



COMPUTER SCIENCE
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Bachelor in Computer Science

PROCEDURAL GENERATION OF INTERIORS IN VIRTUAL REALITY(VR)

EXPLORING NEW NAVIGATION PARADIGMS

MASTER IN COMPUTER SCIENCE
SPECIALIZATION IN SPECIALIZATION NAME

NOVA University Lisbon

Draft: January 21, 2025

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ABSTRACT

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The abstracts' order varies with the school. If your school has specific regulations concerning the abstracts' order, the NOVAthesis L^AT_EX (`novathesis`) (L^AT_EX) template will respect them. Otherwise, the default rule in the `novathesis` template is to have in first place the abstract in *the same language as main text*, and then the abstract in *the other language*. For example, if the dissertation is written in Portuguese, the abstracts' order will be first Portuguese and then English, followed by the main text in Portuguese. If the dissertation is written in English, the abstracts' order will be first English and then Portuguese, followed by the main text in English. However, this order can be customized by adding one of the following to the file `5_packages.tex`.

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1. What is the problem?
2. Why is this problem interesting/challenging?
3. What is the proposed approach/solution/contribution?
4. What results (implications/consequences) from the solution?

Keywords: One keyword, Another keyword, Yet another keyword, One keyword more, The last keyword

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1. Qual é o problema?
2. Porque é que é um problema interessante/desafiante?
3. Qual é a proposta de abordagem/solução?
4. Quais são as consequências/resultados da solução proposta?

Palavras-chave: Primeira palavra-chave, Outra palavra-chave, Mais uma palavra-chave, A última palavra-chave

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ACRONYMS

HMD	Head-Mounted Display (<i>pp. 2, 6, 7, 10</i>)
novathesis	NOVAthesis L ^A T _E X (<i>pp. i, ii</i>)
RDW	Redirected Walking (<i>pp. 7, 10</i>)
UX	User Experience (<i>p. 1</i>)
VE	Virtual Environment (<i>pp. iv, 1–10</i>)
VR	Virtual Reality (<i>pp. iv, 1–5, 7, 9, 11</i>)

INTRODUCTION

[TODO: Completely outdated]

The implementation and exploration of safe, expansive and immersive VEs has evolved with the development of VR and its wide range of navigation techniques. These techniques influence several dimensions of User Experience (UX), such as efficiency, usability, immersion, comfort, and accessibility, and are, therefore, used in different contexts and situations.

In small physical spaces, the most commonly used navigation techniques rely on joystick-based movement and teleportation, due to the physical constraints of the environment. By cutting the use of Natural Walking, these techniques prove to be less immersive and unrealistic, as they trade the realism of walking elements for ease-of-use.

To address these limitations, new navigation paradigms have been developed. Some of these resource to the use of Impossible Spaces and Non-Euclidean Geometry to provide users the ability to naturally walk through extensive VEs, even within restricted physical spaces. By manipulating spatial perception and geometry, these techniques create the illusion of larger virtual spaces, enabling more intuitive and immersive navigation experiences.

1.1 Motivation

1.2 Related Questions

Q1-Is it worthwhile to explore navigation through non-Stride techniques whilst in a constricted physical space?

Q2-Does using hyperbolic strides instead of linear ones lead to increased disorientation and cybersickness?

Q3-Do hyperbolic spaces effectively convey more control to the user compared to spaces with linear strides?

RELATED WORK

With the objective of understanding the current state of the art in the field of Virtual Reality (VR) navigation and locomotion, this chapter presents several topics, techniques and studies that are relevant to this field.

[TODO: Add 'Background' section, introducing HMDs, VEs and give proper definitions on Navigation, Wayfinding and Motion] [11] [1] [17]

[TODO: Find a much more recent font for describing current technologies and devices]

2.1 Virtual Reality

VR has been given various definitions[17], but these tend to converge on the same few essential ideas: It is a real-time, interactive and immersive experience in a simulated 3D World (also referred as Virtual Environment (VE)), created through the use of different technologies as Head-Mounted Displays (HMDs) and several input/tracking devices that have been in active development and research as of late [4].

