Foldable Spaces: An Overt Redirection Approach for Natural Walking in Virtual Reality

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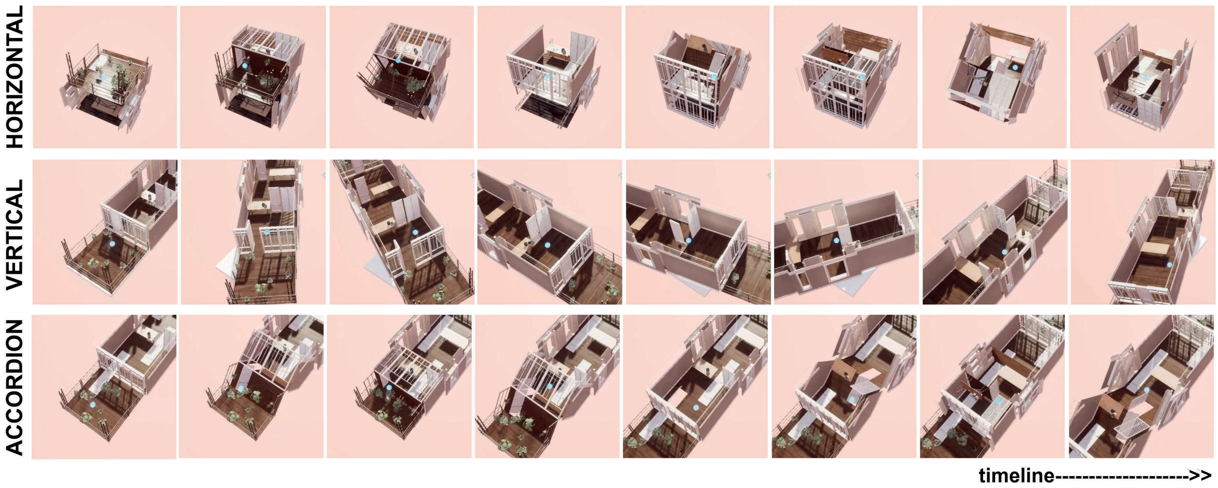

Figure 1: An overview of overt redirection techniques derived from Foldable Spaces (to be seen in conjunction with Fig. 2).

ABSTRACT

Overt redirection is a class of virtual reality locomotion that uses perceptible transformations to enable the user to naturally walk through a virtual environment larger than the physical tracking space. In this research, we propose Foldable Spaces, a novel redirection approach based on the idea of dynamically 'folding' the geometry of the virtual environment to reveal new locations depending on the trajectory of the virtual reality user. Based on this approach, we developed three distinct techniques for overt redirection: (1) Horizontal, which folds and reveals layers of virtual space like the pages in a book; (2) Vertical, which rotates virtual space towards the user along a vertical axis; and (3) Accordion, which corrugates and flattens virtual space to bring faraway places closer to the user. In a within-subjects user study, we compared our proposed foldable techniques against each other along with a similarly situated redirection technique, Stop & Reset. Our findings show that Accordion was the most well-received by participants in terms of providing a smooth, continuous, and 'natural' experience of walking that does not involve shifts in orientation and provides an overarching view through the virtual environment.

Index Terms: Human-centered computing—Interaction Paradigms—Virtual Reality;

1 INTRODUCTION

In real life, walking is generally an intuitive and 'natural' [17] method of travel. In virtual reality (VR), however, walking is a restrictive and challenging mode of locomotion [18]. In this paper, we propose a novel approach to enable natural walking in virtual environments (VEs) that are larger than the available physical walking space. Although alternative, more 'supernatural' methods of VR locomotion exist such as teleportation [4], locomotion research has revealed that compared to other forms of moving, natural walking shows benefits in higher presence [24], spatial understanding [14], and cognitive engagement [34]. However, despite being one of the most experientially pleasant methods of VR locomotion, natural walking easily encounters environmental obstacles when the VE is larger than the available physical space.

Redirected Walking refers to a body of VR locomotion techniques that addresses the challenge of enabling natural locomotion by manipulating the user's trajectory to stay within the bounds of the tracking volume. These techniques can be categorised into manipulations to the mapping or gains between a user's real and virtual movement [19], and manipulations to the architecture of a VE [18]. However, attempting to apply 'subtle' redirection, by which we refer to imperceptible interventions in a VE, typically requires a large amount of space to stay unnoticed by the user [1], especially for redirection techniques based on manipulation gains [32]. Additionally, subtle redirection techniques manipulating the architecture of the VE are typically based on indoor rooms or self-contained spaces within a larger VE, without visual connections (e.g., via windows or terraces) throughout the space in order to hide the technique's intervention in the environment [26]. In contrast, 'overt' manipulation tends to be more flexible in terms of both spatial constraints and the representation of the VE [20, 27, 31], at the risk, however, of inducing a lower sense of presence in participants.

Our contribution in this paper is a novel class of overt redirection, 'Foldable Spaces', that involves dynamically 'folding' the geometry of a VE to enable VR users to naturally walk through VEs significantly larger than the available physical space. We developed three distinct overt redirection techniques based on variations in folding: *Horizontal*, *Vertical*, and *Accordion* (see Fig. 1). In evaluating Foldable Spaces as an experientially viable approach for natural walking, we investigated the following research questions:

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- **RQ1:** To what extent do the foldable redirection techniques affect how users walk in a VE (walking speed and variation, idle time and frequency, walking trajectories)?
- **RQ2:** To what extent do the foldable redirection techniques affect how users cognitively engage with a VE (memory recall, distance estimation, sketch maps)?
- **RQ3:** Does the 'overtness' of the manipulation constitute a break in Presence too great to be ignored?

We conducted a within-subjects study with 20 participants comparing our foldable techniques against each other as well as an adapted implementation of a similarly situated base condition, *Stop&Reset* [8, 20, 31]. Our results indicate that *Accordion* provided the most continuous and natural experience of walking among the four evaluated techniques, in addition to being conducive towards orientation and being ranked first in terms of user preference.

2 RELATED WORK

The VR research community has proposed various methods of natural locomotion, ranging from 'subtle' to 'overt' [18]. Most research has focused on subtle techniques that attempt to remain unnoticed by users. However, subtle redirection [19] poses significant constraints on free exploration and typically requires a minimum walking space of 6 m×6 m to effectively maintain the illusion of walking freely without disclosing the changes imposed by the redirection technique [1, 23]. Additional challenges include the difficulty in leveraging passive haptics [13] or the necessity of imposing specific virtual layouts, e.g., indoor rooms or self-contained spaces [16, 26, 29]. In contrast, 'overt' techniques forgo attempting to hide changes in the VE from the user and tend to be more flexible regarding the spatial constraints and the representation of the VE. In the following, we elaborate on those techniques most closely situated with our work: redirection based on the manipulation of VE and overt redirection.

