UNIVERSIDADE FEDERAL FLUMINENSE

VICTOR FERRARI PINTO SASSI

Accessibility in Virtual Reality: A Proposal for Redirected Movement using Wheelchairs

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Thesis presented to the Graduate School of Computer Science of Universidade Federal Fluminense as a partial requirement for obtaining the Master of Science degree in Computer Science. Field: Computer Science

Advisor:
Esteban Clua

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2023

"Hard work is worthless for those that don't believe in themselves."

Naruto Uzumaki

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Resumo

A presente dissertação é o resultado de uma pesquisa sobre uma nova abordagem de redirect walking e a percepção do movimento na realidade virtual de usuários em cadeiras de roda. A realidade virtual com sua expansão tem atingindo cada vez mais usuários e ultrapassando as áreas de conhecimento especializadas. Com isso, a necessidade de acessibilidade se torna ainda mais urgente. O uso da realidade virtual provoca uma sobrecarga sensorial que acarreta em cybersickness e exige uma análise de redirect walking para que a percepção entre a realidade virtual e atual sejam verossímeis, sem causar mal-estar. Contudo, a hipótese, que se comprovou na pesquisa, é que a percepção de um usuário andando é distinta desse mesmo usuário na cadeira de rodas. Por isso, desenvolveu-se uma nova abordagem de redirect walking para esses casos. O trabalho, assim, avalia e compara o redirect walking do usuário em cadeiras de rodas e cria novos parâmetros de limites para essa adaptação do movimento e da percepção. A partir de uma metodologia empírica de análise quantitativa dos dados, a pesquisa comprovou o uso dessa nova técnica de interface. Os resultados da experimentação demonstraram que os usuários em cadeiras de rodas não identificam extrapolações de 0.45 a 1.7 nesse novo modelo. Isso demonstra a efetividade da nova técnica de redirect walking aplicada a usuários em cadeiras de roda, garantindo a experiência plena e acessível desses usuários.

Palavras-chave: realidade virtual, locomoção em realidade virtual, percepção, redirecionamento de movimento.

Abstract

This dissertation results from research on a new redirect walking technique and its impact on the perception of movement in virtual reality for wheelchair users. With its expanding reach, virtual reality is increasingly accessible to users beyond specialized fields of knowledge. Consequently, the need for accessibility becomes even more urgent. Virtual reality can lead to sensory overload, resulting in cybersickness, and requires redirect walking to make the perception between virtual and actual reality plausible without causing discomfort. However, the hypothesis, confirmed by the research, is that a user's perception while walking differs from when in a wheelchair. Therefore, a new redirect walking technique was developed specifically for wheelchair users. This work evaluates and compares the redirect walking experiences of wheelchair users and establishes new parameters for adapting movement and perception. Using an empirical methodology for quantitative data analysis confirmed the effectiveness of this new redirect technique. The experimental results demonstrated that wheelchair users do not identify gains ranging from 0.45 to 1.7 in this new model. This result illustrates the effectiveness of the new redirect walking technique applied to wheelchair users, ensuring a complete and accessible experience for these individuals.

Keywords: virtual reality, locomotion in virtual reality, perception, redirect movement, redirect walking.

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3D	:	3-dimensions
HMD	:	Head-mounted display
SSQ	:	Simulator sickness questionnaire
VR	:	Virtual reality
VRSQ	:	Virtual reality sickness questionnaire

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Chapter 1

Introduction

The term "Virtual Reality" (VR) was first used by playwriter Antonin Artaud in 1935 to describe how nature and objects could exist in a play as an illusion while creating an ideology called The Theater of Cruelty, where he defends that plays should be more immersive and profound [5]. In the 60s, Myron Krueger used the term "Artificial Reality" with the meaning, as understood nowadays, of an interactive immersive environment [37]. Only in 1982 the term "Virtual Reality" started to be used as it is nowadays, presented in the book The Judas Mandala [11] written by Damien Broderick and explained in this quote:

> "Basically, we're the only dysentropic probability vector in these 'virtual realities': the ontology's plastic. There's a sort of consensual cocoon around us modifying our immediate environment synchronistically."

Since the advancement of technology is a significant factor that has been shaping society's development effectively, VR is extending its possibilities, even reaching the general public beyond specialized knowledge areas. Virtual Reality is a new way to immerse the user in the metaverse. Ball [6] describes the metaverse as:

> "A vast, interoperable network of real-time-rendered 3D virtual worlds that can be experienced synchronously and persistently by an effectively unlimited number of users, each with an individual sense of presence and continuity of data, including identity, history, rights, objects, communications, and payments."

1.1 Motivation

The metaverse exemplifies the increasing integration of VR into daily life, with more people gaining access despite the pay gap, as seen in Fig.1.1. In the US, in 2020, one in every five people has used VR, and 30% of US citizens use it monthly[2]. However, is this reality for all? This project aims to go a step further in accessibility in VR while also developing a new way to move in the virtual environment while paying attention to the user's perception and well-being.

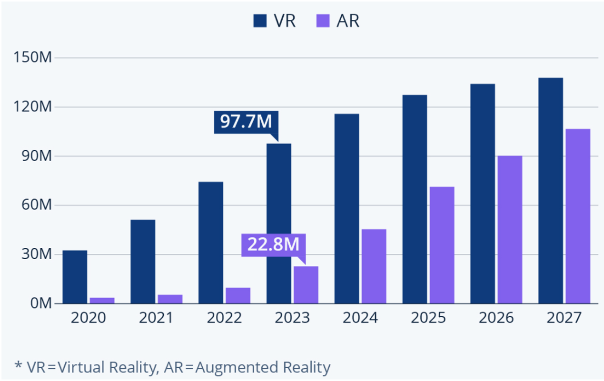

Figure 1.1: Estimated users of VR/AR hardware worldwide.[68]

Users may experience unique sensory perceptions that differ from those in our natural world when accessing the new VR universe. However, the intensity of these sensations can sometimes cause discomfort during the virtual reality experience.

Therefore, when using Virtual Reality, knowing that specific experiences can lead to nausea, sickness, and headaches is essential. These symptoms can be due to visually induced motion sickness (VIMS), and when it occurs during a virtual experience, which is called cybersickness. Several factors can contribute to these symptoms, including locomotion, acceleration, degree of control, duration, field of view, jumping movements, latency, static rest frame, and camera rotation [63, 61]. Several researchers aim to understand and improve VR experiences, such as Porcino [63, 62], who discusses possible causes of these issues and presents possible solutions as design guidelines that may mitigate the cybersickness. Wheech [84] tries to understand how narrative, the feeling of presence, and the gaming experience can diminish cybersickness. Also, Chardonnet[16] developed a new questionnaire based on the simulator sickness questionnaire to quantify the sickness in VR experiences better. In this work, we show a new Redirect Walking method and apply it to users in wheelchairs since we knew that the perception would be different and result in more significant redirect thresholds that result in a better feel of presence and well-being in a VR environment.

1.2 Hypothesis

This research focuses on two factors that can improve immersion and diminish the cybersickness in VR experience: locomotion and acceleration. Sun [78] presents that redirect walking techniques are able to enhance the immersion and visual-vestibular comfort of VR navigation. Porcino [63] explains that changing the acceleration in a VR confuses the brain. As the brain recognizes the velocity disparity between what is seen and perceived, it makes the user sick. Based on those facts, the hypothesis that triggered this research is how it would change the immersion and the perception of movement in virtual environments if the user is in a wheelchair from the beginning and end of any translation when in a wheelchair has a different acceleration than walking.

1.3 Objective

1.3.1 General Objective

This project aims to measure and compare the redirect walking thresholds when users use real wheelchairs as interfaces. There is a motion-like difference in how people move between walking and steering a wheelchair. This distinction will result in different and new data on redirect walking thresholds. As far as the authors know, no previous work was presented in the field.

1.3.2 Specific Objectives

- Propose techniques of redirect walking for wheelchair users, considering previous works related to regular redirect walking.
- Collect the data of people in wheelchairs' perception of redirect walking thresholds.
- Compare and analyze the collected data with other works on threshold evaluation.
- Make data available for the development of new inclusive games.

1.4 Contributions

The main contributions of this thesis are:

1. Increase the accessibility of wheelchair users through the use of virtual reality.
2. Recognize wheelchair users as potential users.
3. Conduct research in the field of computer science focused on human-centered approaches.
4. Develop a new redirect walking technique.
5. Generate new methodologies for creating novel redirect walking techniques.
6. Demonstrate a significant difference in perception between operating a wheelchair and walking. This margin identified in the comparison opens up opportunities for research not only with wheelchair users but also validates the ability to explore people's perceptions when using other modes of mobility.
7. Through this research we have published a paper
   - V. F. P. Sassi, T. Porcino, E. W. G. Clua and D. G. Trevisan, "Redefining Redirected Movement for Wheelchair Based Interaction for Virtual Reality," 2023 IEEE 11th International Conference on Serious Games and Applications for Health (SeGAH), Athens, Greece, 2023

1.5 Dissertation Organization

Five chapters organize this dissertation, and this is the first of them.

Chapter two will address how locomotion works in VR, the concept of RW, and related works that indicate the types of RW, their techniques, and how it evaluates the perception in it. It will also address the concept of inclusion and accessibility in VR.

Chapter three demonstrates the methodology for creating a RW technique for wheelchair users.

Chapter four presents the description of the experiment, detailing the setup, participants, and procedures, along with the analysis of the results obtained, both quantitative and qualitative.

Finally, chapter five presents the conclusions obtained in this work as suggestions for future work.

Chapter 2

Related Works

2.1 Locomotion in VR

Moving is another form of people unconsciously and continuously interacting with their surroundings daily. Locomotion techniques are one way to change the user's state from a passive to an active character in the environment, creating a deep sense of existence and enhancing the experience [39]. However, there are challenges for each type of locomotion in Virtual Reality environments [39, 18]. Albert summed them up into three fundamental challenges: sickness, presence, and fatigue [3]. Beyond the primary specifications, there exist supplementary prerequisites concerning tracking mechanisms, potentially imposing severe constraints on the user's navigable space. These requirements have the potential to significantly limit the user's range of movement within the designated area.

Several researchers proposed classifications for locomotion techniques [18, 8, 3, 9, 4, 77]. Cherni proposes a taxonomy of locomotion techniques in virtual reality based on whether the input is body-centered, external peripheral-centered, or both [18]. Fig. 2.1 shows visually how the techniques are separated. The three main groups' names are User-body centered, Mixed, and External Peripheral centered.

