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Safe Walking Zones: Visual Guidance for Redirected Walking in Confined Real-World Spaces

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Abstract

Walking is usually considered the most natural form of self-motion in a virtual environment (VE). However, the confined physical workspace of typical virtual reality (VR) labs often prevents natural exploration of larger VEs. Redirected walking (RDW) has been introduced as a potential solution to this restriction, but corresponding techniques often induce enormous manipulations if the workspace is considerably small and lack natural experiences therefore. In this paper we propose a user interface approach that supports natural walking in a potentially infinite virtual scene while confined to a considerably restricted physical workspace. This virtual locomotion technique relies on a safety volume, which is displayed as a semi-transparent half-capsule, inside which the user can walk without manipulations caused by RDW. We designed a circular redirection approach when the user leaves this safety volume that is complemented by a deterrent approach for user guidance outside the safety volume. We discuss in detail the process of transferring user movements inside these regions to the virtual camera in order to enable walking between points of interest in VEs, and we present the results of a usability study in which we evaluate the approach.

CCS Concepts

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

1. Introduction

Interactive exploration as supported by immersive virtual environments (IVEs) is often found to improve the perception of space and geometry of three-dimensional (3D) data sets [RL09]. In particular, tracking of head movements and head-coupled virtual feedback on a one-to-one scale supports natural forms of exploration, such as inspecting an object from all sides or walking between points of interest, while keeping the hands free for orthogonal forms of interaction [BKLP04].

Implementations of such walking interfaces, however, are constrained by the available physical interaction space due to the limited range of tracking sensors or physical boundaries of the virtual reality (VR) workspace. While different hardware solutions have been proposed, including omni-directional treadmills [SRS*11], these are not yet generally available or suitable for all VR labs.

Razzaque et al. [RKW01, Raz05] proposed *redirected walking* (RDW) as a solution to unrestricted virtual walking in a limited physical workspace which works by visually manipulating users to walk in circular paths in the real world while they perceive a virtual straightforward path for a potentially infinite distance. RDW benefits from the advantage that it requires only minor changes to the implementation of rendering processes in IVEs, and thus provides a solution that may be applied in arbitrary VR labs.

Perception and cognition research showed that RDW has similar benefits as real walking, in particular, when a physical workspace of at least 50m × 50m is available [SBRH08, SBJ*08, SBJ*10]. However, applying RDW in smaller "Room Scale VR" labs, such as a typical 5m × 5m walking area, proved to be a significant challenge. Naïve implementations tend to cause failure cases, which have to be remedied using less natural *stop-and-go* reorientation techniques [PFW11, NPB*18] or spatial manipulations. For a detailed review we refer to Suma et al. [SBS*12]. These complementary techniques come with high demands on programmers, modelers, or users, which often have to be trained to learn the user interface mechanics [SBS*12].

There is no silver bullet to remedy the problems of RDW in small VR labs, but spatial perception and cognition research suggests that such hybrid implementations of hands-free navigation still provide benefits over joystick or in-place walking user interfaces [PFW11]. We believe that one critical feature of redirected walking interfaces is *safety*, i. e., inducing the feeling of being safe although the user is walking in the presence of physical obstacles in the VR lab [SVCL13]. Another important feature is *predictability*, i. e., transparent user interface mechanics that avoid unexpected or unstable behavior.

In this paper we address these requirements and propose a user interface approach that supports real walking in a potentially in-

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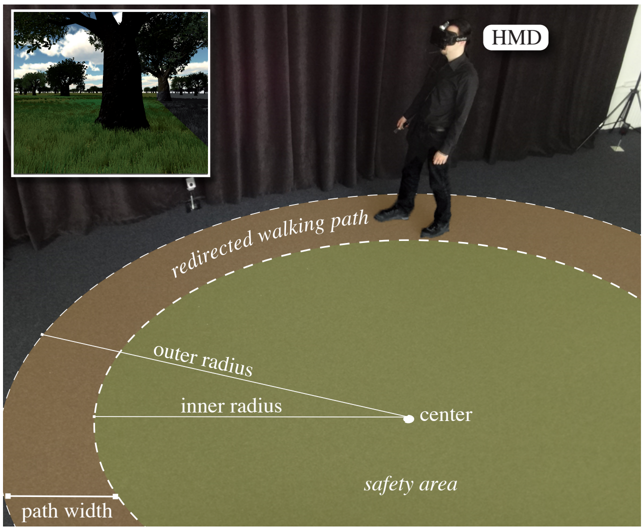