2.1.1 Head-Mounted Displays and Devices

2.1.2 Navigation of Virtual Enviornments

2.2 VR Locomotion Techniques

Locomotion (also denoted as "active travel" or just "travel"[14]), the act of moving from one place to another, is often considered one of the most fulcral aspects of VR interaction[20], as it permits navigation in VEs[3].

Throughout the advancements in VR research and technology, multiple locomotion techniques have been developed, all with different characteristics, addressing different needs and use cases[4]. It's due to the diversity of these techniques that various typonomies and classifcations have been proposed, throughout the years of VR development [4]. The structure of this subsection is based on the typology of VR Locomotion Techniques proposed by Boletsis et al. [4] as it emcompasses most techniques according to the characteristics discussed in this section.

According with Boletsis et al.[4] locomotion techniques are distinguished by the type of interaction they require, the type of motion it produces and the type of VE it is designed for, as seen in Figure 2.1.

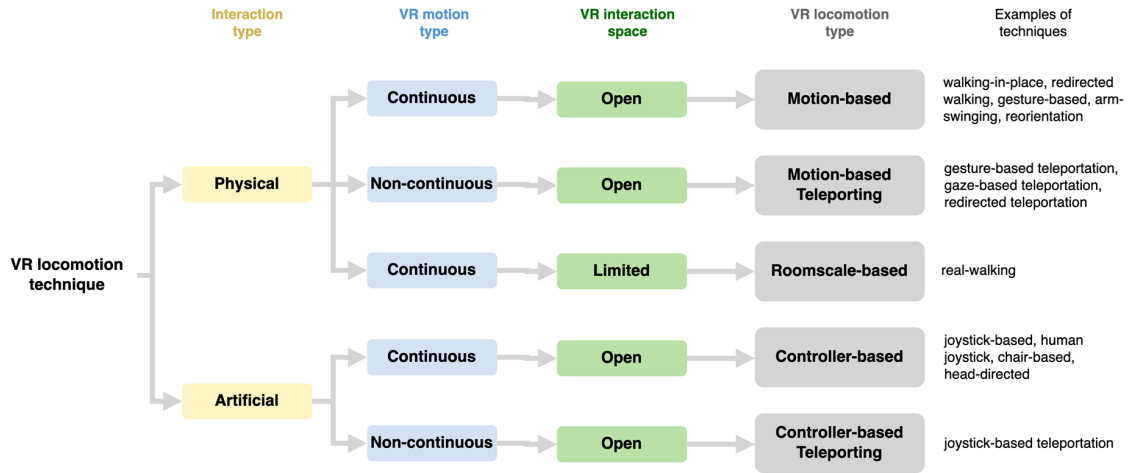


Figure 2.1: Typology of VR locomotion techniques by Boletsis et al.[4]

Regarding the interaction type, a locomotion technique can be "physical" - the input is based on the user's physical movement - or "artificial" - utilizes input devices for direct VR motion and navigation. VR motion types may be "continuous" - the transitions between positions is smooth and non-interrupting - or "non-continuous" - the transitions between positions are abrupt or instantaneous. Finally, the VR interaction space may be "open" - the VE is larger the the user's physical space - or "limited" - the physical environment constraints the VE's size.

Different sets of these characteristics define the different types of locomotion techniques that are to be discussed in the following sections. It is also important to note that these techniques may be used in combination with each other, i.e., a technique integrating two or more other techniques [4].

2.2.1 Joystick

Controller-Based locomotion techniques are used in an open VR interaction space, with continuous motion and require an artificial means of input, such as a controller or other similar input devices[2]. Joystick-based locomotion is not only the most prevalent of this type of techniques, it is also one of the most used techniques in research [4].

