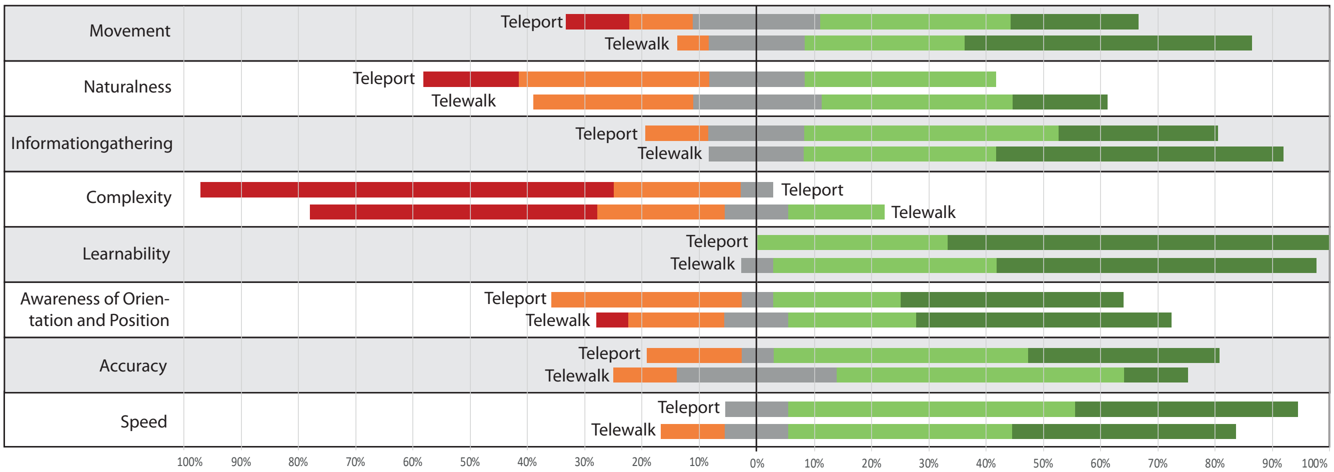


**Figure 4: Diverging Stacked Bar Charts of the single item questions as described in the *Method* section.**

period and with some speed. However, nausea was a real problem for me, reducing the quality of the experience." Similar feedback was given by multiple participants who preferred Teleportation. Besides the feeling of motion sickness, convenience and the increased complexity compared to teleportation were the main reasons why participants rated Teleportation as preferred navigation technique. Some also suggested to combine both approaches by offering both techniques at the same time.

We also asked the participants to state for which kind of application Telewalk or Teleport would be more suitable. Here we could observe clear tendencies. Teleport was most of all preferred for applications in which the world being traveled is not of interest or for traveling very fast between two points. Telewalk in contrast was seen as most suitable for applications that are designed for being immersive, explorations or for scenarios where both hands are needed. These insights support the desire of some participants to offer both techniques at the same time.

### 4.6 Discussion

With Telewalk we aimed at developing a locomotion approach that allows navigation in VR in a more natural way to increase presence and immersion, without limiting other factors that are considered to be relevant for VR navigation. As the significant increase in presence and immersion shows, Telewalk was able to meet these requirements – though not for all participants. The current implementation raised symptoms of motion sickness for some participants, while others showed no symptoms at all. We further found a positive correlation between SSQ and MSSQ scores, indicating that the susceptibility to motion sickness strongly influenced the respective symptoms of simulator sickness during Telewalk. Since motion sickness was named the most important factor to dislike or to avoid the use of Telewalk for our set of participants, we argue that most of all for motion sickness susceptible users further strategies to avoid motion sickness have to be found. In addition, Telewalk was considered to be more complex than Teleport. However, these results are difficult to interpret as the majority of the participants already had VR experience and were familiar with the teleportation metaphor, while being novices using Telewalk.

## 5 LIMITATIONS

### 5.1 Study

Since we used a within-subject design, we cannot guarantee that one condition did not influence the other, which is most of all important for the SSQ scores, since symptoms can last for a longer period of time. Though we told the participants to wait for the second test until they felt like before the first test, an influence by the within-subject design cannot be excluded. Further, our application was designed to be explored, including several points of interest and events occurring during the experience. This could lead to a decrease of the feelings of presence, immersion and enjoyment for the second trial (since everything was already discovered). The counterbalancing should compensate such effects, but there are still possible influences. The application design further could have lead to more positive ratings for the Telewalk condition (at least for some participants), since the exploration of a virtual world was considered to be one of the most suitable applications for Telewalk. We suspect that some of the ratings would have been different if a less spectacular world had been presented or if only reaching a certain point in the virtual world had been chosen as task.