- **User-body centered** are techniques based on the user's movement, such as leaning the head [87, 29], swinging arms [44, 14], or even natural walking as inputs [43, 30, 38].
- **External Peripheral-centered** techniques are hardware-based inputs such as omnidirectional mills [83, 14], teleportation (Fig. 2.2), and the use of a joystick [69, 40, 29].
- **Mixed** techniques apply both categories simultaneously, such as holding a controller

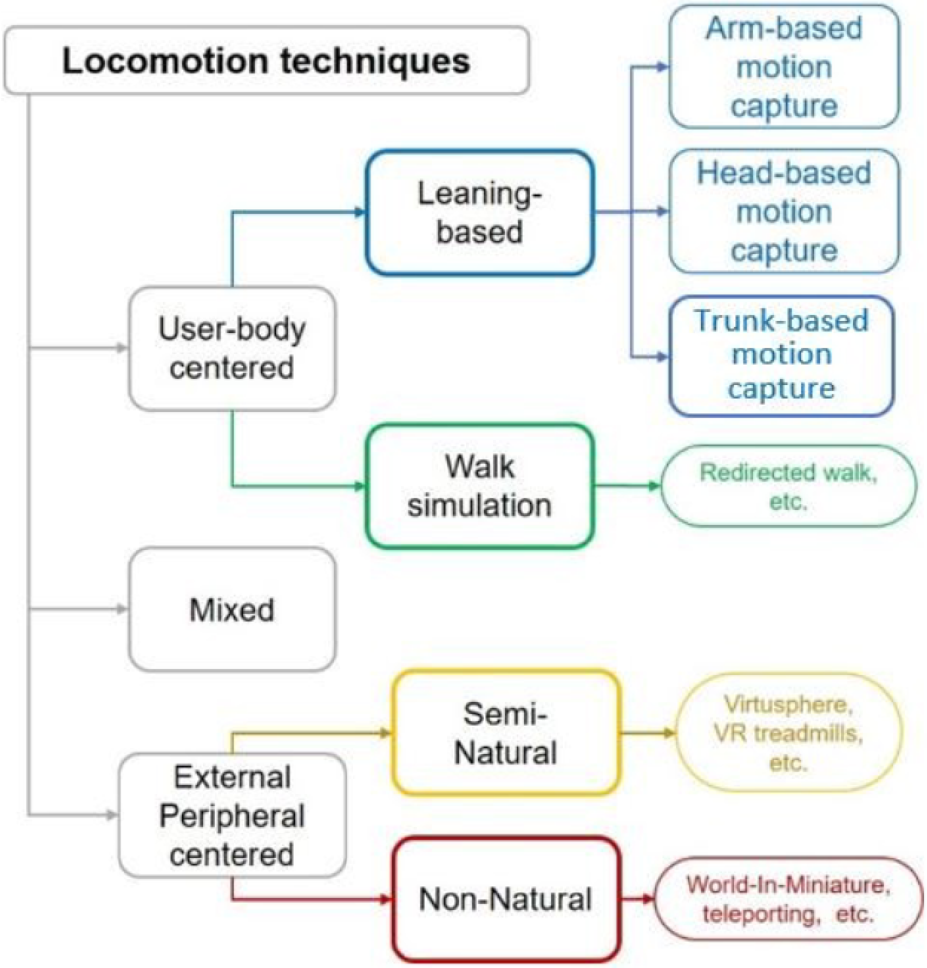

Figure 2.1: Virtual reality locomotion techniques taxonomy. Source: [18]

button while winging an arm or using the joystick to move in the virtual space and rotate by spinning its head simultaneously [69, 29].

Even though there are several solutions for creating a way to move in a VR environment, there is yet to be one better solution for all applications [8, 18, 3]. Each method has pros and cons, but all techniques have typical problems, as mentioned before. The first one, already mentioned in this work, is sickness, caused by dissonance between the motion visualized in the virtual environment and the motion felt in the real world [3]. A problem common in the External Peripheral class is that the ones that reduce motion sickness are the body-centered self-motion techniques [18].

The next challenge is presence, better described as the sense of presence. Slater defines it as the user's sense of being in a virtual world, which enhances immersion, that is, the technical description of the virtual environment capable of producing the sense of presence [3, 74]. Techniques based on natural walking are considered the most presence-enhancing

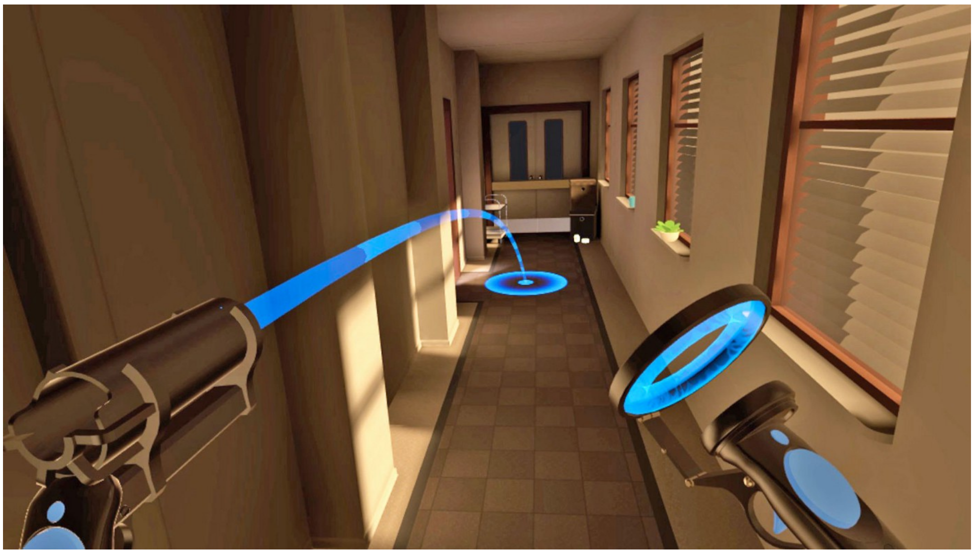

Figure 2.2: Teleport Locomotion Technique. Source: [18]

form of locomotion [39, 77, 52, 65, 8]. However, unlike the other challenges, any technique can break the immersion since its use may create a more profound or shallower interaction depending on the design of the experience [9, 18].

The last main challenge is fatigue. This ergonomic issue is less known than the others since it appears after continued use of the HMD. However, while developing an application, evaluating this problem can determine its success. It is worse in walk-based techniques and treadmills. In other words, techniques where the user needs to move [3, 58].

There are specific challenges for specific solutions, besides the three main problems mentioned by Albert [3], that are worth mentioning. Most external peripheral-centered semi-natural techniques are expensive and challenging to use and maintain, therefore not considered a viable option to implement [18, 14]. However, researchers are working on them because it can be an option in the future to solve the main three problems [28, 7]. Redirect Walking is one of the locomotion techniques recognized as promising to solve those three main problems [15].

This solution aims to create, in the user, the feeling of mimicking his movement by misleading his senses [30]. Redirect walking tricks the user's perception and makes him feel that he is walking forward, but he is in fact walking on a curved path. The main problem with this is how to shift the virtual environment without triggering the user's perception, which can cause cybersickness and break the immersion sensation. Instead of only diverting the player's movement or turning the whole scenery, researchers use devices, tools, and methods to improve Redirect Walking. Methods such as the one pointed out by Sun [78] recognize when there is saccade movement of the eye and shifts the scene simultaneously. Redirect walking is the least used method of movement in VR applications mainly because of the necessity of bigger spaces to fully reach its potential of making the user unaware of the reorientation of his movement. Matsumoto [43] experimented that a circular arc of 22m is necessary to avoid perception, but Rietzler [70] managed to constrain the movements to an area of 6m x 6m. Even though there are advances in this topic, it is still necessary to develop more efficient methods for inferring the smaller required spaces for each situation.

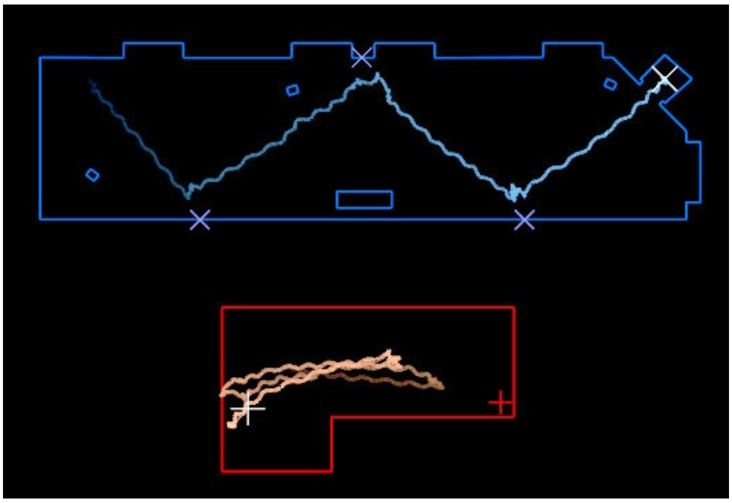

Figure 2.3: Redirect walking overview: The blue region shows the virtual environment, and the blue wiggled line is the virtual path the users chose to move. The red area is the real-life area and the red line is the user's path made imperceptibly. Source: [30]

As said by Qi and supported by other authors, locomotion is one of the most critical forms of interaction in VR [65, 39, 78]. Therefore, choosing which method to implement is crucial. It is a choice based on the use of the application and analyzing which problems are worst to the experience and should be solved. Cherni even adds a table to his work, showing the better techniques depending on which body parts the user will dedicate to the locomotion [18]. Hence the technique should be a design-driven choice.

Rebenitsch et. al [67] has suggested a correlation between locomotion and cybersickness (CS). It has been observed that participants who have greater control over their movements and are able to move around more naturally experience less CS. On the other hand, experiencing continuous visual movement stimulation while resting (known as vection) can induce painful sensations and reduce the comfortable usage time of virtual reality. However, a number of locomotion strategies [63] have been developed to reduce the discomfort and improve the overall VR' user experience. Some of main locomotion techniques that are also shown in Fig 2.1 are described below:

- **Teleportation**: Also known as teleporting, is widely used in most VR applications. This locomotion technique allows users to travel long distances by specifying the destination point using a marker, as described by Langbehn et al. [40]. The process involves the user pointing to the desired location through a controller and then squeezing a trigger button, which instantly transports them to the new location. This technique is commonly referred to as "pointing and teleporting".

- **Blinking**: Similar to teleportation, blinking involves the user closing their eyes briefly and then re-opening them in a new location. Although blinking technique can be useful for reducing cybersickness helping to avoid the visual motion cues that often trigger discomfort, it can also be jarring for some users and may disrupt the sense of immersion in the VE [54].

- **Slowed Movement**: In practice, the technique involves slowing down the movement of the user's avatar or other objects within the virtual environment, which can help to reduce the visual motion that can trigger cybersickness. This can be achieved by reducing the speed of movement, reducing the distance traveled, or both [26].

- **Cockpit View (Static Rest Frame)**: This technique involves creating a static reference frame within the VR environment, which remains fixed relative to the user's body, providing a stable visual anchor for the user's orientation [73].

- **Redirected Walking**: this strategy involves applying imperceptible rotational or translational changes to the user's perceived movement direction. For example, when a user turns his/her ead to the left, the virtual environment will rotate slightly to the right, giving the user the impression that they are turning left in the virtual world. This subtle adjustment can create the illusion of a larger virtual space while still keeping the user confined to a smaller physical area [72].

These techniques can be highly effective in reducing cybersickness when combined with other best practices, such as minimizing sudden movements, providing clear visual cues, and ensuring that the user is comfortable and well-rested before using VR[63].

Among all the mentioned strategies, it is well known that the best locomotion approach is the direct movement, which consists of pairing the virtual and real movement. This is the ideal situation, since the user´s body has total control of the translations, without any artificial manipulation. However, mapping all the real movements to the virtual scenario brings a strong constraint, which consists of the real-world size limitation[78, 20]. This problem is even larger when dealing with wheelchairs as locomotion interfaces in VR environments, due to the larger movements they are capable of producing.