Figure 1: *User exploring a VE using our interface approach. Illustrations show the safety area and the redirected walking path on the ground. The inset shows the user's view with a visual barrier to his right side preventing him from walking into the wall.*

finite virtual scene while confined to a small physical workspace. The technique relies on a safe movement volume [LBS14] (see Figure 1), which is visually indicated to users as a semi-transparent half-capsule (see Figures 2b,d). While the user is within this safety volume, no RDW manipulations are applied, i. e., an object of interest can be explored without interferences caused by manipulated self-motion behavior. Once the user leaves the safety area, a RDW technique based on circular redirected walking is used to support infinite walking while the user is guided on a circular path with optimal radius that leads around the inner area (see Figure 1).

2. Background

A large number of virtual self-motion techniques have been proposed, which can be classified in two categories:

- Virtual *traveling* techniques denote approaches in which the user is actively or passively transported through the VE, such as driving a car or being transported in a train or airplane.
- Virtual *locomotion* techniques are based on self-propulsion through the VE, such as walking, swimming, or bicycling.

Simple traveling techniques can easily be implemented in IVEs using joysticks or gamepads [BKLP04], whereas hands-free traveling techniques are more difficult to implement [ZHF*16]. An example are rate control techniques, in which users initiate and control the speed and direction of traveling by leaning or shifting their body in an interactive volume (see [CMRL09, LEG*15]).

Real walking is considered the most basic and natural form of locomotion among humans, and it is implemented in most of today's IVEs via head tracking technologies [SVCL13]. However, the size of the available walking area differs between IVEs, and often severely limits the ability to reach distant locations in a VE by natural walking. As a solution, redirected walking [RKW01, Raz05] and reorientation techniques [PFW11, BSH09] make use of virtual rotations applied to tracked head motion, which users compensate by reorienting themselves in the physical VR lab. When these manipulations are below the perception thresholds [SBJ*10, BSB*13], users unknowingly compensate for these rotations in their real-world path of travel, effectively walking in circles in the physical VR lab while they perceive a virtual straightforward motion, or when the radius of a virtual curved path is changed [LLBS17b, LLBS17a]. Steinicke et al. [SBJ*10] analyzed human sensitivity to these manipulations and found that users are basically unable to notice if they are redirected on a circular path with a radius of at least 22m in the real world when their intention is to walk straight in the VE. When users are redirected on a circular path with a smaller radius, these manipulations become increasingly noticeable to the point where users do not subconsciously compensate for manipulations any more [Raz05, NPB*18]. Instead, users have to consciously turn their body while trying to maintain a straightforward path [BLS15]. In particular, in smaller VR labs, naïve implementations of redirected walking controllers often lead to manipulations with large magnitudes. These make walking a challenging task when the world is rotating strongly around users, which causes unstable walking behavior and raises the fear to collide with obstacles in the real world [BLS15, SVCL13].

Different approaches have been presented that can be used to provide an environment safe from collisions with objects in the real world. For instance, virtual content can be dynamically registered with physical entities during walking, including corridor walls [MBN*16] and proxy props such as tables or chairs [SBK*08, KBMF05]. Alternatively, interventions may be used, which may take the form of turning the virtual view red in the presence of danger, or providing auditive instructions to stop [Raz05]. Other less intruding approaches are based on dynamically appearing visual barriers that inform users of limits of the physical workspace, such as the magic barrier tape [CMRL09] or deterrents [PFW11]. These barriers or deterrents are objects in the VE that users are instructed to stay away from or not to cross. These barriers fade in as users come near the edge of the physical walking area and fade out as users walk away from the edge. While this approach provides users with a visual cue about the size and orientation of the physical workspace in the VE relative to the user, practical tests usually show that users interpret them as *virtual* objects in the VE or as user interface elements rather than elements from the real world.