Joystick-Based locomotion can be described in the following manner: given a user in a VE from a VR application, the way that they navigate in said VE is dependent on a joystick controller. The joystick rests in a neutral position until the user applies force, changing its value in a certain axis, normally from -1 to 1 (see Figure 2.2). The values registered on the joystick's horizontal and vertical axis will make the user continuously translate from one

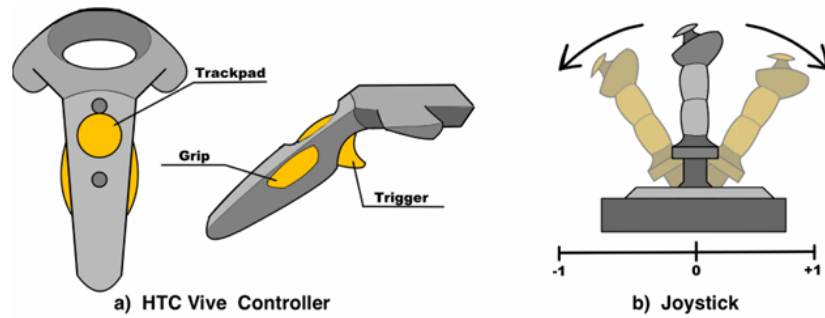


Figure 2.2: Diagram of Vive Controller and Joystick [10]

position to the next in the direction related to the user's gaze direction, i.e., if the user is looking in a certain direction and applies vertical of 1 they will move in the yaw direction of their gaze at full speed [10].

The artificial means of creating input for movement makes joystick locomotion considered not physically demanding and a high ease-of-use technique, especially noticed in users who have prior experience with similar controllers [19]. This locomotion type also registers moderate-to-high levels of immersion when used, mostly due with the motion's uninterrupted nature [3].

Though intuitive and not physically demanding, joystick locomotion has a caveat that pretains to the user's comfort. This locomotion type can create motion sickness, due to the conflicting movement cues from user's proprioception, their vestibular sense and from their vision, as the user is physically stationary whilst they move in the VE[14]. This is especially felt by unexperienced VR users. [19]

It's due to this discomfort and the lack of sufficient levels of immersion that this locomotion technique isn't the most appropriate for the purposes of this research, and thus it will not be implemented. [TODO: Rework this]

2.2.2 Teleportation

Teleporting differs from Controller-Based locomotion techniques in that it is non-continuous, as, instead of moving continuously, users are interruptly teleported from one location to the next during their navigation [2], and much like Joystick-Based locomotion it is one of the most used locomotion techniques[4].

When teleporting, a user dictates where they want to teleport to, usually by holding down some input button on a controller and pointing to the pretained destination with said controller, releasing said input when the destination has been chosen. On release the user moves to the selected destination instantaneously (see Figure 2.3) [10, 19].

The uncontinuity of this locomotion methods' creates strengths and weaknesses. On the positive side, the discrete jumps prevent feelings of cybersickness by not having a conflicting continuous motion occuring while the user is stationary [3, 19], and is generally more efficient at percurring long distances[10]. On the other hand the jumps can create

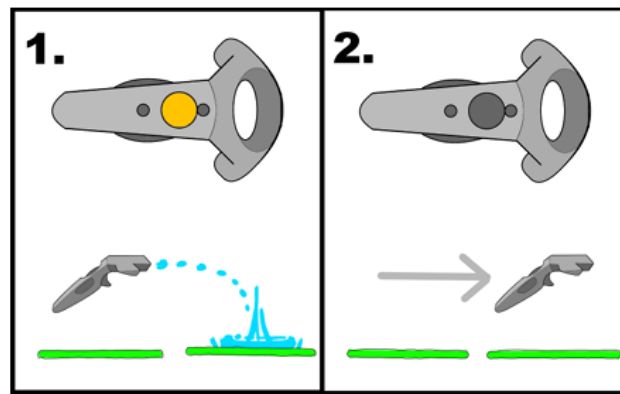


Figure 2.3: Graphical Representation of Teleporting [10]

some disorientation and loss of immersion, as after teleporting the user takes more time to fully comprehend their surroundings [14], exerting more cognitive effort and in turn breaking the illusion of the VE.

To mitigate this lack of immersion, studies tried to provide less artificial manners of performing teleportation. However, even with similar or slightly better results in regards to immersion, users still preferred using controllers rather than the purposed controller-free [5], and even hands-free teleportation techniques [24].