In this research, we will explore the Redirected Walking technique, first developed by Razzaque[30], but reinvented for wheelchairs-based applications, which allows users to navigate large virtual environments while minimizing physical movement. We will discuss the different types of applications for this technique, including its suitability for wheelchair users. Besides introducing the concept of redirect movement for wheelchairs, this paper also contributes finding the limits for the gain coefficients that make the redirection features unnoticeable and comfortable for the users.

By applying these techniques and best practices, VR experiences can become more accessible, comfortable, and enjoyable for a wider range of users.

2.2 Redirect Walking

The word perception is the quality of being aware of things through the physical senses [1]. Virtual Reality researchers work on unraveling triggers that activate the user's perception and detach him from the immersion, in other words, what makes him recognize the difference between virtual and real. There are several ways to analyze what can impact the user's perception. Newman evaluates how a scene's composition can influence the experience [51]. Diemer examines the perception of fear, intending to identify the influence of an emotional experience [22]. Weech tried to understand how the narrative can affect the feeling of presence [84]. Nguyen analyses the effect of the sense of embodiment on curvature redirect walking thresholds [57]. Therefore there are several ways to influence one's perception in virtual reality environments, and there is an effort among researchers the better understand it.

Theoretically, humans use different senses to determine whether they are in motion or if objects in their external environment are moving around them. Vision and the vestibular senses are primarily responsible for providing information to our brain that helps us navigate in the real world. Therefore, when a user is in a virtual environment, it is recommended that they experience a virtual environment that does not conflict with these human senses.

Redirected walking (RW) can not only simulate movement but also enable users to walk in large virtual environments using limited real-world spaces, such as a small room.

Besides, there are different ways to apply RW in virtual reality applications, such as Redirect Translation, Rotation, and Circular Redirection.

2.2.1 Types of Redirect Walking

2.2.1.1 Redirect Translation

Redirect translation can make the user move in the virtual environment more or less than walking in the real world. By tracking his movement, the VR application can apply a gain to his motion and make the user move more or less. The transnational gain can be defined by the equation 2.1 and is visually explained by Fig 2.4[76, 75, 53, 59].

$$g_t = \frac{T_v}{T_r} \tag{2.1}$$

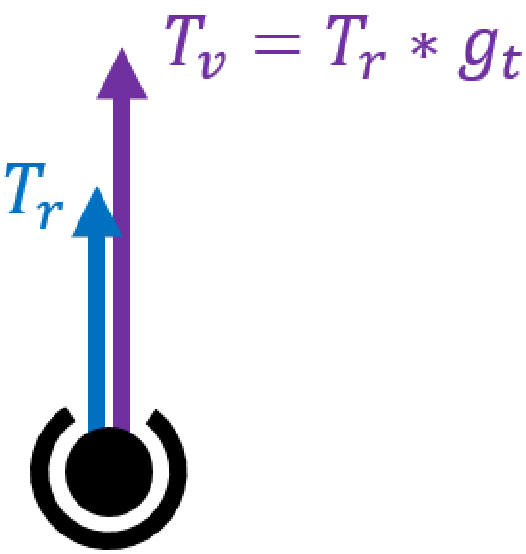

Figure 2.4: Scheme to explain Redirect Translation, the blue arrow represents the physical movement, and the purple arrow represents the virtual movement.

Where g_t stands for translation gain, T_r is the translation in real space, and T_v is the translation in the virtual environment. So, the translational gain is the ratio between virtual and physical movements. If the user moves a distance of 2m and in the virtual environment moves a distance of 3m, the translation gain is equal to 1.5, so the user moved 50% more than the physical distance traveled[33]. This type of redirection can be a vector of three dimensions. In those cases, the user has different gain values for each direction when moving forward, sideways, or leaning up and crouching[76, 75, 53].

2.2.1.2 Redirect Rotation

Redirect rotation can make the user turn in the virtual environment more or less amounts than rotating in the real world while he is not moving forward. With this redirection, we can make the user turn only 90 degrees while he is turning 120 degrees in-game, for instance. In this case, we would have a gain equal to 1.3, so the user turns 30% more without realizing it. Equation 2.2 explains this type of redirection mathematically and Fig 2.5 shows how does it work.

$$g_r = \frac{R_v}{R_r} \tag{2.2}$$

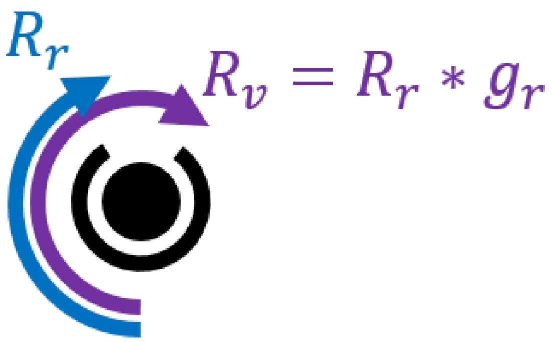

Figure 2.5: Scheme to explain Redirect Rotation, the blue arrow represents the physical rotation, and the purple arrow represents the virtual rotation.

g_r stands for rotational gain, while R_r and R_v denote the rotation in real space and the virtual environment. So, rotational gain refers to the ratio between virtual and physical rotation. If the rotational gain exceeds one, the user will rotate faster than in the real world. Developers can apply this technique in different directions, though it is typically used around the yaw axis (vertical)[76, 75, 53, 59].

2.2.1.3 Circular Redirection

Circular redirection works similarly to rotation redirection, it also applies rotation around the yaw axis, but it is while the user moves forward. This type of redirection aims to allow the user to walk freely in a virtual path while he is moving in circles in the physical path. Equation 2.3 defines the curvature gain (g_c) in terms of the radius of the physical circular path (C_r) traveled by the user. It shows that the larger the curvature gain, the smaller the radius and the greater the translation of the user. Fig 2.6 visually explains this type of redirection[76, 75, 53, 59].

$$g_c = \frac{1}{C_r} \tag{2.3}$$

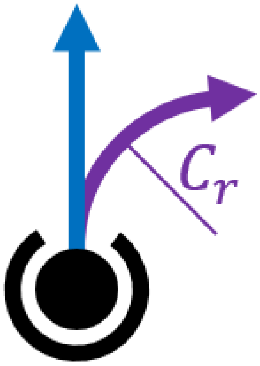

Figure 2.6: Scheme to explain Circular Redirection, the blue arrow represents the physical path, and the purple arrow represents the virtual path taken by the user.

2.2.2 Redirect Walking Techniques

Razzaque first proposed this technique because physical walking is superior to flying or walking in place in terms of presence, ease of use, and naturalness. His goal was to allow users to walk through large virtual spaces[30]. Researchers have published several papers on recreating new redirect walking implementations[66, 79, 23, 71, 13] and evaluating and comparing existing ones[76, 75, 57, 53, 33, 17, 34, 41, 19].

Now there are several new techniques, such as one proposed by Sun[79], which recognizes when there is saccade eye movement and simultaneously shifts the scene. There is also Qi's[66] proposal, which is based on developing an algorithm based on a 2d map of the virtual environment and minimizes the collisions the user can experience in the real world during the virtual experience. Other researchers try to change existing applications, such as Kim's[33] work, where he simultaneously changes the translation gain based on the space size of more than one user. There is also Sakono's[71] proposal, which involves applying dynamic changes to curvature redirections in order to evaluate whether they are more effective than regular curvature redirections. Nevertheless, all of those and other newly created redirections show little interest in considering impairment conditions movements, such as wheelchairs. When deciding on a method to implement, it is essential to make a design-driven choice based on the application's use. Therefore, when designing a new application, accessibility should be considered early during the development.

Table 2.1: Redirect Walking Thresholds Papers

Redirect Walking Thresholds Papers

Paper	Year	Redirected Tested	Profile Data	In Game Question	Questionaires	Trials per Test Subject	Hardware
Steinicke[75]	2008	Rotation Curvature Translation	Experience in Games Experience in VR Age Gender Vision Impairmaint	Larger or Smaller? Left or Right?	Difficulty Fear of Colliding Cybersickness: SSQ	80-110	3D Visor Backpack Computer 3D-Tracking System Wii Controller
Steinicke[76]	2010	Rotation Curvature Translation	Experience in Games Experience in VR Age Gender Vision Impairmaint	Larger or Smaller? Left or Right?	Difficulty Fear of Colliding Cybersickness: SSQ	80-110	3D Visor Backback Computer 3D-Tracking System Wii Controller
Meyer[45]	2016	Rotation Curvature	-	Larger or Smaller? Left or Right?	Cybersickness: SSQ	22	Unity Oculus Rift Backpack Computer 3D-Tracking System
Grechkin[27]	2016	Curvature Translation	Age Gender Vision Impairmaint	Left or Right?	Cybersickness: SSQ	96	Oculus Rift 3D-Tracking System
Rietzler[70]	2018	Curvature	Experience in VR Age Gender	In which one were you redirected?	Applicability	48	Unity Oculus Quest
Karlsson[31]	2020	Rotation	Experience in VR Name Age Gender	-	Presence	4	Unity Oculus Quest
Nguyen[53]	2021	Curvature	Experience in Games Age Gender Vision Impairmaint Handedness Height	In which one were you redirected?	Cybersickness: SSQ	40	Unity Oculus Rift Backpack Computer 3D-Tracking System
Kim[33]	2021	Translation	Experience in VR Age Gender	Larger or Smaller?	Cybersickness: SSQ	56	Unity HTC VIVE Steam VR plug-in
Brument[12]	2021	Rotation Translation	Experience in Games Experience in VR Age Gender Dominant Eye Dominant Foot	Larger or Smaller? Left or Right?	Cybersickness: SSQ Fast-SSQ	8-18	Unity Vive Pro Eye Vive Wireless Adapter

2.2.3 Redirect Walking Thresholds

Table 2.1 presents all papers that evaluate the user's perception of movement while being redirected in VR by calculating their thresholds.

Steinicke, through research conducted in 2008 and 2010, was the only one to test rotation, curvature, and translation redirection. Both studies had similar parameters. The data profiles had experience in games, experience in VR, age, gender, and vision impairment. The questions concerned differences between larger or smaller and left or right movements. The questionnaires validated difficulty, fear of collision, and cybersickness. The number of trials per test subject ranged from 80 to 110, and the hardware and software used included a 3D Visor, Backpack Computer, 3D-tracking System, and Wii Controller.

Chronologically, the subsequent research in 2016 by Meyer focused only on rotation and curvature. Without defining the research profiles, the questions were the same as

Table 2.2: Comparisson between translational gains tresholds from different papers

Paper	**Upper Translation Gain Thresholds**	**Lower Translation Gain Thresholds**
Kim [33]	1.29	0.85
Kim [33]	1.16	0.92
Steinicke [76, 75]	1.26	0.86
Brument [12]	1.32	0.64
Chen [17]	1.12	0.9

in the previous studies: larger or smaller and left or correct movements. The questions related to cybersickness were 22 trials per test subject. The hardware and software stood out for using Unity and were similar to Oculus Rift, Backpack Computer, and 3D-Tracking System.