3. User Interface

We propose a novel user interface approach as an improvement of RDW approaches in small labs. There are two fundamental objectives of the user interface:

- Provide a sense of safety by informing the user of the limits of the physical walking area from within the VE in a compelling way, without breaking the user's sense of presence.
- Provide an integrated locomotion technique that combines an unimpeded sense of walking in a safe area while a tailored RDW

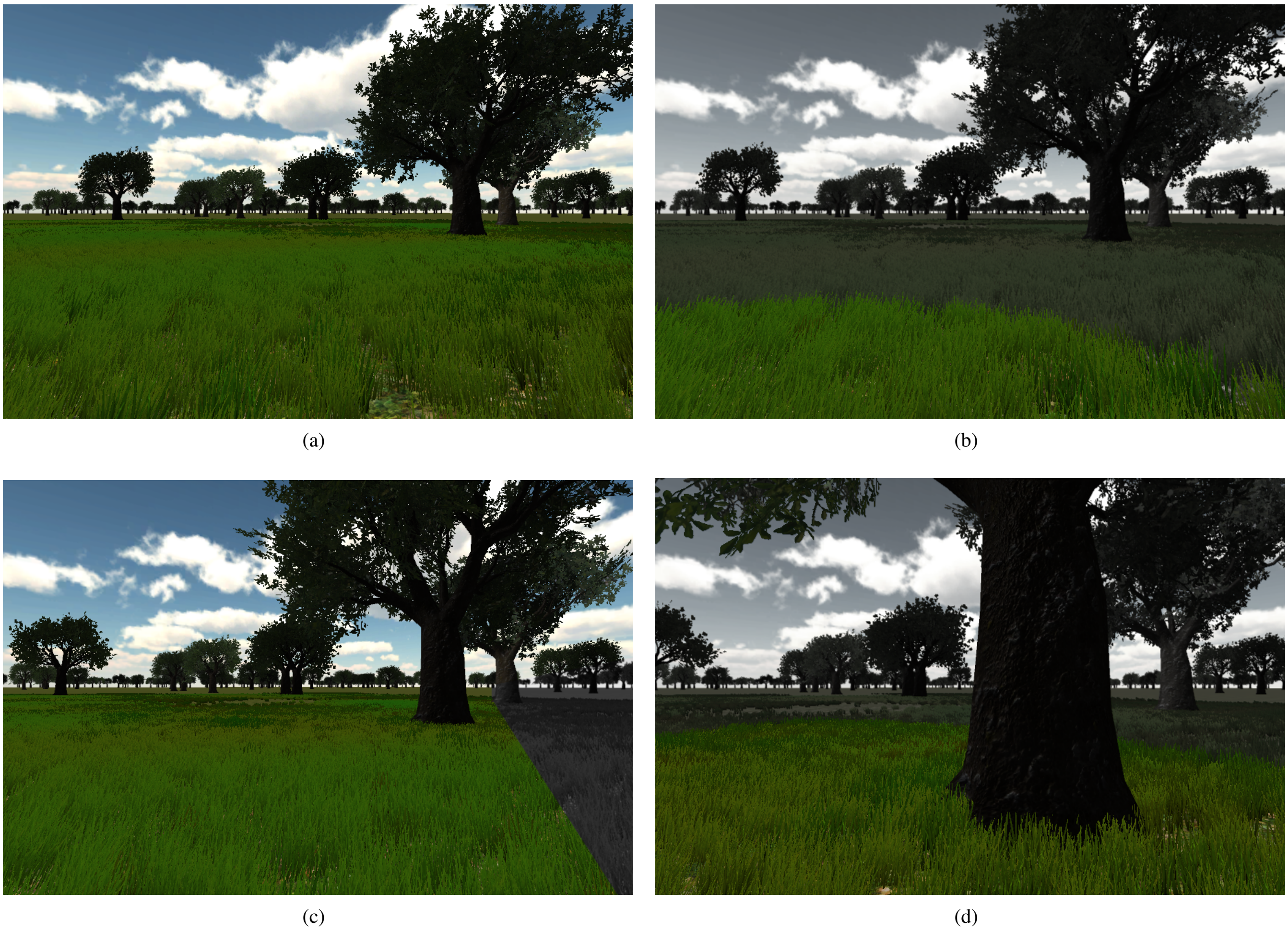


Figure 2: *User's view: (a) inside the safety volume, (b) inside (but close to the border of) the safety volume, (c) on the (counterclockwise curved) redirected walking path, and (d) inside the safety volume again. Note that the safety volume is visible in the background, giving the user also feedback about the distance to the border behind him.*