2.1 Subtle Manipulation of the Virtual Environment

Redirection techniques can be categorised into manipulations of the mapping between the user's real and virtual position and rotation and manipulations to the architecture of the VE [18]. Here, we focus on the latter method of manipulating the VE to redirect the VR user.

Change Blindness Redirection by Suma et al. [25] was the first redirection approach based on manipulations to the VE. This technique influenced the trajectory of a VR user by subtly making changes in the VE while the user was looking away. By changing the location of the doorframe leading into a room, the relocated doorframe redirects a user who wishes to exit the room to face away from physical obstacles.

Change blindness paved way to the concept of Impossible Spaces, which compresses a large VE into a small physical space by overlapping discrete parts of the VE and only visualising the segment that the user is currently located within; e.g., if two rooms connected with a corridor are 'overlapping' in order to fit into the tracking volume, the room that the user is not situated within is hidden to maintain the illusion of a believable non-overlapping VE [26]. Flexible Spaces expands on this work by applying procedurally generated corridors to connect multiple virtual rooms within the same physical space [29]. Scenograph further adapts this class of redirection that relies on overlapping spaces to create a narrative-led, tracking volume independent system of natural walking experiences [16].

However, because these redirection techniques leverage the principles of Impossible Spaces and Change Blindness Redirection to hide how the redirection intervenes in the VE, they necessitate a specific architectural layout consisting of indoor rooms or self-contained scenes connected with corridors. Nevertheless, Impossible Open Spaces [7] begins to tackle this limitation by investigating how overlapping detection thresholds are affected when Impossible Spaces are applied to semi-open VEs. The findings show that the 'subtlety' of a redirection technique may still be maintained even in semi-open conditions, raising the idea of investigating a fully open condition (open corridors and open rooms) as potential future work.

2.2 Overt Redirection

Resetting Controllers is an overt method of reorienting users away from physical obstacles by 'resetting' the user's view in a VE, and a flexible approach of redirection in terms of being effective in any size of tracking space [31]. For instance, resetting controllers after reaching the physical boundaries of a tracking volume would offer users the opportunity to rotate the VE 180° in place, after which the user may continue to walk forward.

Relocation Controllers are designed to enable walking but do not actually involve walking, helping users redirect themselves within a constrained VE via, e.g., teleportation [4], redirected teleportation [15], or sci-fiesque portals [23]. Although these techniques fall under redirection, they are not concretely classified as natural walking [18].

A departure from overlapping spaces for manipulating the VE for redirection is to *warp* virtual space. Sun et al. [27] warps a large VE to an acceptable level of comfort to fit into a comparatively small physical environment by algorithmically computing and re-projecting a warped planar map as an explorable VE. Smooth Assembled Mapping also relies on warping a VE but further minimises geometric distortions [9, 10]. In contrast, Tailored Reality does not introduce warping but instead perceptually restructures a large VE into a smaller space [11]. The technique resizes the virtual layout of the scene while maintaining the spatial adjacencies, thus algorithmically optimising the scene content-to-space ratio.

Another approach, cell-based redirection, subdivides a large VE into discrete spaces. VRoamer [6] procedurally generates a series of discrete virtual rooms in large uncontrolled environments, and accounts for both furniture and non-immersed users found within the tracking space by substituting them with appropriate virtual counterparts. Bookshelf & Bird involves narrative-led redirection [33]. The Bookshelf technique activates a 'false bookshelf', a contraption often found in fiction that reveals a hidden room, which virtually rotates both the VR user and the virtual bookshelf by 180° in the scene. The Bird method uses the metaphor of a large bird to 'pick up' and translate the virtual avatar to a subsequent discrete room.

Space Bender provides another direction for overt methods by introducing the idea of dynamically distorting the VE through 'bending' whenever the VR user comes in close proximity to a physical obstacle [20]. The technique algorithmically bends a part of VE to redirect the user into a different direction, and then straightens the VE to normal after the user has been redirected.

In this paper, we propose *Foldable Spaces*, a new class of overt redirection based on folding the geometry of the VE. Foldable Spaces lies at the intersection of redirection techniques that (1) rely on manipulations to the VE and (2) are overt. Alike change blindness approaches [25, 26, 29], Foldable Spaces manipulates the architectural features of a VE, e.g., doorways and floors, to redirect the user within a physical tracking space. However, Foldable Spaces also presents a clear departure from such techniques in subtle redirection – changes in the VE are 'overt'. Foldable Spaces introduces explicit and dynamic interventions in the VE [20] through cell-based redirection [33], subdividing a large VE into discrete spaces that fold onto each other depending on where the VR user is walking.

3 FOLDABLE SPACES

Based on Foldable Spaces, we developed three novel overt redirection techniques exemplifying distinctive folding transformations. All our foldable techniques are hands-free, only requiring a VR HMD to enable the natural walking experience, and are capable of representing any extent of VE as multiples of the tracking volume. Fig. 2 illustrates the following foldable transformations:

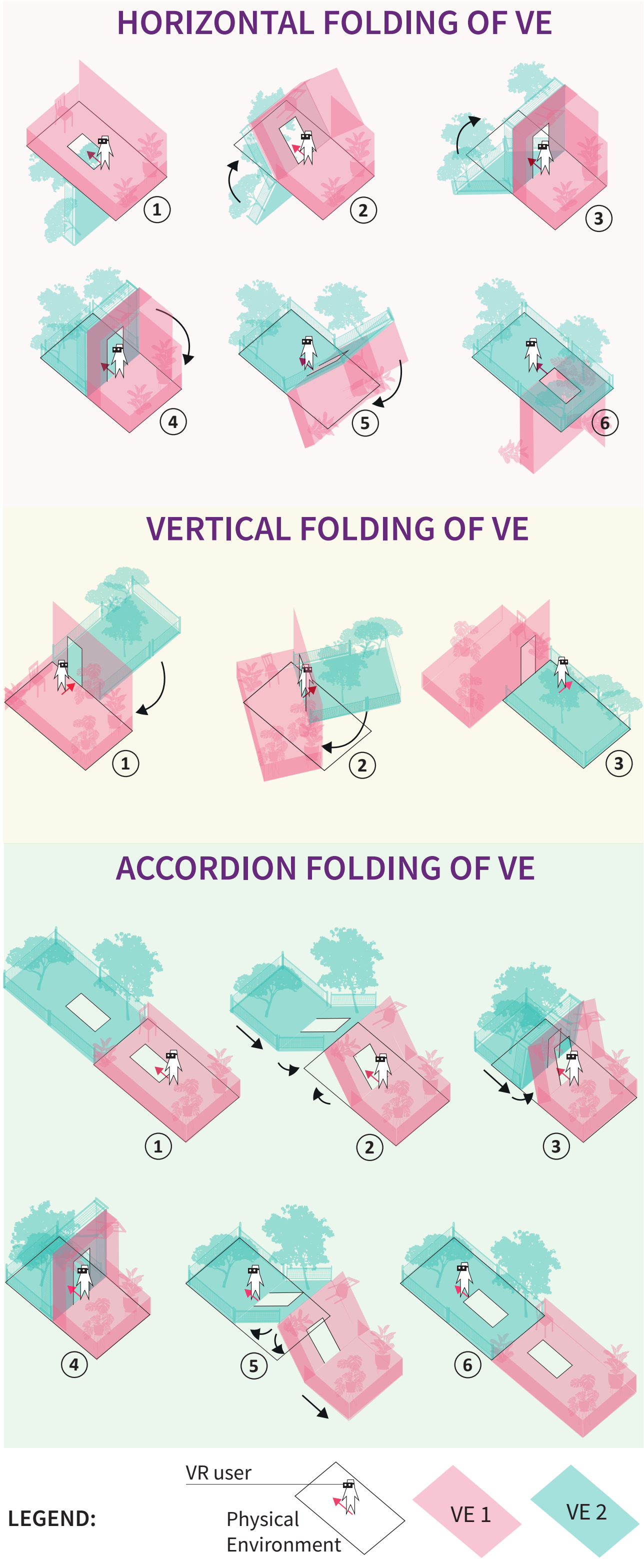


Figure 2: Folding of Virtual Environments: (A) Folding across the **horizontal** axis. (B) Folding along the **vertical** axis. (C) Folding like an **accordion**.

Horizontal. *Horizontal* folds and reveals layers of virtual space like the pages in a book. It subdivides a VE into discrete multiples of the physical tracking volume. There are openings on each 'page' of the book, namely the ground plane, enabling entry into adjacent parts of the VE. The axis for folding the VE is located in the centre of the physical tracking volume. Following the timeline of events for *Horizontal* portrayed in Fig. 2: (1) A user approaches an opening in the ground plane, which provides a view into the next part of the VE as an orthogonally placed page to the VR user's current location. (2-3) Upon entry, half of the current VE along with the subsequent page flips up, placing the user in (4) a transitional environment providing eye-level views of both the current – VE 1 – and subsequent space – VE 2. At this step, the user is located around the middle of the tracking volume, as delineated by the black rectangular outlines in Fig. 2. Should the user decide to step through the opening (5), the orthogonally placed spaces will flip past behind the user and fully place the user in the subsequent space (6). The folding also works in the opposite direction should the user decide to walk back towards the previous segment of the VE. When there is a next part to the VE, a new opening will appear and the user can walk back towards the centre of the current discrete space to proceed forward.

Vertical. *Vertical* rotates adjacent virtual space towards the user along a vertical axis. The technique subdivides a VE into discrete multiples of the physical tracking volume and sets its axis of rotation on the corner of each discrete multiple. Following the timeline in Fig. 2: (1) A user walks towards an eye-level opening in the VE. (2) Upon proximity, the VE rotates on its vertical axis, effectively overlaying a different segment of the VE within the available tracking volume, as delineated by the black rectangular outlines. This enables the VR user to transition through the opening and towards the subsequent space in the VE (3). Should the user decide to walk back towards the previous discrete space in the VE, the user needs to repeat (1-3) through the same opening used to trigger the arrival into the current discrete space. If there is a next part the the VE, a new opening will appear on the other side of the current discrete space through which the user can continue to proceed forward.

Accordion. *Accordion* corrugates and flattens virtual space to bring faraway locations closer to the user. It encompasses a similar but more complex folding mechanic than *Horizontal* as it involves three axes of folding in the VE. However, the additional two axes of folding enable the user to see an overview of the whole VE as opposed to only the discrete parts visible for *Horizontal*. As seen in Fig. 2: (1) The user has an overview of both the current and subsequent space in the VE. (2) Upon walking towards the door, the VE will corrugate (3) and bring the two halves of the current and subsequent parts of the VE together to place the VR user in a transitional environment (4). In this transitional step, the user is located around the centre of the tracking volume. Should the user decide to step forward, the VE will proceed to unravel (5) and flatten completely behind the user (6). Should there be multiple parts to the VE, the user would walk back and forth the openings on the ground to continue to walk forward in the VE.

3.1 Technical Details

We developed our novel system for foldable redirection in Unreal Engine 4 (UE4). We created three distinct blueprints, a type of UE4-specific scripting system, for each foldable technique. Developers can input numbers for the width and length parameters on our UE4 blueprints to adjust the size of each blueprint object to the size of the physical tracking volume. Developers are also free to customise these blueprints as both indoor and outdoor environments, as long as a virtual barrier (e.g., fence, wall with window) demarcates the boundaries the blueprint object. Afterwards, developers simply need to drag and drop the blueprint objects into the UE4 editor, and use these as 'building blocks' to create as large of a VE as they would like as multiples of the physical tracking volume. At this current stage, our system enables natural walking through these blueprint objects as a *sequential* narrative (as opposed to a branching narrative), and is fine-tuned to adapt to minimum 3 m×3 m of physical floorspace.

4 USER STUDY

In a within-subjects study, we compared our three proposed methods of folding (*Horizontal, Vertical*, and *Accordion*) with each other along with a base condition, *Stop&Reset* [8, 20, 31] for a total of 4 trials per participant. We selected *Stop&Reset* from the pool of redirection techniques due to the fact that the technique was (1) overt, (2) did not permanently distort the VE, and (3) mapped real to virtual user movement at 1:1 scale. *Stop&Reset* was originally inspired by the techniques Bookshelf [33] and Freeze-Turn [31], involving virtually rotating the user 180° to introduce new discrete parts of the VE. To make the technique further comparable with our foldable methods, we implemented a hands-free adaptation of *Stop&Reset* where HMD proximity to, e.g., a virtual door, triggers the overt transition. We evaluated the VR user both quantitatively (walking and cognitive task performance) and qualitatively (subjective ranking, questionnaires, thematic analysis of interviews and sketch maps), as further detailed in our procedure.

4.1 Test Environment

Fig. 3 visualises the scalar differences between the physical and the virtual environments to describe the context in which the VR simulation took place as well as the VE used for this user study.