In the same year, Grechkin tested curvature and translation redirection. The user profiles had age, gender, and vision impairment. The in-game questions were about right and left movements, and the cybersickness inquiry remained consistent from 2008 to 2016. Grechkin's research conducted 96 trials per test subject, and the hardware and software focused on Oculus Rift and the 3D-Tracking System.

In 2018, Rietzler evaluated curvature in his test. Data profiles were assessed based on experience in VR, age, and gender. Without in-game questions, the inquiries pertained to presence. There were four trials per test subject, and the hardware and software used were Unity and Oculus Quest.

In 2021, there were three redirect walking thresholds studies by Nguyen, Kim and Brument. They tested curvature, rotation and translation. Nguyen defined profiles related to game experience, age, gender, vision impairment, handedness, and height. The game asked, "In which one were you redirected?" and inquired about cybersickness. There were 40 trials per test subject, and the hardware and software included the Backpack Computer, Unity, Oculus Rift, and 3D-tracking System. Kim focused on Experience in VR, age, and gender as profile data, and the question was "larger or smaller." Similarly, the inquiry was about cybersickness. There were 56 trials per test subject, and the hardware and software involved Unity, along with the distinctive use of HTC Vive and the Stream VR plug-in.

2.3 Inclusion in Virtual Reality

In 2015, the Brazilian Law on Inclusion of Persons with Disabilities (Statute of Persons with Disabilities), also known as Law 13146/2015, was passed to ensure that individuals

Table 2.3: Articles and Dissertations gathered from Portal Capes.

Portal Capes					
Descriptor	**Filter**	**Period**	**Exclusion Criteria**	**Founded**	**Selected**
Inclusion Virtual Reality	Peer-review Dissertations Articles	2001 - 2023	Architectural Projects Assistive Technology Interactive Art Cyberspace Distance Learning Digital Access Education and Technology Stroke Parkinson‘s Diesease Hypermedia	71	6
Wheelchair User Virtual Reality	Peer-review Dissertations Articles	2001 - 2023	-	0	0

with disabilities have equal access to fundamental rights and freedoms. The law aims to promote social inclusion and citizenship for people with disabilities.[10] However, society, including Brazil, still needs to work on inclusion due to norms prioritizing standardization and exclusion, which stem from an economic system that perceives disability as a problem. The challenges are numerous in the face of the obstacles that people with disabilities encounter, so developing a mindset in which inclusion is present in all its aspects should be a concern of education and academic research, which are still in their early stages.[25].

We searched the main national academic databases for studies on inclusion, virtual reality, and wheelchair users. However, from the readings, we have observed a gap in the relationships between these terms.

Initially, we used the descriptors separately: inclusion and virtual reality, and subsequently, wheelchair users. We looked for these terms in academic databases such as the Biblioteca Digital de Teses e Dissertações (BDTD) and at the Catálogo de Teses e Dissertações Capes, as well as in journal databases such as Scielo e Periódicos Capes.

As shown in Table 2.3, we searched for articles on the CAPES Portal, a peer-reviewed platform. We applied filters and found 71 articles that had the keywords "inclusion" and "virtual reality." Out of these, only six articles were regarding rehabilitation. After reviewing these articles, we found that none discussed the relationship between wheelchair users and virtual reality.

Regarding research in the Biblioteca Digital Brasileira de Teses e Dissertações, we found 91 dissertations and 39 theses using the descriptors "inclusion" and "virtual reality", as shown in Table 2.4. However, none established a relationship between virtual reality

Table 2.4: Articles and Dissertations gathered from Biblioteca Digital Brasileira de Teses e Dissertações.

Biblioteca Digital Brasileira de Teses e Dissertações					
Descriptor	**Filter**	**Period**	**Exclusion Criteria**	**Founded**	**Selected**
Inclusion Virtual Reality Wheelchair User	Peer-review Dissertations Articles	2001 - 2023	Wheelchair users with visual impairmaint Physical Disability and Virtual Characters	2	0

and wheelchair users.

We expanded the search by including the descriptor "wheelchair user," which led to the discovery of one thesis and one dissertation. These respectively addressed the issue of visual impairment in a wheelchair user and the creation of a virtual character with a physical disability.

The search for these works highlighted the lack of research that indicates a connection between virtual reality and inclusion, especially concerning wheelchair users. Therefore, it underscores the importance of expanding research on the use of virtual reality as a means to enhance and broaden inclusion in society.

2.3.1 Accessible by design

Several VR developers do not consider accessibility during their applications' development [49]. Consequently, making VR applications accessible is an after-work where the user's needs are adapted to make him able to interact with an already implemented system. To solve this problem, developers can think based on the Ability-Based Design (ABD), which is a method to develop applications based on what users can do and how systems and environments should adapt to the user and not the other way around.[86]. In this sense, if developers start considering the ABD method, accessibility ceases to be an afterthought feature, and people with disability will receive full experiences and not just adapted ones.

Mott[49] defines five areas that the VR community should consider so virtual experiences are accessible by design:

- **Accessibility of VR content**: There is not an agreed standard method, but VR experiences should have the ability to convey content in alternative modalities like sound-to-text closed captioning, alternative text for 3d objects, and others.
- **Accessibility of interaction techniques**: While VR applications can give users

capabilities like teleporting and flying to have these "superpower" abilities, there is a physical input barrier to overcome. The standard one-size-fits-all VR controllers need full fingers, wrists, and arms articulation. So including multiple interaction methods, such as motion, eye gaze, and audio sensors, can help make interfaces more accessible.

- **Device/hardware accessibility**: New VR headsets aim to reduce the number of hardware components and add backward compatibility with older applications that support novel or customized controllers. We can see an evolution of the flexibility towards this topic that benefits accessibility.

- **Inclusive user representations within VR environments**: Virtual reality applications enable users to create virtual avatars with traits that may differ from their physical appearance. For this reason, the VR avatar must be inclusive and representative of the diverse population of users. Therefore, by offering avatars with various physical characteristics, like avatars using wheelchairs, white canes, and hearing aids, users with disabilities can choose to control or embody avatars that resemble their physical appearance providing more inclusivity and options for users.

- **Accessibility-focused application areas for VR**: By creating VR applications that prioritize accessibility, new opportunities emerge in areas related to skill development, rehabilitation, and other special needs of people with disabilities. VR can democratize rehabilitation for people with limited motor abilities and has potential therapeutic applications. We can also consider other uses besides treatments, like inclusive games with users with disabilities as target audiences.

2.3.2 Accessible VR applications

Numerous accessible applications treat differently each of the five areas mentioned before. There is a majority aimed at promoting accessibility structured in the form of therapeutic simulations[82, 46, 47, 50, 64, 21]. Vailland's[82] created a power wheelchair VR simulator with the purpose of comparing users' performance in both simulated and real-world environments. Miyata[46] created a VR-based wheelchair simulator with visual and motion feedback at a low cost using an optical see-through HMD and an embedded computer. Coben[21] developed a VR simulation controlled by a power wheelchair to evaluate the user perception and discover the importance of feeling, in reality, the motion made in a virtual environment.

Many other applications are not therapeutic simulations, such as the game Arca's Path VR. This game was developed from the start to be an accessible game by implementing head tilting and gaze as inputs. The developers said they try to democratize the way to play VR[24]. Moss is another VR game that shows another relevant case of accessibility by making the main character mute and talking to the player in ASL (American Sign Language), this is a case of inclusive representation.[60]. Our experiment is also a VR-accessible application because we tried to consider all five topics while designing the experience. All needed interactions could be done with gaze or steering the wheelchair, and the controller was fixed in the wheelchair leaving the user's hand free for manipulating it. The user can see himself in the game as a wheelchair user and can see the wheelchair he is seated on during the whole game. Furthermore, we developed our experiments in a way to be played only in a wheelchair.

Chapter 3

Reinventing Redirect Walking for Wheelchair Interfaces

This chapter will present how we developed the novel redirection technique for a user in a wheelchair. We will showcase the formulas and highlight the main differences between this application and other already-known ones.

3.1 Redefining Redirect Movement for Wheelchairs

The primary purpose of this work is to develop a new redirect movement method and explore the nuances in the user's perception of motion while navigating in a wheelchair. This study dives into the unique contrasts between the motions involved in walking versus maneuvering a wheelchair, offering valuable insights into variations in motion perception. This distinction will result in different and new data on redirect walking thresholds. After calculating this new translational gains threshold that the user cannot perceive, developers can use this locomotion method in practical projects in an inclusive way by reusing the method developed and the data gathered in this work.

The culmination of this research embodies a leap forward in the field of virtual reality accessibility. Our exploration and subsequent findings serve as a cornerstone for future endeavors, paving the way for more nuanced, user-centered design principles. The implications extend far beyond the confines of this study, heralding a shift in how we approach inclusive design and technological innovation. By acknowledging and addressing the diverse needs of users, we not only redefine the standards for VR experiences but also set a precedent for an inclusive, adaptive technological landscape where all users can engage seamlessly, irrespective of their physical abilities. This research stands as a testament to the potential of technology to bridge gaps, empower individuals, and reshape the landscape of user experience design.

The experiment has another layer of difficulty in the implementation. Since we are interested in enhancing the sense of embodiment and are creating an inclusive experience, we wanted to show the representation of our target users in-game. To represent the wheelchair accurately, we tracked its position and direction by attaching the controllers to the armrests. We use the midpoint from both controllers to track the distance traveled by the user and apply the redirection. In other words, it is the wheelchair translation that has its position redirected.

Our efforts in this project centered on the technical aspects and striving to guarantee a holistic user experience. We dived into the psychological and emotional dimensions of navigation in virtual spaces, aiming to provide functional, immersive, and empathetic interactions. By considering the distinct challenges and experiences of wheelchair users, we intended to refine the mechanics of virtual movements and create an environment that fosters empowerment, comfort, and a sense of seamless integration for all users in virtual environments. This human-centric approach drove our methodology, ensuring that a deep understanding and respect for the diverse user base complemented the innovation in locomotion.

3.2 Implementation Details

$$GPos = g_t * d - d \tag{3.1}$$

Our project also aimed to create a redirection for commercial purpose, so we chose not to use external hardware to track the user's position. We developed our redirect movement algorithm to track and change the user's position using only an all-in-one HMD. Since we needed the user's position in every frame to check the distance traveled, we could not change it during the game, so we changed the guardian's position. The guardian is the playable area set on the Oculus Quest, and Unity translates it as a Game Object with collision boundaries. Since the user's position is attached to the guardian, we can update the distance traveled by the user in every frame by relocating the guardian. Equation 3.1 explains how we calculated the guardian's position $GPos$ in every frame based on the user's distance d traveled and the redirect translation gain g_t. Fig 3.1 visually explains how we translated the guardian on every frame.