approach with transparent mechanics is used to reach any point of interest in the VE.

To address these requirements, we support walking in a safe area that is indicated by a virtual barrier, which represents the safe region of the physical workspace. For long-distance walking we designed a circular RDW technique around this safe area. We integrated the two concepts, providing an all-walking integrated virtual locomotion interface which improves usability aspects of redirected walking interfaces in small physical workspaces.

3.1. Virtual Workspaces

When walking through a VE we distinguish between three stages in the user interface: (1) walking in the safe inner region, (2) redirected walking around the outer path, and (3) a transition between these two stages.

3.1.1. Safe Inner Region

Inside the safe inner region, movements in the physical workspace are mapped one-to-one to the virtual workspace, i. e., translations and rotations are coherent between the real and virtual space. The boundaries of the virtual workspace are represented by a semi-transparent half-capsule, which is fully transparent when the user is at least a step away (based on measured step length) from the boundaries of the safety region (see Figure 2a), and become progressively visible as the user gets closer (see Figures 2b,d). This approach informs users of the available size of the safe area in which they can freely walk to explore or interact with elements of the VE that reach inside the safety region.

3.1.2. Transition

When approaching the boundaries of the safe inner region, the opacity of the barrier increases to inform users that they are about to leave the safety volume, and enter the redirected walking path.

When the user walks through the semi-transparent barrier, we start to apply camera rotations to guide the user on the path that leads around the inner safety area (see Figures 1, 3). Therefore, we compute the minimum angle we have to reorient users onto the path depending on which direction they were heading towards when exiting the safety region. By rotating the virtual camera using a linear transition from the moment users exit the inner region to the distance of half the width of the walking path, they are quickly able to continue walking in the desired direction.

3.1.3. Redirected Walking

After users transitioned onto the redirected walking path, visual cues in the form of a virtual barrier are used to inform users that this path is located close to the boundaries of the workspace (see Figures 1, 2c). The barrier provides a visual deterrent for users not to move over that barrier, which is important to avoid collisions considering that they are walking close to physical obstacles in the real world. Since the redirected walking path leads around the safety area, users are always redirected on a circular path with the maximum possible radius in the physical workspace, thus providing a near-constant and predictable magnitude of manipulations.

The mapping from movements in tracking coordinates to virtual camera motions follows the *curvature gains* approach by Steinicke et al. [SBJ*10] with a fixed circle radius. As illustrated in Figure 3 when the user's head position changes between frames $n \in \mathbb{N}$ and $n+1 \in \mathbb{N}$ from position $p_n \in \mathbb{R}^2$ to $p_{n+1} \in \mathbb{R}^2$, the mapped virtual position $V(p_{n+1}) \in \mathbb{R}^2$ is computed from the previous position $V(p_n) \in \mathbb{R}^2$ using movement components along the virtual path and in the orthogonal strafe direction.

We compute the movement l_{n+1} along the virtual path using the covered distance on the redirected walking path with the following equation:

$$l_{n+1} = \alpha \cdot r_{path} \cdot g_s \tag{1}$$

with r_{path} the circular redirected walking path radius and α the corresponding covered angle (in radians), i. e., the virtual covered distance is computed from the arc length of the physical path (see Figure 3). Additionally, we introduced a *speed gain* $g_s \in \mathbb{R}^+$, which can be freely chosen to scale translational movements, so that walked physical distances can be transferred to longer or shorter covered distances in the virtual world [WNM*06]. We apply this gain only to scale movements in the main movement direction. Hence, unintended lateral shifts can be prevented (see [IRA07]).