Physical Context. The VR experience takes place in a rectangular physical environment with a walkable floorspace of 5 m×5 m. For the user study, we constrained the tracking volume of the VR simulation to 4 m×4 m (16 m^2) with an offset of 0.5 m within the physical environment as a safety measure should VR user accidentally walk outside the boundaries of the tracking volume.

Virtual Environment. The VE is six times the size of tracking volume, with a walkable floorspace of 4 m×24 m (96 m^2). It simulates a longitudinal domestic 'home' inter-spaced with both indoor and outdoor terrace spaces (see Fig. 1). Balconies, windows, and glass walls provide views throughout the VE. Virtual walls and other barriers demarcate the boundaries of the tracking volume.

4.2 Task

Participants were tasked with finding three instances of a specified virtual object in the VE for each locomotion condition, with a maximum of 3 minutes to explore the VE. After each trial, we asked the participants to remove the VR HMD and participate in a cognitive exercise consisting of two parts: (1) A 10-question custom memory-recall test (see Table 1) based on the 'Knowledge' category of Bloom et al.'s taxonomy of cognitive domains [3] which involves the recognition of specific information. (2) A sketch map exercise [2] in which participants were asked to draw and/or annotate their spatial experience of the VE and mark down the approximate locations of the three virtual objects specified by the search task. Each trial took place in the same VE with the same number of virtual objects; however, the location of these virtual objects differed. Each VE contained 3 bottles, 3 pictures, 3 books, 2 chairs, 2 tables, 2 trees, 1 fox, 3 pots without plants, and 6 indoor plants (see Fig. 3).

4.3 Procedure

We invited participants to read a consent form and an information letter outlining the details of the study. After consent was obtained, participants completed a demographics survey and a Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [12] to assess their pre-exposure to VR conditions. Next, we guided participants into the centre of the experiment area, where they were given the opportunity to adjust and wear the VR HMD.

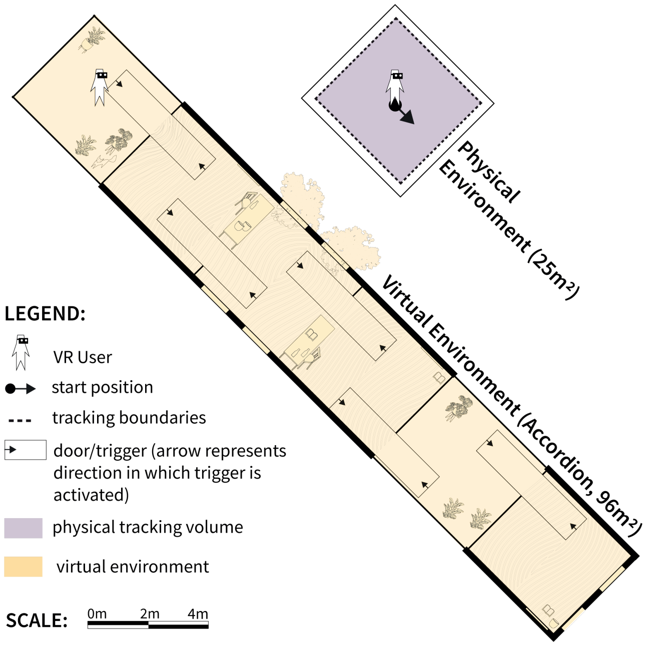


Figure 3: Comparing the scale/appearance of the VE (for 'Accordion') with the physical environment in which the VR simulation took place.

Table 1: Custom 10-question memory-recall test. True or False?

1 – One part of the roof was a different colour/material.
2 – If a deer was present in the VE, it was looking towards the building.
3 – If a fox was present in the VE, it was standing up.
4 – There are two different kinds of chairs in the environment.
5 – At least one glass bottle in the VE had a red label.
6 – All the plant pots were on stilts/stands.
7 – Trees could be seen outside both sides of the building.
8 – All the tables were made of the same material.
9 – All the windows were the same size.
10 – Not all the doors were white.

Before beginning the study, we placed participants in a training VE populated with the virtual objects used for the search task and memory-recall exercise. We asked the participant to identify the objects (pots, bottles, frames, and books) for the search task and recite the 10 memory-recall questions (Table 1). We informed participants that although these questions would be the same for each trial, the answers would differ as the position or material of these virtual objects changed between different redirection techniques. As we implemented a within-subjects design, all VEs in the study contained the same (or comparable, if made of a different material) virtual objects. We only changed the position or material of the virtual objects to prevent participants from benefiting from the learning effect when performing the search and memory-recall exercise.

After participants identified the search objects in the training VE, we begun the user study. The order of presenting the four techniques was counterbalanced, and we briefly described the redirection technique to the participant before every trial. The participant was given a maximum of 3 minutes to explore the VE, during which we logged the user's coordinates (taken from the position of the headset) at a rate of 60 times per second. These data logs would be used post-experiment to calculate walking performance metrics (e.g., distance travelled, velocity, gait changes, rest frequency, and idle duration).

Afterwards, we invited the participant to draw a sketch map of the VE and fill in the custom cognitive questionnaire, the SSQ [12], and

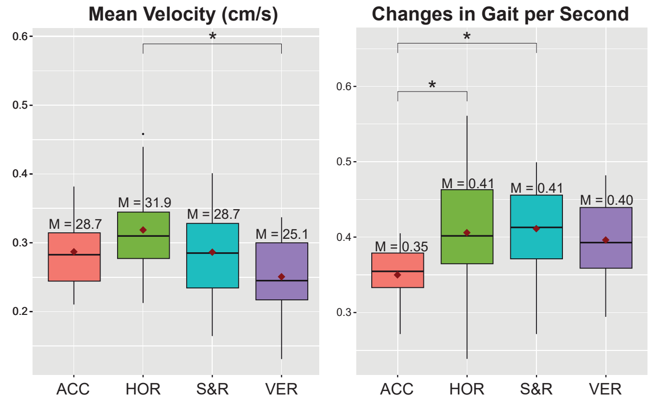


Figure 4: Walking: mean velocity (cm/s) and changes in walking gait (Δ/s) in the VR experience, grouped by technique.

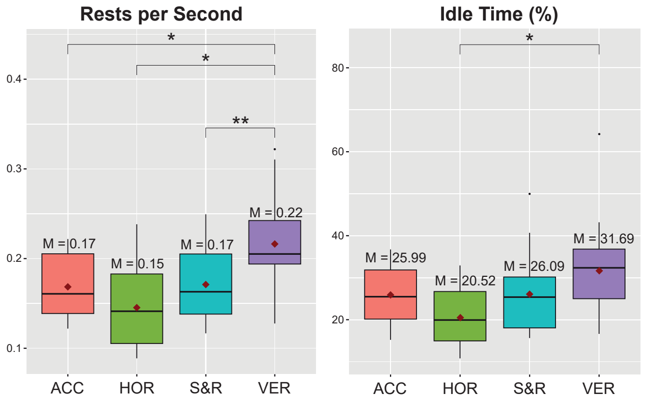


Figure 5: Idleness: frequency (rest count/s) and periods of rest (%) in the VR experience, grouped by technique.