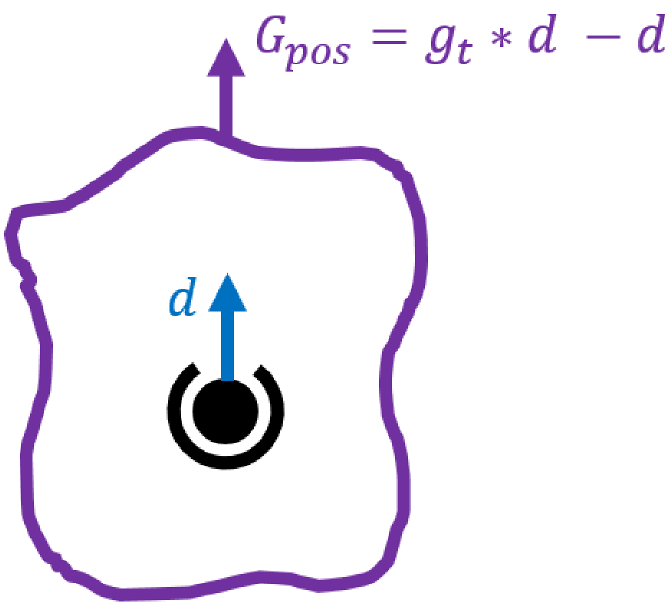

Figure 3.1: The purple area represents the guardian and shows how much is translated based on the user's physical movement.

All those GameObjects mentioned before are arranged in the Unity Inspector, as shown in Fig 3.2, to implement the Redirect Walking for wheelchairs. Now, we will explain how we use each one in the project.

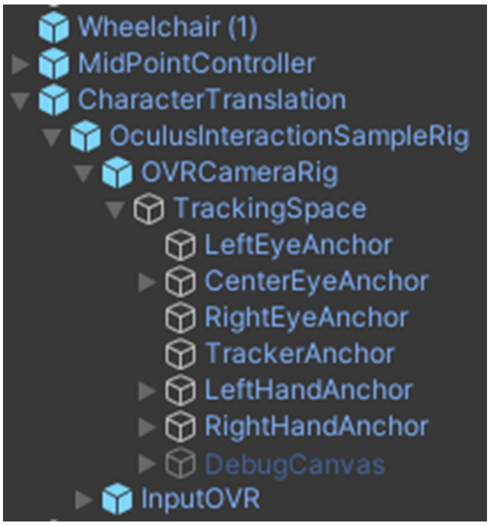

Figure 3.2: How the Unity's components were arranged.

- **Wheelchair (1):** The wheelchair GameObject represents the actual wheelchair and is used to enhance the embodiment. The MidPointController sets its rotation as is seen in the code Character Center Controller shown in Appendix B, and the CenterEyeAnchor sets its position by coping it's position.

- **MidPointController:** The GameObject keeps track of the midpoint between both controllers in the wheelchair's armrest and calculates the wheelchair's rotation by calculating the direction in which the wheelchair is facing from the cross product between the distance vector between two controllers with the up vector. Fig 3.3 and Appendix B and C show all those calculations and how we implemented them.
- **CharacterTranslation:** The GameObject that holds the redirect translation scripts, shown in Appendix A, and has as children the Oculus Quest's prefabs, the guardian (Tracking Space), the user's headset (Eye Anchors), and the user's controllers (Hand Anchors).
- **OVRCameraRig:** Functions as a controller overseeing stereo rendering and head tracking. It manages three anchor transforms linked to the positions of the left and right eyes, along with a virtual center eye positioned midway between them.
- **CenterEyeAchor:** All gaze interactions happen in this GameObject, and we track its position to get the user's movement in the real environment to calculate the redirected walking.

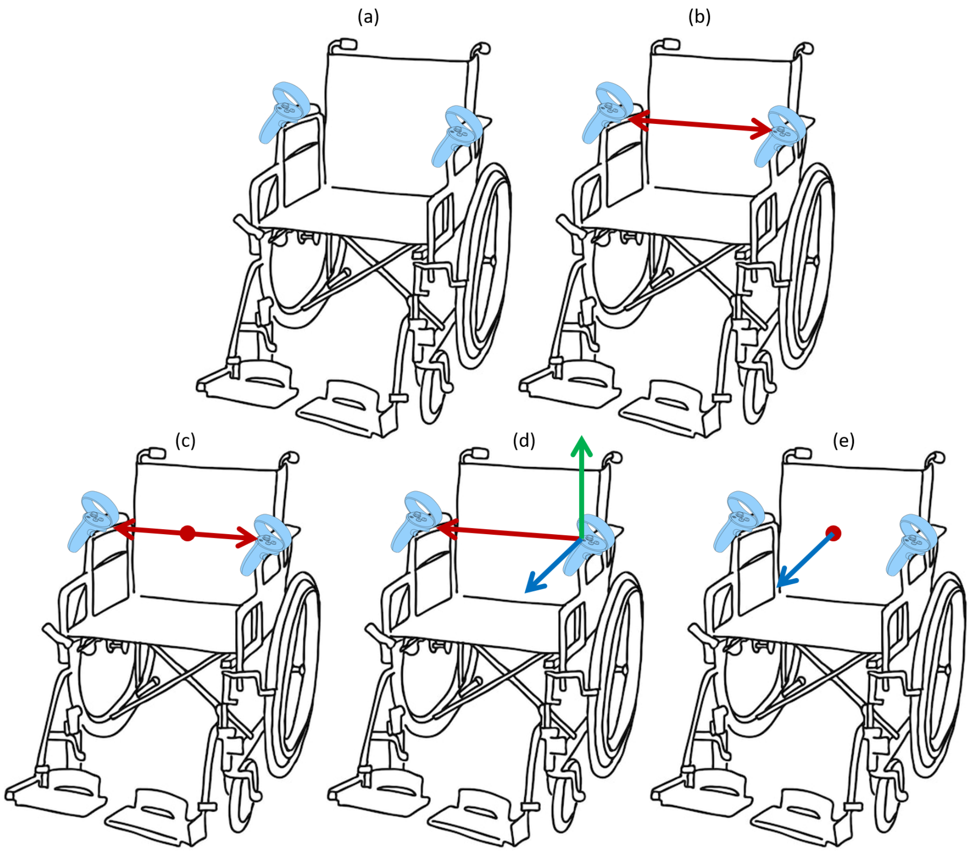

Figure 3.3: Diagram of how the program calculates the real wheelchair position and rotation from the VR controllers. (a) Shows the position where the controller was attached to the wheelchair. (b) First, the system calculates the distance between the controllers based on their positions; the red arrows are the distance vector. (c) Then, we calculate the midpoint from the distance vector. (d) By doing a cross-product with the distance vector and with an up vector, we can get the direction in which the wheelchair is facing. (e) With the mid position and the vector that the wheelchair is facing, we can put the virtual wheelchair in the same place, facing the same direction.

Chapter 4

Experiment and Results

This chapter will present a discussion on research involving motion perception experiments. The chapter will progress through several key stages. First, there will be an explanation of how the tests in this work function, and then the development process will be described, along with the display of images of the virtual environment. The research that serves as the foundation for this study will also be introduced, including the justifications for their selection. The tests conducted in this research encompass various components, such as obtaining informed consent through an Informed Consent Form (ICF), administering questionnaires and profiling participants, giving instructions, and capturing data automatically. This automatic data capture includes recording the time to complete specific objectives and measuring the distance covered in real and virtual environments. Additionally, objective and subjective data will be collected, including responses to the Simulator Sickness Questionnaire (SSQ). This chapter will also discuss the expected results, which involve comparing and analyzing the limitations of redirection in this research compared to previous studies. Furthermore, the chapter will look into a comparison of redirection limits between wheelchair users and non-wheelchair users and demonstrate the potential for developing an inclusive application based on the data acquired in this research.

4.1 Experiment

4.1.1 Design

In order to find the redirect coefficients, we created different virtual spaces with varying wheelchairs in the pilot tests. The pilot tests were made with groups of 3 people to

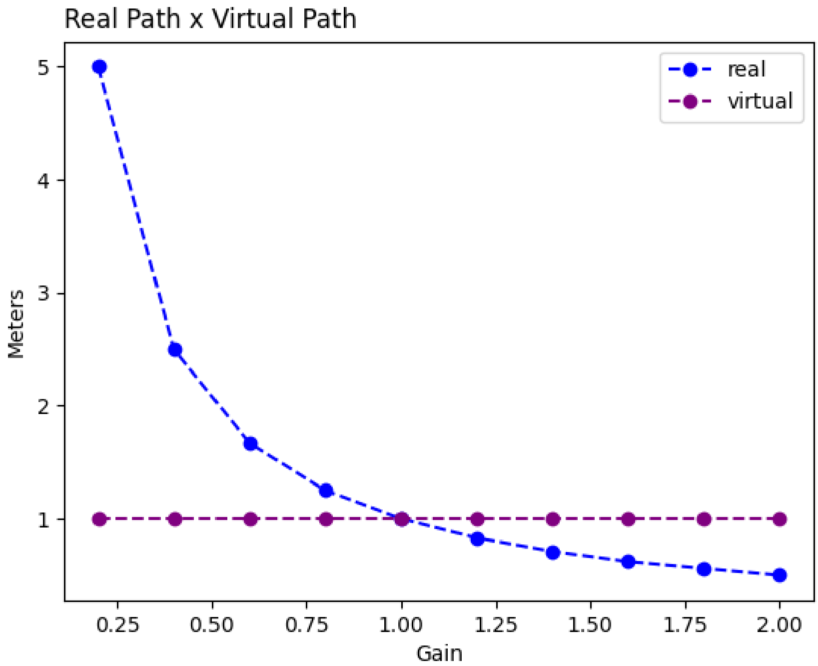

Figure 4.1: Graph showing the difference in the virtual and real path length per gain.

validate how the test would work. The objective of the experiment was to collect data to develop a usable application. Since we want to test bigger and smaller gains than usually seen in other papers, Fig.4.1 shows that at least 5 meters are needed for the user to move in the real environment to test gains values until 2. So, the experiments were executed at places with at least a 5m x 2m area, as shown in Fig.4.2. Therefore, we could have enough space for the user to move without seeing the Oculus Guardian or colliding with any object or wall, we defined this measure with those pilot tests and acknowledged the area needed.

We used the game engine Unity to develop the virtual environment, shown in Fig.4.3, using the Oculus SDK toolkit for an Oculus Quest based application. To create an experience that could match a usable application, we developed a virtual environment resembling a video game. We also implemented the user's surroundings with several visual references to make it easier for the user to perceive his movement, as well as the audio ambiance and a wheelchair to create greater immersion. With all these implementations, we can increase the sense of agency and the sense of embodiment that makes the user more susceptible to detecting his redirection[57, 32].

We based the test on Steinicke's experiment[76]. The test starts with the user looking at his goal, which, in the case of our implementation, is a star. The user must move towards the goal and return to the initial position, with another star marking its new

Figure 4.2: Physical environment set up for performing the user test.