Strafe movements d_{n+1} orthogonal to the main walking direction are computed using the distance from the user's position to the center c of the circular workspace minus the radius r_{inner} of the inner region:

$$d_{n+1} = ||p_{n+1} - c||_2 - r_{inner} \tag{2}$$

To give the user the impression of walking straight in the VE, we rotate the virtual camera using the angle α that the user walked on the circle. Additionally, we found that introducing an additional time-dependent *steer-to-orbit* gain [Raz05] helped users slightly change their intended movement direction in the VE.

Once a user stops in front of an object of interest in the VE, we slowly start rotating the world around the user using a *steer-to-center* gain [Raz05], such that the region of interest moves into the inner safety region. Once the user takes the last steps towards the object, he then can perform tasks within the virtual safe workspace at the new location.

3.2. Implementation

As shown in Figure 1, we used a wireless Oculus Rift DK1 HMD with an attached active infrared (IR) target. The target was tracked with an optical WorldViz Precision Position Tracking (PPT X4) system with sub-millimeter precision for position and orientation data in a small 6m×6m lab room. We used an inertial InertiaCube 4BT sensor for head orientation tracking. We used an Asus WAVI wireless transmitter box to transmit the images at 60Hz from a rendering computer to the HMD. As claimed by the manufacturers, not more than 2ms latency were introduced due to the wireless connection. The HMD and wireless transmitter box were powered by an Anker Astro Pro2 portable battery. The boxes were carried in a small belt bag. The VE was rendered with Unity and our own software on a MacBook Pro laptop. As illustrated in Figure 2, the virtual world consisted of an outdoor scene with landmarks that were spatially separated and randomly distributed over the plain. The safety region was located in the center of our workspace with a 3m diameter using 0.8m wide redirected walking paths, which we based on typical shoulder widths plus a safety offset.

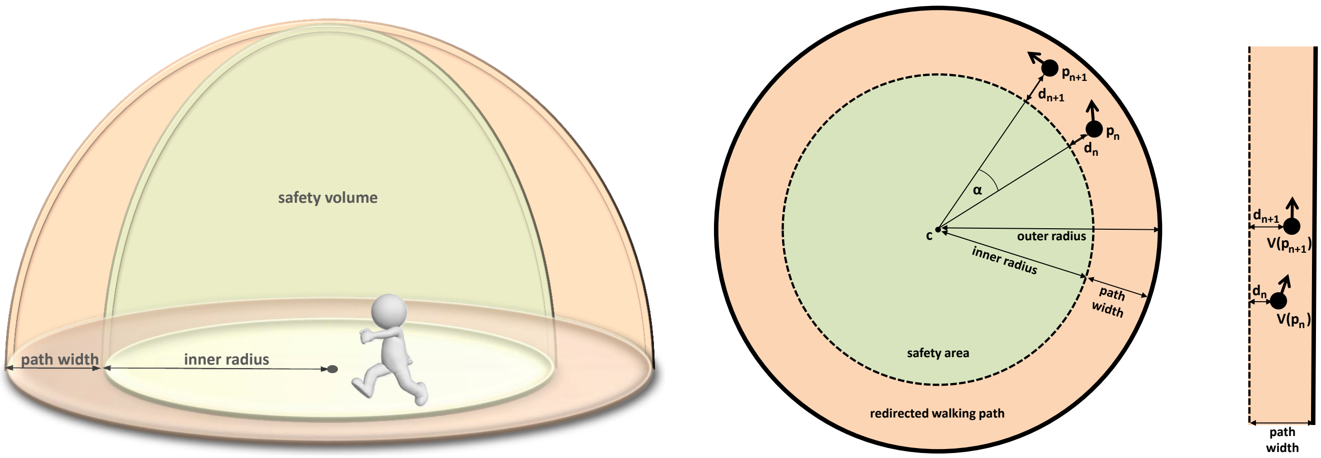
Considering that most VR labs have a rectangular workspace, it appears odd that we deliberately chose a circular inner region and outer path for the user interface. However, it comes with certain benefits: First, RDW relies on angular manipulations which guide users on circular paths, i. e., we designed our interface in such a way that the maximum circle could be used, thus providing per definition optimal redirected walking performance. Second, the circular design does not require large dynamic changes in curvature gains and reduces the magnitude of manipulations during transition from the inner region to the outer redirected walking path compared to rectangular shapes.