SUS Presence [28] questionnaire. Lastly, we asked the participant to subjectively rank the techniques and take part in a brief semi-structured interview for feedback on the natural walking experience.

4.4 Participants and Apparatus

We recruited 20 (5 female, 15 male) participants, with a mean age of 27 years (SD = 4.87). We recruited them through posters and social media channels and offered vouchers for compensation. We asked participants to rate their experience with immersive technologies (e.g., VR, AR, mobile-based) on a 7-point scale from no to expert experience (M = 3.65, SD = 1.69). Participants wore the Oculus Quest 2 HMD and did not carry controllers for the entire session. We used the Oculus Air Link for wireless operation.

5 RESULTS

From data logs on user coordinates, we calculated the following quantitative measures of walking behaviour: *velocity*, *changes in gait per sec*, *frequency of rests*, and *idle time*. We used a Friedman test to detect any significant differences between the four redirection techniques, and unless otherwise stated, proceeded by using a pairwise Wilcoxon sign test (Bonferroni-corrected) to identify where these significant differences occurred. We also analysed our questionnaire data (SUS [28], SSQ [12], custom cognitive questionnaire) and conducted a thematic analysis on the sketch maps and semi-structured interviews.

5.1 Walking Behaviour

Walking. To describe *how users walked* through the VE, we calculated walking speed (measured as mean velocity) and walking variation (measured as changes in walking pace over time), as illustrated in Fig. 4. Velocity was calculated as distance travelled over time. Participants generally walked significantly faster ($p = 0.02$) in *Horizontal* (M=31.9 cm/s, Max=45.8 cms) compared to *Vertical* (M=25.1 cm/s, Max=33.8 cm/s). In contrast, participants walked at comparable speeds for *Accordion* (M=28.7 cm/s, Max=38.2 cm/s) and *Stop&Reset* (28.7 cm/s, Max=40.1 cm/s).

Walking variation was calculated as changes in gait per second. By ‘changes in gait’, we refer to counting instances when a user would shift from speeding up to slowing down, or vice-versa. This was calculated as the number of shifts between positive/negative acceleration over time. We filtered our data through two thresholds: a minimum velocity of 10 cm/s to differentiate walking from staying idle [20], and a minimum duration of 1 s during which the acceleration/deceleration had to be maintained. Participants showed a significantly more regular gait in *Accordion* (M=0.35Δ/s, SD=0.04) than in *Stop&Reset* (p=0.03, M=0.41Δ/s, SD=0.06) and *Horizontal* (p=0.04, M=0.41Δ/s, SD=0.08). No other significant differences were identified, but *Accordion* also performed marginally better than *Vertical* (M=0.40Δ/s, SD=0.06) in terms of inducing a more regular manner of walking.

Idleness. In addition to how users move during a natural walking experience, we also analysed *how users rest* through frequency and periods of idleness. In the context of this study, idleness does not necessarily imply inefficient walking as participants were not tasked to walk as quickly as possible. For instance, multiple participants were intentionally idle as they chose to pause, stand still, or meander slowly during parts of their VR experience. As seen in Fig. 5, frequent rests typically correlated with longer periods spent idle.

Idle behaviour was calculated as the frequency of rests in a natural walking experience. By ‘frequency’, we refer to the number of times a user stopped walking to rest, regardless of the duration of the rest. A threshold of 1 second was used to differentiate a ‘rest’ from a momentary pause during the walking experience. Participants stopped to rest significantly more often in *Vertical* compared to all the conditions: *Horizontal* (p<0.01), *Stop&Reset* (p=0.03) and *Accordion* (p=0.03). No other significant differences were identified.

Idle time was calculated as the percentage of time spent resting. A threshold of 10 cm/s was used to differentiate rest and sporadic movements of the head from intentional walking [20]. Participants were significantly more idle (p=0.014) in *Vertical* (M=31.7%, SD=10.9) compared to *Horizontal* (M=20.5%, SD=32.9). The idle time for *Accordion* (M=26.0%, SD=6.87) and *Stop&Reset* (M=26.1%, SD=9.18) was very similar.

Safety. One of the priorities in redirected walking is to ensure a *safe* walking experience. However, during the experiment we noticed that users occasionally left the tracking area in *Stop&Reset* if they accidentally continued to walk through the door as opposed to ‘stopping’ to reset. E.g., in Fig. 6 the user briefly leaves the tracking area at point (200 cm, 0 cm). This is not ideal for safety as these users risk colliding into walls and other obstacles if they leave their tracking space. We thus analysed our data logs and quantitatively calculated ‘safety’ as a boolean on whether a user left the tracking area during a VR experience. We set a threshold of 10 cm to account for the distance that the VR HMD protrudes from a user’s head (Oculus Quest 2 = 6.8 cm depth). A Friedman test showed a significant difference ($p < 0.01$) for safety between the conditions. Following a sign test (Bonferroni-corrected), *Stop&Reset* was considered significantly more unsafe ($p = 0.047$) than both *Accordion* and *Horizontal*. 50% of users briefly left the tracking bounds in *Stop&Reset* and to a lesser extent, 10% of users in *Vertical*. *Accordion* and *Horizontal* can be considered the safest redirection techniques of those tested in this study, as no users left the tracking area in these conditions.

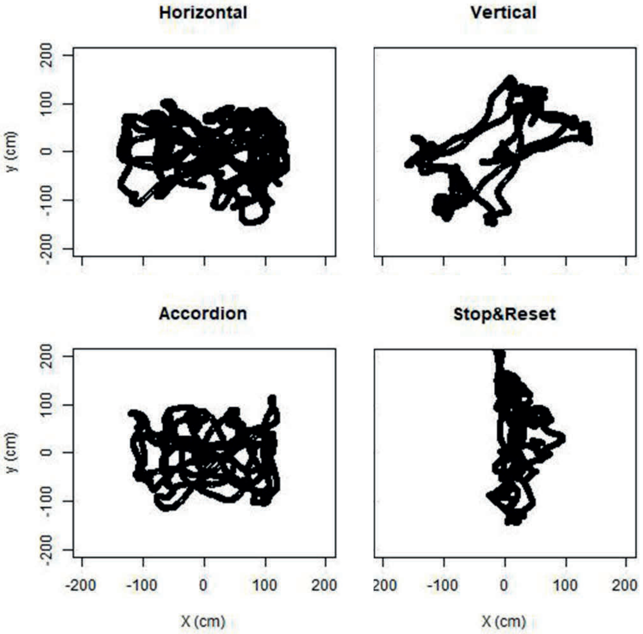


Figure 6: Plotted coordinates for the walking paths of a participant within a $4\,\mathrm{m} \times 4\,\mathrm{m}$ tracking space.