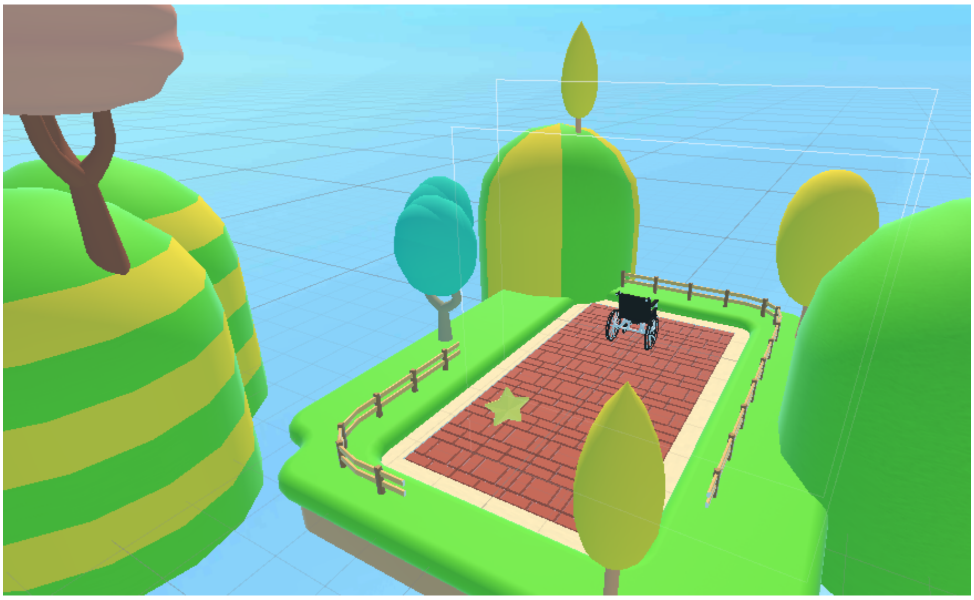

Figure 4.3: The virtual environment of the experiment

position. Users are asked about their perception whenever they return to their initial position. He had to repeat this action ten times, and we applied a different gain to the user's movement each time. The applied gains were between 0.2 and 2 in steps of 0.2. Fig.4.1 shows all those gains and how many meters the users move in the virtual and the actual space. All participants experienced the same ten different gains in random order. The question we chose to value the user's perception was, "Is the path you moved in the game larger or smaller than in the real world?", as shown in Fig. 4.4. If the user says it filled the same, he was encouraged to answer one option. We developed the question based on Steinicke's question [76], and the main difference is changing the "virtual" to "in-game" because the users in the pilot tests had difficulty understanding it. Therefore, it is easier to understand if a question is according to the user's sensation.

To make the experience accessible for wheelchair users, we used Mott's[49] concepts in developing a VR-accessible application.

- **Accessibility of interaction techniques**: Users can interact using only their movements and gaze without needing a controller.
- **Inclusive User Representation within the VR environment**: The user is represented in the game by their wheelchair, which has its position and rotation updated with the actual wheelchair.
- **Accessibility-focused application areas for VR**: The application is designed exclusively for users on wheelchairs.

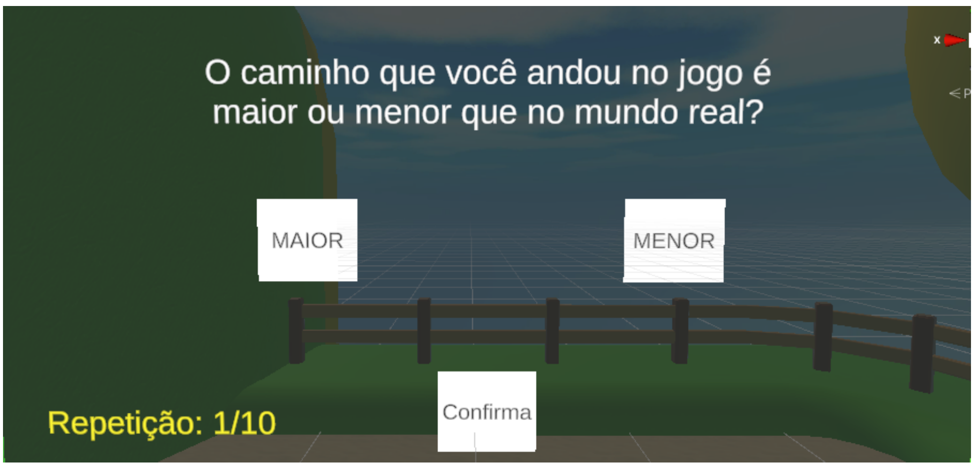

Figure 4.4: In game question

4.1.2 Setup

The user wore the Oculus Quest 2 during the experiment but did not use the controls. Since it is an inclusive experience for wheelchair users, their hands must be accessible the whole time. The controls were attached to the wheelchair's armrest so we could track its position and direction during the experiment, as shown in Fig.4.5. Whenever the user needed to interact with the environment, he would use his movement or gaze.

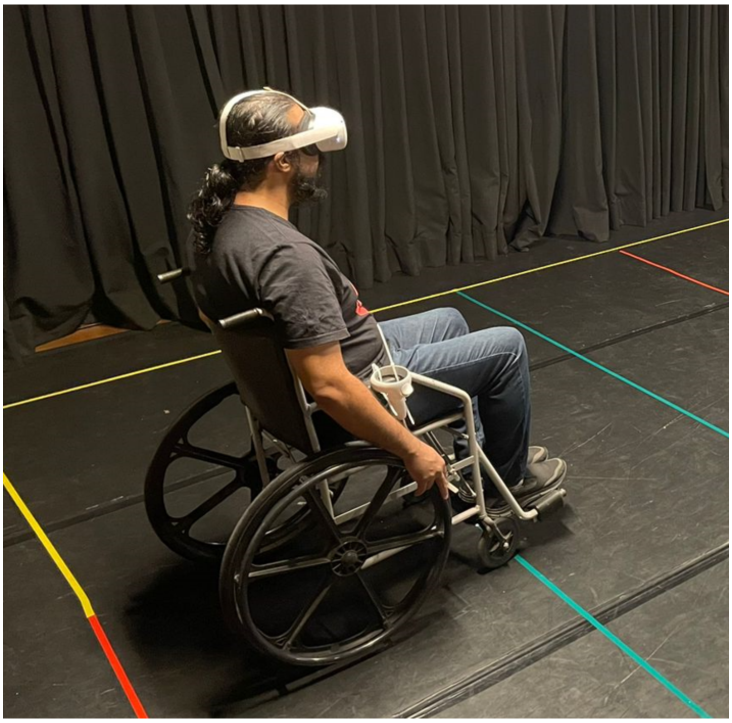

Figure 4.5: Participant during the test

4.1.3 Participants and Procedure

We recruited twenty-one people, thirteen males and eight females, from ages 15 to 57, to participate in the experiment. Ten had some visual impairment, only three did not have video game experience, and only nine had experienced virtual reality before. Three subjects did not give usable data during the experience since their answers showed they misunderstood the task. Table 4.1 shows the data gathered from the profile form. During the experiment, we also collected the answers from each participant for each gain. Table 4.2 shows an example of the answers from one subject.

In favor of creating cohesive tests and coherent results, we created a guide to follow on every test:

Table 4.1: Data gathered from the users with the profile form.

Collected Profile Data		
Age	from 15 to 57 years old	
Gender	13 males	8 females
Visual Impairment	10 yes	11 no
Experience With Games	18 yes	3 no
Experience With VR	9 yes	12 no

Table 4.2: Sample of data gathered from one user during the experiment.

Collected Answer From One User	
Translation Gain	Answer
1.8	Larger
0.8	Larger
2	Larger
1.6	Smaller
1.4	Larger
0.6	Smaller
0.2	Smaller
1	Smaller
0.4	Smaller
1.2	Smaller

1. The test had to begin with the Oculus, and the controllers were charged and already attached to the chair.

2. We asked the subject to fill out three forms:

    (a) A research consent form (a free informed consent form (ICF)), shown in Appendix E in Fig.E.1.

    (b) User's Profile Questionnaire, shown in Appendix D in Fig. D.1, with questions about participants such as age, gender, visual impairment, game experience, and VR experience, as the data is shown in Table 4.1.

    (c) The Virtual Reality Sickness Questionnaire (VRSQ)[36, 80, 23] shown in Appendix F in Fig. F.1.

3. If the user is unfamiliar with using a wheelchair, he could drive it freely through the course to adapt himself to the motion.

4. Whenever the user is ready, we position him on one edge of the area and ask him to wear the Oculus.

5. We explain his objectives when he confirms that he can see the star.

6. During the test, the user could stop in the middle and was oriented to ask if he had any doubts.

7. After finishing the test, the user had to fill out the VRSQ again.

4.2 Results and Discussion

4.2.1 Quantitative Results

The test has a question with only two answers because we use the 2AFC (two-alternative forced choice) task. The result of a 2AFC test is a psychometric function, as shown in Fig 4.6 [53]. This type of function allows us to predict sensory performance from empirical data. The vertical axis corresponds to the probability of receiving a correct response and the function represents the influence of a stimulus in the answers to a question [81]. So, in Fig 4.6, the greater the gain or stimulus, the more likely the subject will answer that he perceives the virtual path as being larger than the physical.

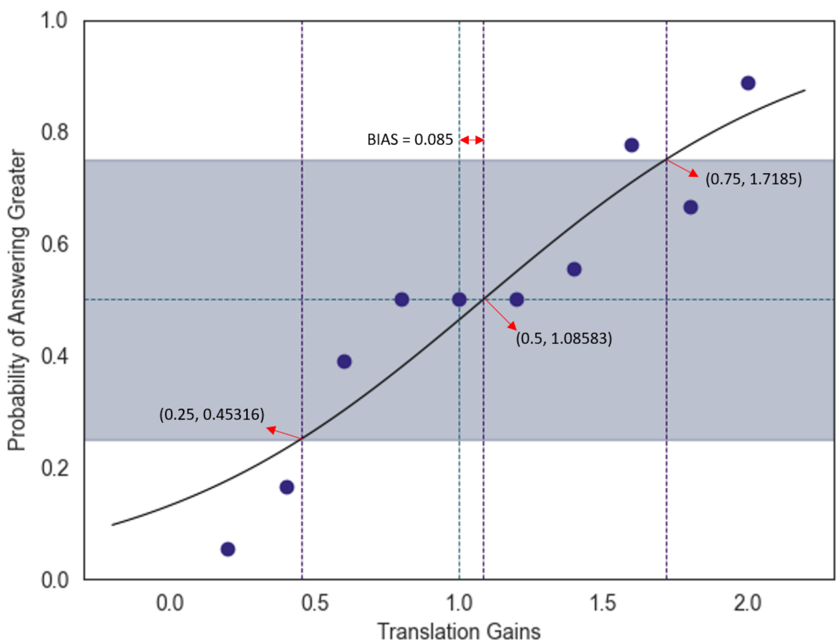

Figure 4.6: Results from the discrimination of real and virtual movements for **all participants**. The x-axis is the translation gains applied during the tests. The y-axis represents the likelihood that users will view the virtual path as longer than the actual path.

One generalized way to represent the psychometric function is the sigmoidal function shown in equation 4.1 with real numbers as a and b [76]. After fitting equation 4.1 in our

Table 4.3: Comparisson between translational gains tresholds from different papers and this paper

Paper	**Upper Translation Gain Thresholds**	**Lower Translation Gain Thresholds**
Kim [33]	1.29	0.85
Kim [33]	1.16	0.92
Steinicke [76]	1.26	0.86
Brument [12]	1.32	0.64
Chen [17]	1.12	0.9
This Paper	1.72	0.45

data, we got a as 1.73647314 and b as 1.88550958, giving us the graph in Fig 4.6.

$$f(x) = \frac{1}{1 + e^{-a*x+b}} \tag{4.1}$$

The BIAS in Fig 4.6 expresses what Steinicke[76] calls a point of subjective equality (PSE). This point in the graph represents the moment the subjects cannot differentiate between the real and the virtual movement. At this point, the probability of answering right is 50%. Therefore, we can interpret it as if the users were guessing. Since our PSE was 1.085, our subjects perceived they walked 0.92m while walking 1m.