4. Usability Study

We evaluated the user interface using the setup described in Section 3.2. In this study we focused on the general usability of our technique rather than on the performance metrics in comparison to other approaches such as joystick-based navigation.

4.1. Participants

We recruited nine participants for the evaluation, six male and three female (aged from 22 to 45, M=31.1). The participants were students or professionals of human-computer interaction or computer science. None of the participants reported known vision disorders or a displacement of balance. Three participants had prior experience with RDW with HMDs, the other participants were naïve to IVEs.



(a) (b)

Figure 3: *(a) Illustration of the safety volume and redirected walking path running around the inner region in the physical workspace, and (b) redirected walking mapping from the walking path in the real world (left) to the virtual straight walking path (right).*

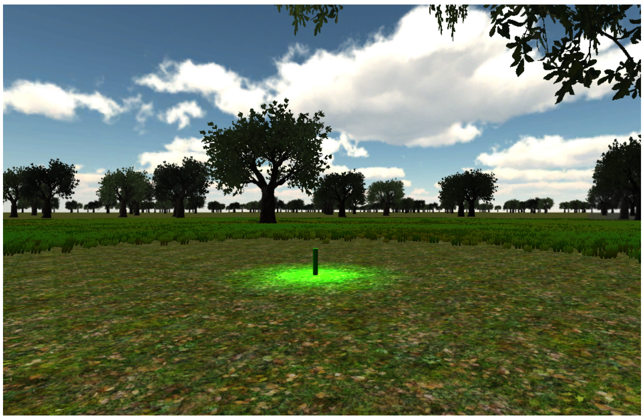


Figure 4: *Virtual environment used during the user study. Users had to walk between points of interest indicated by the illuminated vertical cylinders, which were displayed at 5m, 15m, or 25m distance from the user.*

4.2. Protocol

At the beginning of the user study, participants filled out a simulator sickness questionnaire (SSQ) [KLBL93] and a demographics questionnaire, and were then immersed in the VE shown in Figure 2. Participants were instructed to explore 9 landmarks sequentially, of which only one was visible at any time. We tested 3 landmarks at a distance of 5m from the user's position, 3 landmarks at a distance of 15m, as well as 3 landmarks at a distance of 25m. The landmarks were randomly distributed in the VE and tested in random order. Landmarks were indicated by virtual cylinders of 1m height that were brightly illuminated by a spot light to make them easier to spot from a distance (see Figure 4). The task of the participants was to walk to the currently visible landmark, and touch the tip of the cylinder. Afterwards, the cylinder vanished and the next landmark appeared. After participants touched the last cylinder, we asked them to fill out an SSQ and Slater-Usoh-Steed (SUS) [UCAS99] presence questionnaire, as well as a NASA Task-Load-Index (TLX) [Har06] and AttracDiff [HBK03] questionnaire.

Afterwards, we performed a semi-structured interview with the participants, asking about the three main parts of the user interface mechanics described in Section 3, and giving them the opportunity to comment on the approach. The user study took about 30 minutes per participant.

4.3. Results

We measured a mean SSQ-score of M=10.8 (SD=16.5) before the user study, and a mean SSQ-score of M=29.5 (SD=30.2) after the user study. The increase in simulator sickness is in line with results of typical RDW studies over the time of our user study [SVCL13]. The locomotion user interface does not further increase simulator sickness symptoms than other RDW techniques.

The mean SUS-score for the reported sense of feeling present in the VE was M=4.76 (SD=1.28), which indicates a reasonably high level of presence [UCAS99]. Participants judged their level of fear to collide with physical obstacles during the user study on a 5-point Likert scale (1=no fear, 5=strong fear) with M=1.78 (SD=0.97), which shows that they felt reasonably safe in the IVE. Subjective feelings of safety and thus an unimpeded sense of presence in the VE were two of the major goals of the proposed technique.