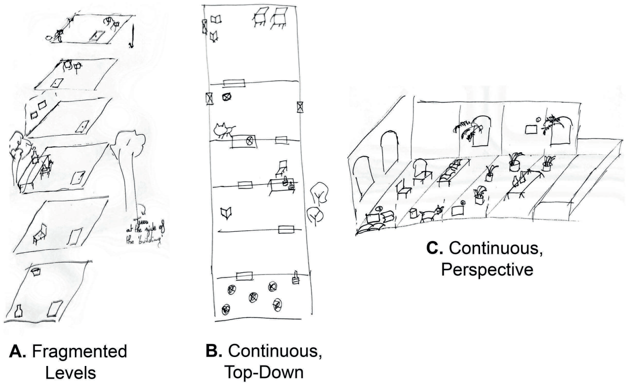
5.2 Cognitive Engagement

After each VR simulation, we asked participants to complete a custom cognitive questionnaire and draw a sketch map of their impression of the VE and mark the locations of the three specified virtual objects from the search task. We neither prevented nor encouraged participants to draw any additional details from the VE.

Memory Recall. We asked participants to complete a custom 10-question memory-recall questionnaire based on details that they observed in the VE. We used a competence calculation (True Positive Rate - False Positive Rate) [30] to analyse the extent to which a VR user cognitively engages with the VE despite the 'overtness' of the employed redirection technique. In this context, Competency refers to the probability of a VR user correctly recalling details of the VE without guessing and not by chance. A Friedman test showed no significant difference ($p = 0.41$) in the mean competence across the four redirection techniques. From highest to lowest mean competencies: *Vertical* (M=0.44), *Accordion* (M=0.30), *Stop&Reset* (M=0.18), and *Horizontal* (M=0.05).

Spatial Perception. We calculated how accurately participants perceived the spatial qualities of the VE through *distance* and *area* estimation. Accuracy was calculated as a percent error, ($(V_o - V_a)/V_a * 100\%$), in which V_o was the observed value and V_a was the value accepted as truth. The closer the value is to 0%, the higher the accuracy. For *Distance Estimation*, the V_o is the estimated walked distance and V_a is the real distance walked as calculated by our data logs of the user's coordinates. A Friedman test showed no significant differences ($p = 0.079$) between the four techniques. However, participants underestimated walking distance in all the techniques, as indicated by the negative percent errors. From higher to lower accuracy: *Vertical* (M=$-$48.4%, SD=29.8), *Stop&Reset* (M=$-$57.1%, SD=26.3), *Horizontal* (M=$-$61.3%, SD=16.5), and *Accordion* (M=$-$63.9%, SD=14.7).

For *Area estimation*, V_o was the perceived size of the whole VE as a multiple of the physical space and V_a was calculated as a ratio of virtual to real floorspace ($96\,\mathrm{m}^2/25\,\mathrm{m}^2$). A Friedman test indicated no significant differences ($p = 0.759$) between the four techniques, though all techniques showed that participants tended to overestimate the size of the VE. From highest to lowest accuracy: *Horizontal* (M=10.7%, SD=49.2), *Vertical* (M=23.7%,SD=53.4), *Accordion* (M=31.5%, SD=77.7), and *Stop&Reset* (M=34.1%,SD=82.0).


A. Fragmented Levels

B. Continuous, Top-Down

C. Continuous, Perspective

Figure 7: Sketch Maps: (A) Sketch of *Horizontal* as fragmented levels. (B) Top-down sketch map format used by most participants. (C) Perspective sketch map of VE.

Sketch Maps. The sketch maps were evaluated both quantitatively through an object position score as well as qualitatively through thematic analysis. Object position score was calculated by the number of virtual objects correctly drawn onto a sketch map. An object was considered correctly positioned if its relative position to adjacent objects was accurate, adding a value of 1 to the object position score. An object was considered only partially correct if its adjacencies were accurate but orientation within the VE was inverted, e.g., located on the other side of the room, adding $\frac{1}{2}$ to the calculation. We calculated two object position scores: firstly, a *significant object position score* (SOPS) based on correctly positioning the 3 specified virtual objects for the search task and secondly a *miscellaneous object position score* (MOPS) based on correctly positioning virtual objects outside of the search task. Both scores were based only on virtual objects that changed positions between the different trials. A Friedman test showed no significant differences for both SOPS ($p = 0.330$) and MOPS ($p = 0.473$). From highest to lowest SOPS: *Accordion* (SOPS=2.5, MOPS=1.275), *Horizontal* (SOPS=2.3, MOPS=1.025), *Vertical* (SOPS=2.125, MOPS=1.325), and *Stop&Reset* (SOPS=2.125, MOPS=0.875).

We also analysed the sketch maps qualitatively through a visual inspection, identifying two overarching themes: the *shape* of a drawn VE and the *characteristic features* in a VE. Regarding *shape*: Despite the techniques representing the same VE, 7 participants did not draw *Horizontal* as a continuous space (Fig. 7.B) but rather as fragmented layers of space (Fig. 7.A). Moreover, although most participants drew their sketch maps in top-down perspective, 2 participants consistently drew in perspective for all the techniques (Fig. 7.C), suggesting that eye-level information was important to portray for these participants. 1 participant explicitly used perspective to portray only the *Horizontal* technique (Fig. 7.A). Regarding the *characteristic features* in a VE, we observed that 12 users drew virtual objects unrelated to the search task in *Accordion*, compared to 10 in *Vertical* and 9 in both *Stop&Reset* and *Horizontal*. Regarding looking outside, 7 participants in *Vertical* drew windows while only 3 in *Stop&Reset*. Regarding looking up, 2 participants in *Accordion* and 1 in *Vertical* mentioned the colour of the ceiling, and no other drawings of the ceiling was observed for the other techniques.