We define the detection threshold (DTs) for gains larger than the PSE to be the value of the gain at which the subject has a 75% probability of choosing the "greater" response correctly and the detection the threshold for gains smaller than the PSE is the value of the gain at which the subject chooses the "greater" response in only 25% of trials (since the correct response "smaller" was then chosen in 75% of the trails)[76, 33].

Therefore, based on our findings, we have determined that the threshold for detecting translational movement is 1.7185 for gains greater than 1, while it is 0.45316 for gains less than 1. This indicates that users were unable to accurately distinguish between a physical distance of 1.7m and 0.45m while walking 1m in the virtual world.

Table 4.3 compares the thresholds detected throughout different papers. Our work stands out with a smaller lower threshold and significantly higher upper thresholds than others. Therefore, we can stretch the translational gains when the user moves in a wheelchair. This happens mainly because of two reasons connected with motion perception.

- While in a wheelchair, the user is seated. There is a significant correlation between cybersickness severity and postural stability change during VR exposures [42].

Table 4.4: Discreted redirect walking thesholds per participant‘s group

Redirect Walking Thesholds per Group

	Upper Translation Gain Threshold	Lower Translation Gain Treshold
All Participants	1.72	0.45
Male	1.75	0.52
Female	1.65	0.31
Has VR Experience	1.66	0.57
Has No VR Experience	1.79	0.33

- The user’s acceleration during the motion is significantly different than when walking. Locomotion and acceleration are two variables that may directly influence cybersickness [61].

During our evaluation, we also assessed the thresholds that distinguish users based on their gender and VR experience, as shown in Table 4.4. A wide range of values reported for redirecting walking thresholds has led to several studies investigating this phenomenon, comparing users’ differences. Some papers focused on how environmental size [35, 34, 55], hand dominance, gender [56, 85], level of embodiment [57], and several other characteristics can impact redirect walking thresholds.

We encountered a significant gap between male and female values, respectively shown in Fig 4.8 and in Fig 4.7. While the male participants had a 1.74661 gain threshold for detecting redirect translational movement for gains above 1, they had a 0.52231 threshold for gains lower than 1. Compared with the female participants, with an upper threshold of 1.65410 and a lower threshold of 0.31302. These findings support other research that recognizes the difference in perception by gender [56, 85]. Although men are generally described as more sensitive [56], they were less sensitive to gains greater than one, while women were more sensitive to gains larger than 1.

The graphs shown in Fig 4.9 and Fig 4.10 demonstrate the expected result when comparing the perception gap between participants with VR experience and those without experience. Participants with VR experience had a 1.65915 gain threshold for detecting redirect translational movement for gains above 1 and a 0.57089 gain threshold for gains lower than 1. We expected users with no VR experience to have higher thresholds for gains above 1 and lower thresholds for gains lower than 1 since they are not used to VR environments, and the result was an upper threshold of 1.79793 and a lower threshold of 0.33283.

We used the VRSQ to analyze if the subjects suffered from cybersickness with our

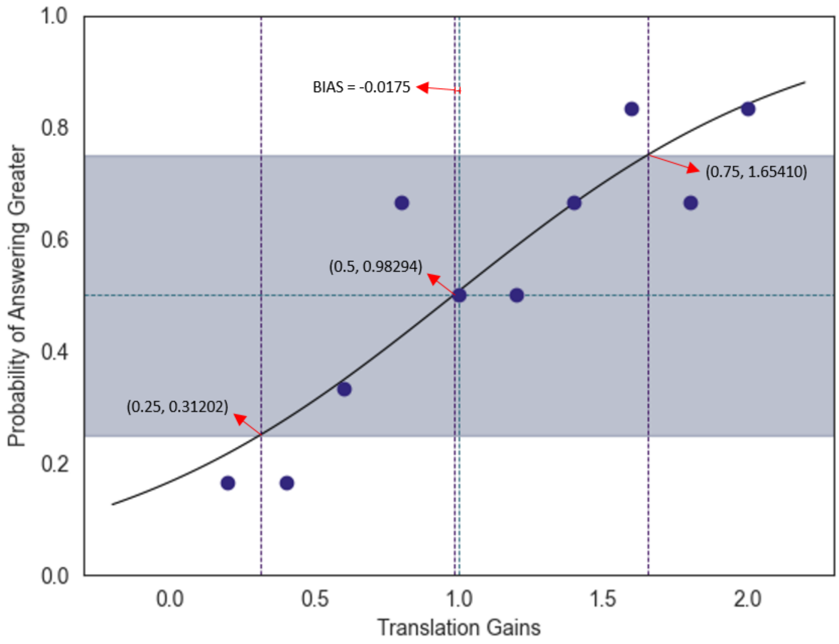

Figure 4.7: Results from the discrimination of real and virtual movements for the **female participants**. The x-axis is the translation gains applied during the tests. The y-axis represents the likelihood that users will view the virtual path as longer than the actual path.

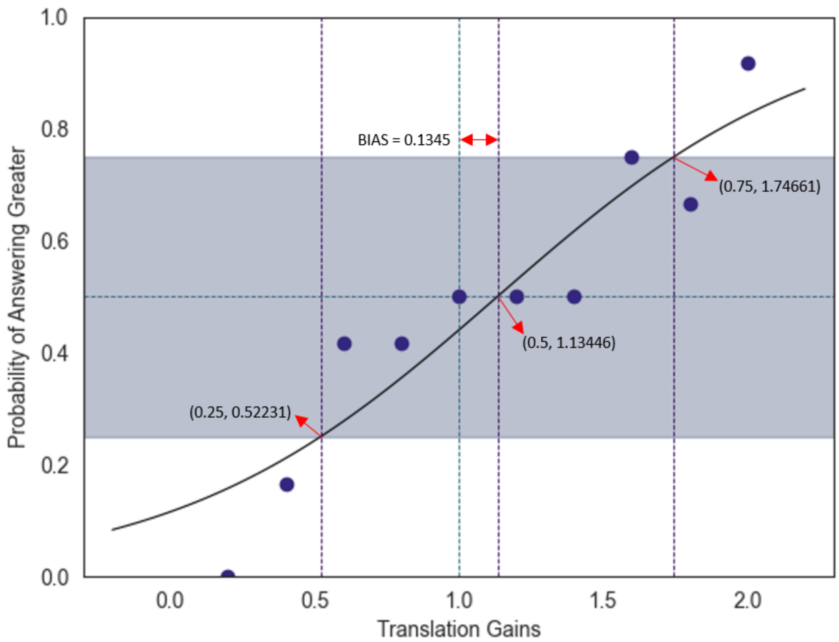

Figure 4.8: Results from the discrimination of real and virtual movements for the **male participants**. The x-axis is the translation gains applied during the tests. The y-axis represents the likelihood that users will view the virtual path as longer than the actual path.

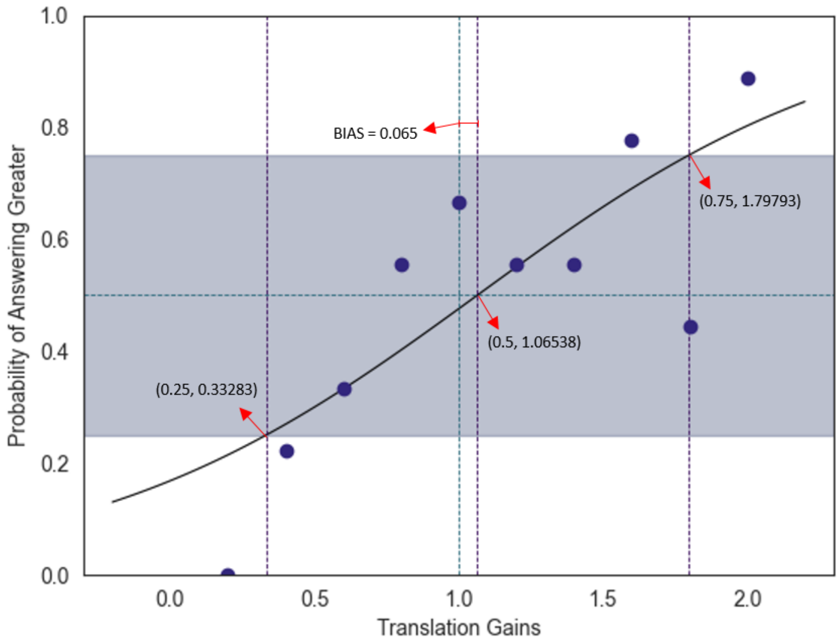

Figure 4.9: Results from the discrimination of real and virtual movements for the **participants with no VR experience**. The x-axis is the translation gains applied during the tests. The y-axis represents the likelihood that users will view the virtual path as longer than the actual path.

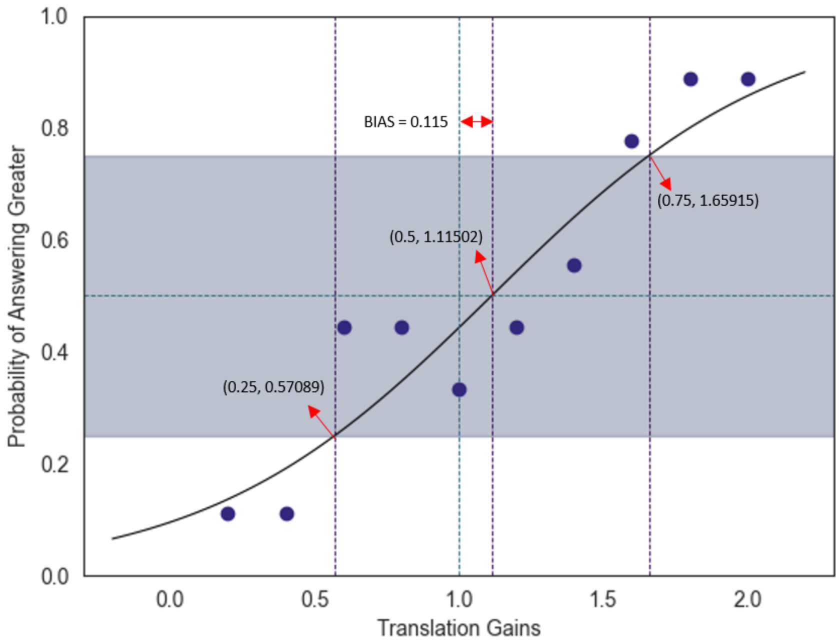

Figure 4.10: Results from the discrimination of real and virtual movements for the **participants with VR experience**. The x-axis is the translation gains applied during the tests. The y-axis represents the likelihood that users will view the virtual path as longer than the actual path.

Table 4.5: Symtoms evaluated in the VRSQ form

VRSQ Symtoms	
Oculomotor Disturbance Symtoms (O)	**Disorientation Symtoms (D)**
General Discomfort	Headache
Fatigue	Fullness of Head
Eyestrain	Blurred Vision
Dificulty Focusing	Dizzy
	Vertigo

application. Table 4.4 shows what data we gathered with the form. From it, we calculate the average final score for oculomotor disturbance, which was 1.14; for disorientation, it was 3.64; and the total final score was 2.39. So, the effects of our application, according to Chardonnet [16], can be categorized as minor cybersickness symptoms since our total score is lower than 5.