Even so, in various comparison studies, teleportation has been identified as a preferred locomotion method over other frequently used alternatives, mostly due to the lack of motion sickness and high ease-of-use [3, 14].

Although comprehending this technique's strengths and weaknesses is important for the full understanding of the problem at hand, teleporting proves to be a non suitable technique for this research, due to the lack of immersion it provides, and therefore its implementation was not considered.

2.2.3 Omni-Directional Treadmills

As a type of locomotion techniques that require physical interaction for continuous motion in open VR interaction spaces, Motion-Based techniques are rooted on the user's physical movement for their navigation in a VE [2], which poses the question: How can a user physically navigate a VE larger than their physical environment without reaching the limits of their available space?

According to Nilsson et al. [21], it's possible to identify yet another three sub-types of Motion-Based locomotion techniques, all of which try to solve this problem, with these being Repositioning Systems, Proxy Gestures and Redirected Walking.

Repositioning Systems refer to input devices that try to counter-act users' forward motion when walking, essentially keeping them in place, ranging from more devices with a more "active" approach to the repositioning like treadmills to more "passive" options like friction-free platforms Figure 2.4.

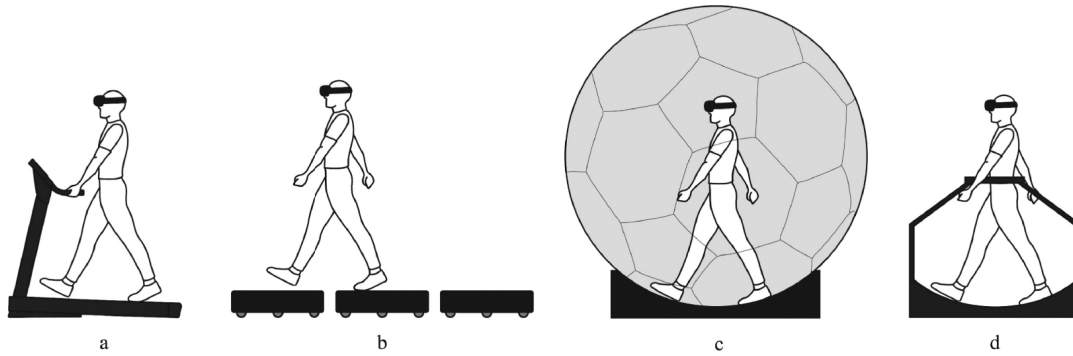


Figure 2.4: Four examples of repositional systems: (a) Traditional Linear Treadmill, (b) motorized floor tiles, (c) a human-sized hamster ball, and (d) a friction-free platform. [21]

One of the most common Repositioning Systems are Omni-Directional Treadmills - devices that sense the direction of users' steps whilst walking in a 360 degree space, maintaining the user at the center of their available space, translating the users steps as movement in the VE. User studies seem to indicate that the motion caused, although not reaching quite exactly the feeling of real walking (with some users indicating a feeling more similar to running or skating rather than walking), this locomotion method evokes high levels of presence, similar to real walking [30].

However, despite taking an almost accurate walking motion as input, offering high levels of immersion and providing a promising solution for the physical limitations of walking in a constricted space, these devices are often expensive and tend to be difficult to operate [8]. In addition, performing quick turns or side-steps may cause users to lose balance [21] and more natural walking techniques like the later discussed [Redirected Walking](#) are preferred by users [30]. It's for these reasons that this research pretends to provide a more suitable, immersive and affordable alternative to a technique like Omni-Directional Treadmills, thus this technique was not chosen for further study and/or improvement in this research.

2.2.4 Walking-In-Place and Arm-Swinging

Proxy Gestures techniques, contrarily to Repositioning Systems like the [Omni-Directional Treadmills](#), offer inexpensive and easy-to-learn solutions to the problem caused by physical constraints during Motion-Based locomotion techniques [21]. Locomotion in these techniques is based on gestures that emulate walking motions, keeping users moving their limbs, but stationary at the same time.

Walking-In-Place is the most common of these techniques [3, 21]. To emulate walking, users perform a gesture comparable to "marching on the spot" in order to move in the direction they are facing, sometimes relying on sensors for detecting the legs' movements [8], yet the detection can recurr solely to HMDs [15].