### 5.2 Approach

The study results suggest two main assumptions. On the one hand, the Telewalk mechanism seems to be very well suited for exploring immersive worlds. How suitable the mechanism would be for other tasks would have to be shown by further studies. On the other hand, it has also turned out that the current implementation is not yet applicable for all users. The strong correlation between MSSQ and SSQ scores suggests that the Telewalk in its current state is particularly suitable for users without motion sickness susceptibility. We assume that by further optimizing the algorithms or choosing additional or modified gains, the motion sickness can also be reduced. Additionally we aimed at highly reducing the space requirements thus the used space was 3m x 3m. If more space is available, both gains could be reduced which assumably would decrease the feelings of motion sickness.

It might also be of interest to investigate long-term effects on motion sickness in the future. Recently it was shown that the sensitivity to notice curvature gains changes over time [8]. Similar effects could also occur in the field of motion sickness. In the present study, however, the duration of the VR experience was too short to be able to make any statements about this. Since motion sickness is currently the biggest limitation of the presented technique, we consider it useful to conduct further studies with the focus on the causes and possible prevention.

# 6 IMPLICATIONS

What we proposed in this paper is one of many possible ways of implementing a Telewalk technique. A future implementation of Telewalk could for example make use of different or additional RDW gains (like rotation gains), use a different way to realize directional changes, or include additional visual guidance strategies. Furthermore, the possibility of predicting the walking path could allow for adaptive paths to avoid obstacles (e.g. a table in a typical living-room situation).

Though, we found some requirements the different parts have to ensure to implement which we will describe in the following.

The most obvious is that the applied gains have their limits. In our implementation only curvature gains are used to keep the user inside the tracking space, while the translation gains are used to let the user move slower. Using the Telewalk, the user is always forced to walk on a perfect circle around the tracking center. This allows a perfect prediction of required gains as well as the required space. In our case using a tracking space of around 3m x 3m we applied gains of $38.2°m$. Testing other radii could lead therefore lead to less or more symptoms of motion sickness. Future implementation could make use of additional types of gains to either further reduce the required space or to reduce the symptoms of motion sickness.

In our application, turning around was realized by rotating the head. This constant change of the character's rotation while turning the had was stated to have the highest impact on motion sickness. In first tests, most participants had no problems walking a straight line, but some failed on turning around. This is the same problem as VR games have when played with a controller and when navigating with a joystick. A potential solution could be to apply no continuous reorientation, but a discrete one that e.g. rotates the user every 0.5s with an angle depending on how far she looks away from the optimal path. Similar to the instant translation that is applied during teleportation, such instant reorientation could lead to less motion sickness. Another approach could be to give the user more control (e.g. by using a controller). Our implementation that uses the head as an input device has the advantage of enabling hands-free navigation on the one hand, but can also lead to problems, as for example head movements when looking around can lead to unintentional rotations.

The visualization of the optimal walking direction goes hand in hand with the head controller we implemented. In earlier implementations we tried not only the used straight line but also the display of curves, which should rather correspond to the real path. For our implementation, however, the straight line turned out to be the best visualization. However, if, for example, additional gains or another camera control is used, the adaptation of the visualization could bring further advantages.

# 7 FUTURE WORK

With this paper we explored a novel interaction technique for traveling virtual worlds that combines perceivable RDW gains with a novel head based camera control. The current implementation and its settings were determined by informal user tests. The study can be interpreted as prove of concept of such a technique. We propose to investigate the observed effects more closely to get more insights on how the different interaction mechanics work and interact together. One example could be the relation between higher translation gains (as used by the presented Telewalk implementation) to the real world walking pace or step length. It is also of interest how strongly the translation gains interact with the acceptance of curvature gains. On the other hand it could be of value to determine the origin of motion sickness. Since in our study all concepts were combined to an overall system, the influence of the individual mechanics on motion sickness could not be examined in detail.

As already mentioned, a future implementation of Telewalk could not be based on just one pre-defined perfect circle. Through variable gains it is possible to use any predefined real path as a template to make optimal use of the available physical space. This would not only make the best possible use of the available space, but also extend the walking distances. This would make it possible to reduce the necessary curvature gain, which in turn could have a positive effect on motion sickness.

# 8 CONCLUSION

In this paper we presented Telewalk, a locomotion approach that allows infinite walking in VR on small tracking spaces. Telewalk utilizes high and perceivable curvature gains and forces the user to walk slower by scaling the user's translation. In contrast to general RDW, which is designed to be an unperceived manipulation, Telewalk deliberately uses perceivable gains. A further difference to general RDW is that the user is guided to walk an optimal path (in our case a perfect circle around the tracking center) by substituting directional changes by using the head rotation as input device. This makes it possible to fully predict the user's real world path and ensure that the tracking space will never be left and that there are no obstacles on the user's way.

In a user study we found that Telewalk is a good alternative to Teleportation that results in a stronger feeling of presence and immersion. Though, most of all motion sickness susceptible users struggled with respective symptoms. Future implementations of a Telewalk approach could investigate how such symptoms can be avoided by utilizing different gains or other mechanisms to realize directional changes.

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