The results of the NASA TLX questionnaire showed scores for mental demand (M=49.4), physical demand (M=53.9), temporal demand (M=25.0), performance (M=31.1), effort (M=49.4), and frustration (M=35.0) (see [Har06]). The results indicate that the mental demand of learning to use the interface was relatively high, as were the required physical demand and effort. On the other hand the frustration of the participants was relatively low.

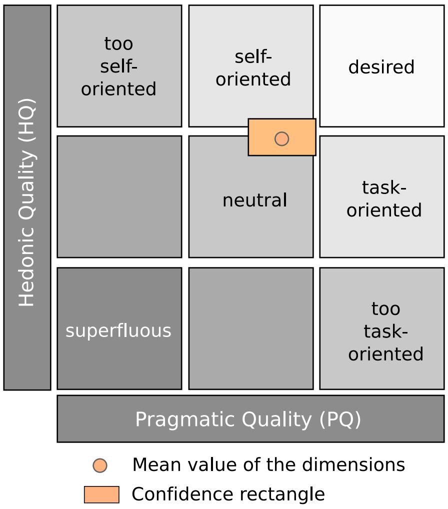


Figure 5: *Results of the AttracDiff questionnaire: Medium values for the dimensions pragmatic quality (PQ) and hedonic quality (HQ) and the confidence rectangle.*

The results of the AttracDiff questionnaire are shown in Figure 5. The results show that the *pragmatic* quality, i. e., an indication of the usability, of the user interface was reasonably high, with room for improvement [HBK03]. The *hedonic* quality, i. e., the extent to which users may identify with the product or its support for subjective development and progress, also shows that the user is stimulated by the product, but shows room for improvement. Moreover, the *attractiveness* of the user interface was judged as M=1.0, which shows that it was comparably attractive.

The semi-structured interview revealed that all participants judged the safety area approach as very useful once they understood that barriers provided visual feedback about potential collisions. The need to learn the user interface mechanics was judged as the main limitation of this approach by the participants. Regarding the transitions between safety area and RDW path, all participants stated that they had to train it a few times before they felt safe transitioning between the areas, but they reported having no trouble doing it at the end of the user study. Four of the participants stated that they felt that the transitions induced postural instability. For some trials the participants actively reduced the amount of reorientation by leaving the inner area at an acute angle. When questioned about walking on the outer RDW path, all participants unanimously stated that they felt very safe due to the visual barrier, and only three of them even noticed to be redirected. In particular the three professionals stated that they never walked so fast and felt so safe from collisions with RDW in the past. The virtual barrier enabled them to walk through the VE without having to focus as much on compensating for manipulations as in other RDW implementations. While, in theory, the approach could work with VR labs of arbitary size, the circular shape may restrict its usefulness, which might be compensated by using elipsoid forms, but this limitation and potential compensation methods should be evaluated in future work. An in-depth evaluation of the relation between the walking path width and size of the inner region should be conducted in future work to provide guidelines for practitioners in this field. Last but not least, since the visual appearance of the VE is changed using this approach, more research is necessary to identify and compare the least obtrusive forms of visual changes.

5. Conclusion

In this paper we introduced a novel locomotion user interface approach that integrates a safe workspace with RDW in small VR labs. We showed how user movements can be mapped from the physical workspace to the VE to enable natural exploration of regions of interest and redirected walking between locations at arbitrary distances in VEs. We described the design choices and characteristics of the user interface approach and discussed results in the scope of an implementation in our VR laboratory. We reported the results of a qualitative usability study of the user interface. The results suggest that the approach can improve the user's sense of feeling safe in the IVE during walking.

Since the first results suggest that the user interface may help to reduce the perceptual and cognitive demands of RDW interfaces, we plan to further evaluate the technique in different VEs such as indoor or more cluttered environments. Furthermore, we aim to extend the interface with passive haptic feedback approaches using registered real-world proxy objects in the safety region, such as a table or chair. Moreover, we aim to investigate multi-user scenarios, i. e., multiple users may group within the safety volume, while a user may lead the others to regions of interest via RDW.

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