Although it might sound counter-intuitive for simulating physical walking, Arm-Swinging is a technique that switches the motion performed by users from the lower body to the upper body. In this technique users swing their arms back and forth interchangeably, to move in the direction they are facing. The objective is to perform a gesture comparable to how humans naturally swing their arms when they walk, with the arm's movements being detected either by armband-like sensors [8], or just by controllers users hold in their hands [10].

The fact that both these techniques have the capability to only rely on HMDs and their associated Controllers makes them more accessible, easier to use and thus a more prevalent technique for common users [21]. Additionally, the motion-based input provides a more appropriate proprioceptive feedback similar to real walking than Joystick and Teleportation techniques and hence usually grade higher in immersion ratings [3].

Despite this, these techniques present some caveats. Walking-In-Place can be physically demanding and potentially induces motion sickness after prolonged use [3, 8], making it not the best solution for use-cases in which users have to navigate an extensive VE. Arm-Swinging, although not in the same magnitude, is also limited by this weak point [10], but it is additionally limited by the fact that users can't use their arms for interaction while moving [21].

Although both techniques prove useful for addressing the problems caused by physical limitations while moving, their strong points and weak points indicate them as non suitable for the context of this research. [TODO: Rework this]

2.2.5 Redirected Walking

Motion during navigation in VR is an added value to immersion. The previously mentioned techniques - Omni-Directional Treadmills, Walking-In-Place and Arm-Swinging - proved this, since they are regarded as high immersion techniques compared to techniques with artificial means of input (Joystick and Teleportation), due to their reliance on gestures that simulate walking [19]. Additionally, Motion-Based techniques also tend to score higher in spatial orientation/awareness, compared to artificial means [8, 10]. Even so, users tend to prefer using Redirected Walking (RDW) over these techniques [14, 30].

RDW is not a particular technique, but rather an umbrella term for all techniques that allow users to physically walk in a VE by controlling their path in ways that keep them from reaching the edges of their available physical space [21]. Despite the multitude of possible implementations, RDW aims to follow 4 criteria: **Imperceptability** - users should be as less aware as possible of the redirection taking place - **Safety** - users should feel as safe as possible from reaching the boundaries of their available physical space - **Generability** - the technique's correct functionality should be as independent as possible from the physical environments in which they might be used - and **Absence of Unwanted Side-Effects** - the technique should aim to be devoid of side-effects as those of cybersickness and disorientation [20].

Literature on this topic has recognised two common types of redirection strategies adopted by these techniques [20, 21]:

- **Perspective Manipulation** - RDW techniques that steer users away from the edges of their tracking space by manipulating the mapping between the user's real and virtual movements. Manipulation is accomplished by applying repositioning and orientational transformations, like gains to the users translational and rotational movements i.e. if a gain of 2.0 is applied to the user's forward translation, then they will travel twice as fast in that forward motion in the VE
- **Environment Manipulation** - These techniques rely on the VE's layout and characteristics in order to accomplish redirection. This is done by either building a VE with a pretended path or by changing the VE's properties whilst the user is navigating it, in order to change the users' routes and keep them away from the limits of their available space.

To further categorize these techniques, Suma et al.[27] purpose a taxonomy of techniques (observable in Figure 2.5) according to whether these are **Repositioning Techniques** - techniques that compress the VE by manipulating the correspondence between points in the real and virtual environments - and **Reorientation Techniques** - techniques that attempt to rotate the user's facing direction away from the edges of their tracking space. These techniques can then be **Overt** - easily noticed by users - or **Subtle** - changes are hidden from users - and either **Continuous** - the changes are slowly applied - or **Discrete** - changes are immediate.