5.3 Presence and other measures

Presence. We analysed our presence data by counting the number of answers that scored higher than 5. A Bonferroni-adjusted Wilcoxon test showed no significant differences between the SUS values for the

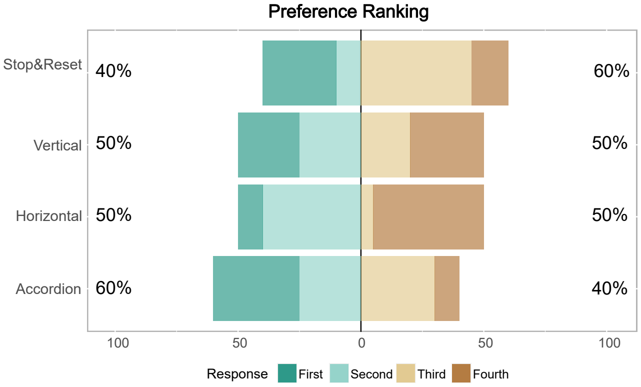


Figure 8: Ranking of conditions according to preference.

four techniques. From highest to lowest presence: *Vertical* (M=2.55, SD=2.45), *Stop&Reset* (M=2.45, SD= 2.46), *Accordion* (M=2.20, SD=2.12) , and *Horizontal* (M=1.05, SD=1.43).

Simulator Sickness. From the five conditions, the pre-experiment condition and the four foldable techniques, a Friedman test revealed no significant differences ($p = 0.14$) in simulator sickness. From highest to lowest mean values in simulator sickness: *Vertical* (M=41.4, SD=54.1), *Accordion* (M=32.0, SD=36.7), *Horizontal* (M=31.6, SD=25.5), *Stop&Reset* (M=31.0, SD=36.7), and *pre-experiment* (M=16.1, SD=12.3).

Preference Ranking. Participants significantly preferred *Accordion* over *Horizontal* ($p < 0.01$) and *Vertical* ($p = 0.03$), with 60 % ranking it at first or second place. Both *Vertical* and *Horizontal* were ranked first or second by 50 % of participants. Only 40 % of participants ranked *Stop&Reset* in first or second place. However, *Stop&Reset* also has a comparable number to *Accordion* of participants who ranked this technique as their favourite method of walking, perhaps substantiating the lack of significant difference between *Stop&Reset* and *Accordion*.

5.4 Interviews

We examined our interviews using thematic analysis [5] and identified four overarching themes for liking/disliking a redirection technique: Natural Walking, Wayfinding, Motion Sickness, and Interrupted walking. Regarding the notation of the following text, we use '(n)' as a shorthand to refer to the number of participants who mentioned a specified statement.

Natural Walking We observed different uses of the word 'natural' when participants described their VR experience, ranging from whether the locomotion was contextually believable or kinetically realistic. 10 participants expressed an explicit dislike towards techniques incorporating doors flat against the ground plane, e.g., '*In the conditions where the door is on the floor (Accordion and Horizontal), it is not natural*", as they were not contextually natural. In contrast, only 1 participant indicated a preference towards flat doors. Interestingly, 4 of these 10 participants who disliked flat doors also mentioned *Accordion* and/or *Horizontal* as more kinetically natural: "*Horizontal felt more like natural walking. In Stop&Reset it feels like you're naturally walking but it sometimes stops*". No participant who preferred techniques employing flat doors mentioned that *Stop&Reset* or *Vertical* felt more kinetically natural.

Wayfinding. 6 participants indicated that *Stop&Reset* was particularly difficult for navigation as it was easy to lose track of their orientation in the VE after the overt transformation: e.g., "*I have difficulties mapping the space after the reset.*" In contrast, participants elevated both *Accordion* (4) and *Vertical* (4) as conducive for orientation. Although not always related to a participant's sense of orientation, 9 participants expressed a dislike for *Horizontal* because they were unable to see the whole environment: e.g., "*I didn't like Horizontal because I didn't have an overview of the room, while I did for the others through the doors and windows*".

Motion Sickness 12 participants expressed that *Vertical* was particularly nauseating, e.g.,"*dizzy, because I had the feeling of moving more*". 3 participants expressed *Horizontal* was nauseating for a different type of movement, namely "*the feeling of 'tipping over'*". In contrast, participants highlighted *Accordion* (3) as stable and *Stop&Reset* (2) as comfortable.

Interrupted Walking. 6 participants in *Stop&Reset* and 3 in *Vertical* expressed that their experience of natural walking was choppy or discontinuous. For instance, a participant critiqued that the walking experience was interrupted when "*it (Vertical) bashes the (virtual) wall in my face*". In contrast, participants enjoyed *Accordion* (2) and *Horizontal* (2) due to the continuous quality of walking , e.g., "*In Horizontal, the passes between the rooms were fluid.*".

6 DISCUSSION

We aimed to investigate how our novel redirection approach, Foldable Spaces, influenced how users walked **(RQ1)** and cognitively engaged with the environment **(RQ2)**, as well as the believability of the experience **(RQ3)**. Our results reveal that *Accordion* provided a significantly smoother walking experience than our base condition *Stop&Reset* and foldable condition *Horizontal*, as well as a significantly more physically-engaging walking experience than *Vertical*. *Accordion* also ranked the highest of all tested techniques in terms of user preference, and was significantly the most preferred of all the foldable techniques. Although we did not identify any significant differences in how VR users cognitively engage with their VE, a thematic analysis of the sketch maps combined with the interviews suggest that different redirection conditions imprint distinct spatial impressions on users. Lastly, our findings also reveal that a user's sense of presence in a VE does not necessarily correlate with how 'natural' a user found a redirection technique - interviews suggest that for several participants, the sense of presence is attributed to the appearance of the VE rather than redirection employed by the tested locomotion technique. In the following, we discuss how we met our three research questions to further detail.

6.1 Walking Behaviour

In response to **RQ1**, our results show that *Accordion* promoted smoother, more continuous, and safer walking behaviour in participants. However, smooth and continuous walking is not necessarily correlated with a user's preference for a specific redirection technique. Our preference ranking scores (Fig. 8) show that although participants generally prefer *Accordion* over *Stop&Reset*, a comparable number of users ranked both as their favourite technique. Our interview analysis shows that these two groups of users liked each technique for disparate reasons: Users who preferred *Stop&Reset* generally enjoyed the break in walking and were unperturbed by the 180 degree shift in orientation, e.g., "*Stop&Reset gives me time to prepare my mind to go into another room...I feel comfortable, I feel prepared*". In contrast, users who disliked the break in walking tended to prefer *Accordion* instead, e.g., "*(I dislike) Stop&Reset because there is a fade out and I need to communicate with you (researcher) to find my direction...I think it's easier in Accordion to go through the door and get to the next space*". Additionally, users would occasionally forget to stop in *Stop&Reset* and a significantly higher number of users would leave the physical tracking volume compared to both *Accordion* and *Horizontal*. As leaving the physical tracking volume creates the risk of colliding into walls and other obstacles, *Accordion* is a safer option for redirected walking.