Subtle Continuous Repositioning and **Reorientation** techniques are associated with the use of Translational and Rotational Gains, respectively, and these could be considered the most prevalent techniques of the mentioned Perspective Manipulation strategy for redirection [21]. These gains compress the VE by deliberately altering the mapping between the users' movements in the physical and virtual spaces (Figure 2.6). Translation Gains scale the users' steps, whilst Curvature Gains are a continuous small rotations applied while the user is walking forwards, creating the possibility for users to walk infinitely along a virtual path while walking in circles in their tracking space. Bending Gains are another type of gain that works similarly to Curvature Gains, but these are used in already curved virtual paths. Both Curvature and Bending Gains require either *a priori* knowledge or a good prediction method of the path users take in the VE [20].

Most of the techniques in this taxonomy are associated with a Perspective Manipulation strategy. However, **Subtle Discrete Reorientation** techniques do directly alter the VE making them accurately follow the Environment Manipulation strategy. Change blindness redirection [29] serves as an example of how a technique like this might be used, as it discretely changes the environment without users noticing, leading them to take different paths without breaking immersion.

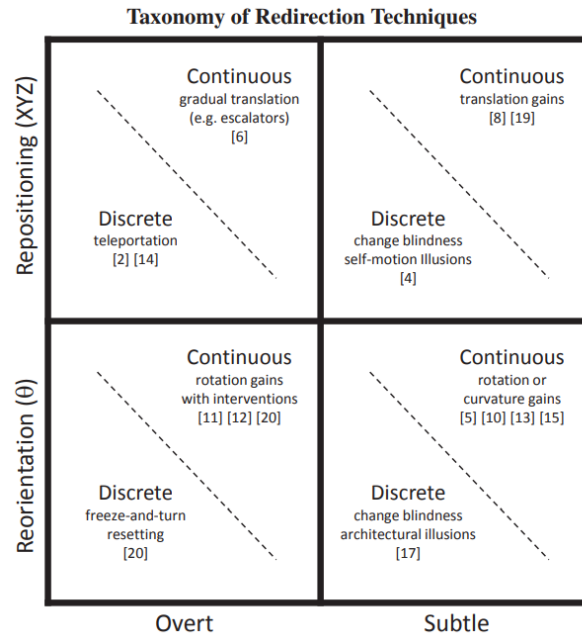


Figure 2.5: Taxonomy of redirection techniques for supporting natural walking through immersive VEs. The vertical axis distinguishes how the technique is applied in the environment. The horizontal axis provides a ranking in terms of noticeability to the user. The division in cells represents distinct implementation strategies for each type of technique. [27]

With the given nomenclature, **Subtle Discrete Repositioning** might seem counter-intuitive, for how can a VR application make discrete jumps in users' positions without their awareness? Bruder et al. [6] purposed a solution by creating visual optic flow effects, reminiscent of filters or tunnel vision, to mask the discrete jumps in the users position. User studies performed with the implementation of this technique revealed that users weren't able to discern the difference between real and virtual movements while influenced by the technique, proving that this it succeeds in its imperceptability.

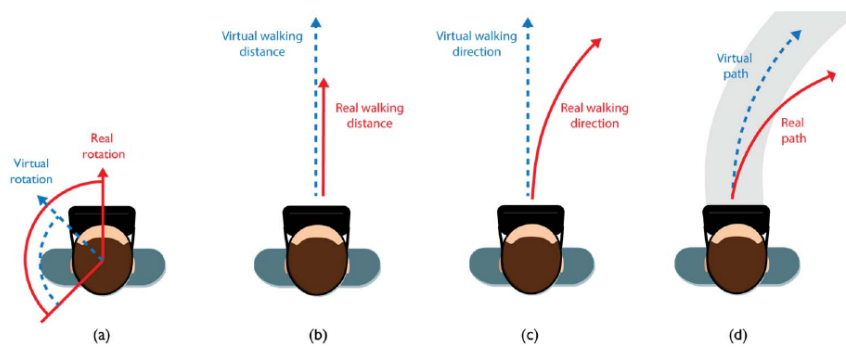


Figure 2.6: Illustration of four types of gains used to manipulate the mapping between the user's real and virtual movement: (a) rotation gains (user stationary), (b) translation gains (user moving forward), (c) curvature gains (user moving forward), and (d) bending gains (user moving on a curve). [20]

As mentioned, RDW techniques should aim to be as unnoticeable as possible [20], but overt techniques prove valuable in limiting conditions to assert that the technique is safe for use. **Overt Discrete Reorientation** techniques are associated with techniques used to redirect users to the available space when they are near of its limits. Freeze-and-turn is an exemplary "failsafe" emergency technique [33]. When a user is nearing the edge of their tracking space, the display on the users' HMDs freezes and prompts them that a reset is required. Once the user has completed a 180 degree turn, the display resumes. Even if the redirection is easily noticeable, Safety can be prioritized over Imperceptability for extreme cases such as these.

Overt Continuous Reorientation techniques are then comparable to the previously mentioned type of technique. The difference lies in the fact that when the system is resetting, the display doesn't freeze, as when the user is prompted to turn 180 degrees, they're movements are being translated as a full 360 degree turn in the VE, allowing them to proceed their virtual path without reaching the edges of their tracking space.

Overt Discrete Repositioning relies simply on teleporting the user from one position to the next, which may be disorienting if users aren't given enough context and aren't expecting the instantaneous change in space. This is mitigated through the use of portals, making the transition more deliberate and potentially a more immersive experience [27]. This serves as an example that overt techniques don't necessarily reduce feelings of presence in a VE.

Overt Continuous Repositioning techniques simply translate the virtual environment about the user's position continuously, in order to achieve repositioning. This then allows the user to walk on areas in the virtual environment that were not previously accessible within the confines of the physical workspace. To minimize the jarring sensations these techniques may feel, they can be coupled with the use of known metaphors associated with motion such as escalators, elevators and vehicles.

It's important to note that techniques may incorporate more than one of the mentioned strategies and types of techniques. The work by Rebelo et al. [0] is an example of this, as the developed techniques rely on the use of portals, alteration of the VE's structure and translation gains, in order to permit the navigation of an extensive VE in a room-scale physical space.

[TODO: adress RDW limitations] [26] Telewalk -> Working with RDW limitations

[TODO: Address that due to the high levels of ease-of-use and immersion, this is the indicated type of locomotion for addressing the problem of maintaining high immersion levels in VR whilst there are constraints in physical space during Navigation]

2.2.6 Summary

[TODO: Present table with techniques, comparing strong and weak points]

[TODO: Go over why continuous motion-based locomotion provided by RDW is the most relevant for this research and connect it with the Motivation (address the gap for

high immersion yet physically limited locomotion)]

2.3 Non-Euclidean Spaces in VR

[TODO: Add an introduction to the topic. Explain Euclidean vs Non-Euclidean.] [23] [32] [13] [12] [18] [25] [31] [28] [9] [16]

[TODO: Shorten this and add relations with other articles [11]. Much of the core concepts here (Cognitive Maps, Wayfinding etc.) might be addressed in the soon to be Background section]

In 2019, Warren conducted an experimental biology paper on Non-Euclidean Navigation[32], with the purpose of defying the assumptions of how humans and animals navigate. Traditionally, according to the Cognitive Map Hypothesis, humans rely on Euclidean cognitive maps, essentially a mental map, for orientation and navigation. Warren, though, purposes a new hypothesis instead: humans navigate according to Cognitive Graphs, stating that spatial knowledge is instead described as a labeled graph with nodes that link places and paths, each with their own local metric data for distances.

To test his theory he conducted a VR experiment in which two groups of users had to traverse a maze, yet one group traversed the maze normally whilst the other traversed a maze with the inclusion of invisible wormholes that seamlessly transported them from one position to another creating a Non-Euclidean Impossible space, as seen in Figure 2.7.

After being firstly tasked to explore the mazes and find four of the objects present in the maze and not the route they took between them (Bookcase to Cactus and Well to Sink), the groups were then prompted to go from object 'A' to an object 'B' without the mazes structures and relying on their spatial knowledge alone. The results shown in Figure 2.8 and the paths from the first task on Figure 2.7 reveal that the participants in the Non-Euclidean maze were biased by the use of wormholes, revealing that despite the irregularities created by the presence of wormholes, participants were able to reach their targets even with the geometric discrepancies created by the wormholes, and that local metric cues and graph-like navigation strategies were enough to guide users to the pertained destination.