As the task in this experiment is to search for virtual objects within the VE, our results for walking behaviour concern how users *explore* and *investigate* the VE. We observed an inverse relationship between mean velocity and idleness, in which users typically walk slower when taking frequent and longer rests in a natural walking experience. For instance, participants walked significantly faster and spent less time idle in *Horizontal* than *Vertical*, suggesting that *Horizontal* induces a comparatively fast-paced exploration with few rests in between. In contrast, *Vertical* induces a slower pace with longer idle periods of looking around as a method of exploring a VE. To speak in more qualitative terms, *Vertical* encourages more meandering while *Horizontal* encourages a more upbeat manner of walking. Additionally, participants in *Accordion* had a significantly more regular walking gait than those in *Stop&Reset* despite users walking at comparable speeds, suggesting that redirection through *Accordion* provides a smoother walking experience. Our quantitative data is further substantiated by our interviews, e.g., "*Accordion felt like I kept walking and walking and walking. I even checked through the hole in the VR headset to check whether I was going to bump into a (physical) wall because I've been walking for so long.*"

6.2 Cognitive Engagement

In response to **RQ2**, we found no significant differences regarding memory-recall, distance and volume estimation, and the object position score in the sketch map exercise. However, deviant results for *Horizontal* suggests that the spatial experience for this technique was distinct among the three redirection conditions. Unlike the other conditions, 4 participants specifically drew their sketch maps of *Horizontal* as a series of fragmented levels (Fig. 7.A) as opposed to a single, continuous VE. Interestingly, 3 interviewees associated their movements in *Horizontal* as an up-and-down transition between vertically stacked spaces as opposed to transitions between horizontally-adjacent spaces, e.g., "*It felt like I was climbing up or down somehow and in the other cases it felt like I was in some long corridor. The fact that I could feel like I'm climbing up or down is a good experience.*" This suggests that instead of the single-storied home used for the experiment VE, *Horizontal* is more suitable for VEs with multiple levels, e.g., flats, that involve moving up and down between floors. *Horizontal* offers the possibility of enabling natural walking along a vertical axis in a VE, an otherwise impossible act in reality and unique as a VR experience.

Furthermore, *Horizontal* and *Accordion* were the only two techniques participants preferred because of the fluid and playful nature of the natural walking experience. Notably, although 60% of participants disliked the fact that the entire VE was not visible in *Horizontal*, one participant explicitly preferred *Horizontal* over others because of the lack of an overarching overview. The participant described, "*I like the Horizontal the most because it was the most interactive...I could go and everything could change. I felt like I need more from this...and I want to discover more about the experience.*".

6.3 Presence

Regarding **RQ3**, we did not identify a significant difference in SUS presence between the four techniques. However, responses from our interviews suggest that the appearance of the overt transformation trigger, namely the 'door', influenced the believability of the VE. 50% of participants explicitly criticised the flat door, e.g., "*I didn't like the doors being on the floor*", as opposed to the one participant who preferred flat doors over upright doors. Nevertheless, the 'door' in this study is not necessary to enable the foldable transformation and mainly serves as a narrative device to cue users towards the transformation trigger. To improve believability, this 'door' can simply be substituted [21, 22] with a more appropriate virtual object for the VE. Many participants offered viable suggestions, and most revolved around eye-level virtual objects: "*ladder, a vertical ladder*" or "*I was thinking stairs, because it's weird to have a door there*". Interestingly, although participants found foldable techniques using vertical doors more realistic than techniques with doors on the floor, the contextual realism of a VE did not always correlate with the kinetic realism of walking: "*Horizontal one felt less realistic because I had to open the doors which were on the floor but somehow the transitioning made it more realistic (for natural walking).*"

6.4 Application

Overt redirection is useful for representing VEs that do not specifically need to follow a certain architectural typology yet would nevertheless still benefit from natural walking, namely an experience or a journey that includes meandering, pacing, lingering, and changing perspectives. We see the potential for Foldable Spaces to be implemented in the following application domains: VR exhibitions, in particular those created and tailored as a digital experience; physical therapy in VR that involves walking, such as rehabilitating paraplegia; and Room-scale VR games and sports, especially those which are designed around cell-based environments.

7 LIMITATIONS AND FUTURE WORK

Unidirectional to Multidirectional Folding. The greatest limitation in this study is the unidirectional method of folding, which only enables users to walk through a sequential narrative of corridor or hall-like VEs. In future work, we aim to enable multidirectional folding, which would enable VR users to not only walk up and down a hall-like VE but also move left and right into adjacent rooms, terraces, gardens, etc. Multidirectional folding would enable walking through a complex VE through branching paths, as well as enable a more flexible representation of VE contexts. We plan to enable this feature by algorithmically subdividing a large VE into a grid-like structure to create 'creases' for folding, enabling folding in any orthogonal direction. For instance, the folding algorithm currently allows movement back and forth a VE by creating an axis for folding down the middle of each discrete segment of the VE. By implementing an axis that intersects the current one at an orthogonal angle, we can enable folding for sideways movement.

Adapting Foldable Spaces to smaller spaces. In this study, we used Foldable Spaces in a 4 m×4 m area. Although we tried implementing these foldable techniques in smaller spaces while developing our system (tested in 3 m×3 m area), VEs of this scale have not been tested with users. We expect smaller spaces to cause greater discomfort or fatigue as more folding would be required. Nevertheless, we find it important to adapt this technique for smaller spaces for accessibility: statistics released by Valve (2016) [1] reveal insights about the 'accessible' dimensions for room-scaled VR: 65% of VR users are using a minimum 2 m×2 m space, while only 0.4% of VR users are using a play area of 4 m×4 m.

8 CONCLUSION

We thus contribute Foldable Spaces, a novel class of overt redirection that relies on folding the geometry of a VE to enable natural walking. Within Foldable Spaces, we developed and evaluated three techniques based on distinct folding transformations. Our findings show that *Accordion* was the most well-received by participants in terms of providing a smooth, continuous, and natural experience of walking that does not involve shifts in orientation and provides an overarching view through the VE. Foldable Spaces offers a distinct but complementary class of overt redirection to the current body of redirection techniques: it can easily be combined with subtle redirection techniques such as distance gains, and shows a compelling potential to complement other overt redirection techniques such as the Space Bender [20] to create incredibly dynamic and interactive environments that both bend and fold depending on user movement. The overt nature of a redirection technique, if not detrimental for how users feel and perceive a VE, has the potential to evoke natural walking experiences in seemingly supernatural environments only possible in VR and offers possibilities for aesthetic application domains, physical therapy or sports, and playful spaces.

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