Further proving his hypothesis, Warren demonstrates how Non-Euclidean spaces are primed for use in VR Navigation that provide advantages for Natural Walking VR applications, as seen in the following sections.

2.3.1 Impossible Spaces

[TODO: Present various papers on Impossible Spaces]

2.3.2 Hyperbolic Spaces

[TODO: Present various papers on hyperbolic Spaces]

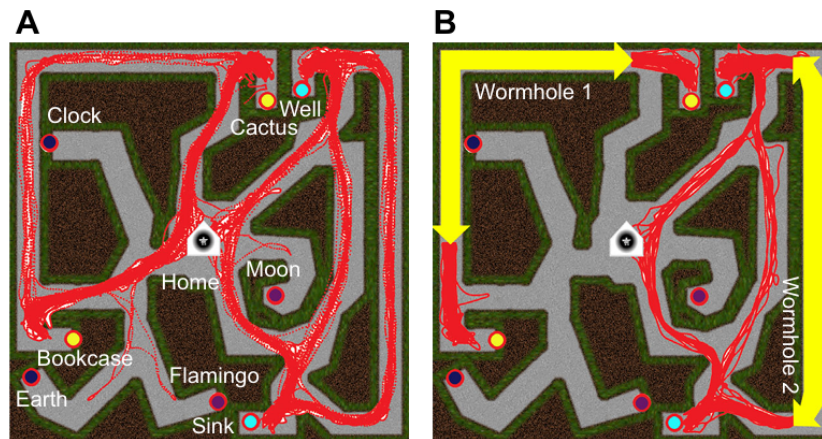


Figure 2.7: Traversed mazes in Warrens' study. Red lines indicate the paths users took. A is the Euclidean maze, B is the Non-Euclidean maze [32]

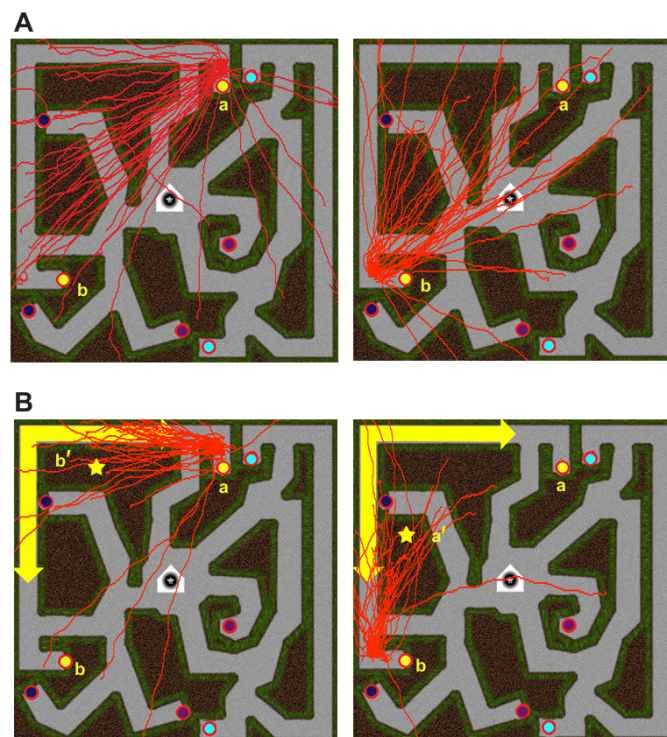


Figure 2.8: Paths taken between objects Bookcase and Cactus in Euclidean maze A and Non-Euclidean maze B. Stars in maze B indicate the location of the object in Euclidean coordinates [32]

2.4 Space Modification Techniques

[TODO: Add proper introduction. This section is for common techniques used to create the spaces referred before]

2.4.1 Procedural Content Generation

[TODO: Introduce the basics of PCG and how to use it for VEs] [\[7\]](#)

2.4.2 Spatial Compression

[TODO: Present papers on Spatial Compression]

PLAN AND ANALYSIS

CONCLUSION

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