4.2.2 Users Perceptions During The Tests

During the experiment, users expressed their perception of what was happening. In extreme gains, they all told in different ways that they were surprised at how fast or how long it took to get to the star. For example, one user said, *"It seems the star is getting farther."*. Several users also thought that sometimes they were not physically moving more or less, but the star in the game was spawning in different positions. Only one user correctly expressed the feeling of being redirected. When the gain was 0.2, he said, *"Why am I being pushed backward?"*.

Other user comments confirmed some design choices. Many users reported feeling like they were inside a video game. One subject even compared the experience to being in a Mario game. Some users expressed how interesting it was to have the same wheelchair in reality and in-game. It was a perception driven by the sense of embodiment.

While designing the test, we ran it with a wheelchair user. Before testing our project, he was worried since he had never played a game in VR where he could move during the experience. He explained his situation: *"All the games I played until today were very limited."*. He proceeded to list the games he played, including several top-selling games. During the test, he seemed most fascinated by the gaze interaction and how he could use his hands during the whole experience just for steering the wheelchair.

Chapter 5

Conclusion

This study explores Redirect Movements within VR environments designed explicitly for genuine wheelchair-based interaction. Our research has revealed compelling insights through experimentation, indicating that users exhibit limited perceptibility to redirection gains ranging from 0.45 to 1.7 in our developed redirection technique. These findings are significant in crafting authentic and immersive experiences tailored for wheelchair users engaging in various activities.

The implications extend beyond mere technological innovation, therapeutic applications, exercise regimens, and the creation of inclusive games. By seamlessly integrating these redirection techniques into VR experiences, a remarkable potential exists to elevate the quality and depth of games while concurrently fostering therapeutic and inclusive virtual environments. This research stands at the forefront of advancing the boundaries of wheelchair-based VR interaction, promising a future where virtual experiences are realistic and transformative for individuals with diverse needs and abilities.[49, 48].

5.1 Limitations

During the development of this project, we recognized points that needed improvements, such as the controller position on the wheelchair. By testing with wheelchair users, we acknowledge that not all wheelchairs have armrests, so we can attach the controllers to the user's leg or create support to place the controllers to get the same result and include different types of wheelchairs.

5.2 Future Work

In our ongoing pursuit of advancing the field of virtual reality and its accessibility, there are several promising avenues we intend to explore in future work.

First and foremost, we aim to broaden the scope of our research by applying the same tests to wheelchair users, allowing us to make a meaningful comparison with individuals who do not rely on wheelchairs for mobility. This comparison will yield valuable insights into the challenges and opportunities that may arise in VR experiences for these two distinct user groups. Additionally, we will examine various redirection techniques, exploring how different methods impact wheelchair users' experiences in virtual environments. This comparative analysis promises to comprehensively understand how VR technology can cater to diverse user needs.

In the ever-evolving virtual reality landscape, one striking trend we have identified is the standardization of VR controllers. While this may bring a sense of uniformity and ease of use, it has decreased experimentation with unique interaction methods in virtual spaces. In future research, we aspire to rekindle the spirit of innovation by exploring alternative approaches to VR interaction. By developing and testing novel ways for users to engage with virtual environments, we aim to push the boundaries of what VR can offer and uncover more immersive and inclusive experiences.

Furthermore, our ongoing work has highlighted the importance of creating a comprehensive taxonomy for accessible VR design. Rather than simply evaluating whether a VR application is accessible, we believe it is essential to categorize accessibility based on the depth and type of implementation. This taxonomy can distinguish between VR experiences where accessibility features can integrate into the core design and those added as supplementary layers to an existing application. Such categorization will provide a clearer perspective on accessibility in VR and guide developers in making informed choices regarding their design strategies. It needs to have a taxonomy that can improve with the evolution of technology since the existing taxonomies are already unfit for newer techniques.

By pursuing these avenues of exploration and fostering innovation in VR accessibility, we aim to contribute to developing a more inclusive and diverse virtual reality landscape. Our research journey continues, driven by the vision of making VR technology an accessible and enriching medium for all.

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APPENDIX A – Code Redirect Translation

Listing A.1: Redirect Translation

```
public class RedirectTranslation : MonoBehaviour
{
    public float gain;
    public GameObject GetMovementFromThis;
    public GameObject MoveThis;
    Vector3 lastHeadPos;
    Vector3 nowHeadPos;

    //Called once in the begginig
    void Start()
    {
        //Get initial position from objects
        lastHeadPos = GetMovementFromThis.transform.position;
        nowHeadPos = GetMovementFromThis.transform.position;
    }

    //Called once per frame
    void Update()
    {
        RedWalkTrans();
    }

    //Redirect Translation
    void RedWalkTrans()
    {
        nowHeadPos = GetMovementFromThis.transform.position;
        Vector3 distance = distanceVectorInXZPlane(lastHeadPos,
            nowHeadPos);
        lastHeadPos = nowHeadPos;
        if (distance.magnitude > 0.00001f)
        {
```

```
            MoveThis.transform.position += distance * gain - distance
                ;
        }
        nowHeadPos = GetMovementFromThis.transform.position;
    }

    //Get the distance between 2 points just in the plane XZ
    Vector3 distanceVectorInXZPlane(Vector3 before, Vector3 now)
    {
        Debug.Log(new Vector3(now.x - before.x, 0, now.z - before.z).
            ToString());
        return new Vector3(now.x - before.x, 0, now.z - before.z);
    }
}
```

APPENDIX B – Code Character Center Controller

Listing B.1: Character Center Controller

```
public class CharacterCenterController : MonoBehaviour
{
    //Called once per frame
    void Update()
    {
        //Get controllers position
        Vector3 handLeftPosition = (OVRInput.
            GetLocalControllerPosition(OVRInput.Controller.LTouch));
        Vector3 handRightPosition = (OVRInput.
            GetLocalControllerPosition(OVRInput.Controller.RTouch));

        //Get mid point from both controllers
        this.transform.position = (handLeftPosition +
            handRightPosition) / 2;

        //Get the direction the chair is facing
        Vector3 distance = handLeftPosition - handRightPosition;
        Vector3 frontDirection = Vector3.Cross(distance, Vector3.up);

        //Turn the virtual chair
        this.transform.rotation = Quaternion.Euler(-90, (Mathf.Atan2(
            frontDirection.x, frontDirection.z) * 180 / Mathf.PI) +
            180, 0);
    }
}
```

APPENDIX C – Code Wheelchair Controller

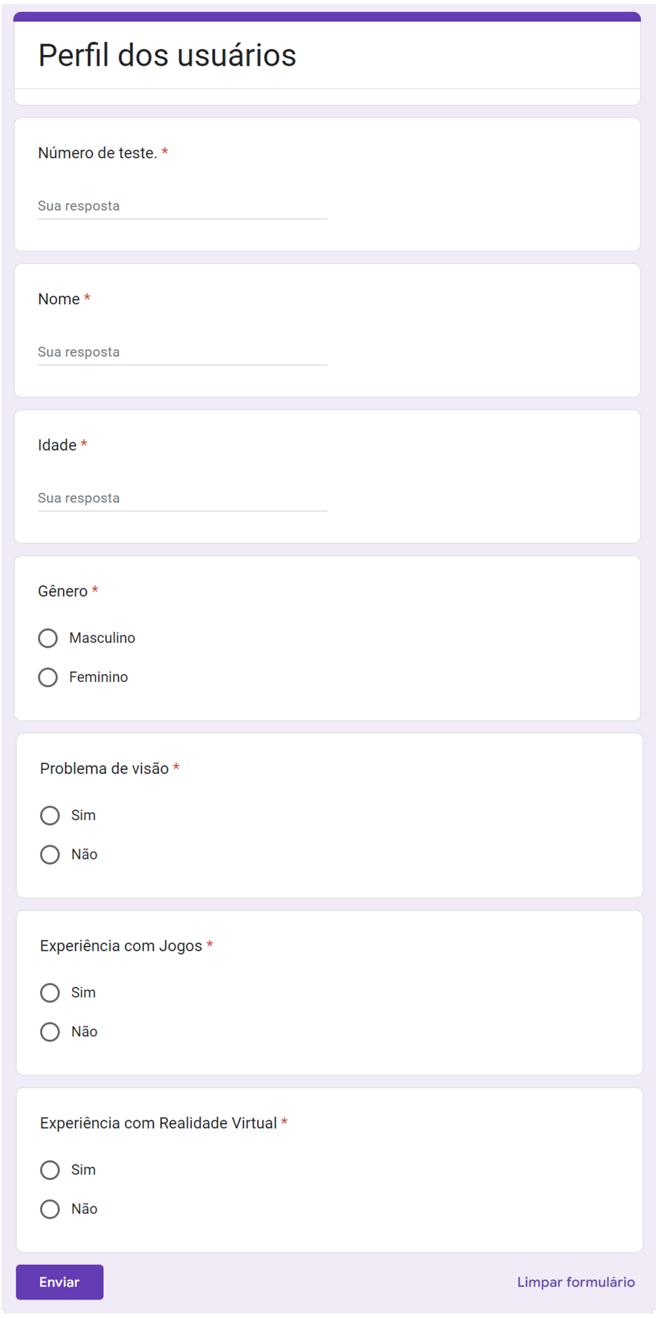
Listing C.1: Character Center Controller

```
public class WheelChairController : MonoBehaviour
{
    public GameObject FollowPosition;
    public GameObject FollowRotation;
    public RedirectRotation redirectRotation;
    public TMP_Text debugText;

    // Update is called once per frame
    void Update()
    {
        if (redirectRotation.angFactor <= 0)
        {
            //If not redirecting the rotation
            this.transform.rotation = Quaternion.Euler(new Vector3(
                this.transform.rotation.eulerAngles.x, FollowRotation.
                transform.rotation.eulerAngles.y, this.transform.
                rotation.eulerAngles.z));
        }
        else
        {
            //If redirecting the rotation
            float angSomap = FollowRotation.transform.rotation.
                eulerAngles.y + redirectRotation.angSoma;
            string s = "antes: "+angSomap.ToString();
            if (angSomap > 360) angSomap = angSomap - 360;
            else if (angSomap < 0) angSomap = 360 + angSomap;
            s += "\ndepois: " + angSomap.ToString();
            debugText.text = s;
            this.transform.rotation = Quaternion.Euler(new Vector3(
                this.transform.rotation.eulerAngles.x, angSomap, this.
                transform.rotation.eulerAngles.z));
```

```
        }
        this.transform.position = new Vector3(FollowPosition.
            transform.position.x, this.transform.position.y,
            FollowPosition.transform.position.z);
    }
```

APPENDIX D – Profile Questionnaire


Perfil dos usuários

Número de teste. *

Sua resposta

Nome *

Sua resposta

Idade *

Sua resposta

Gênero *

Masculino

Feminino

Problema de visão *

Sim

Não

Experiência com Jogos *

Sim

Não

Experiência com Realidade Virtual *

Sim

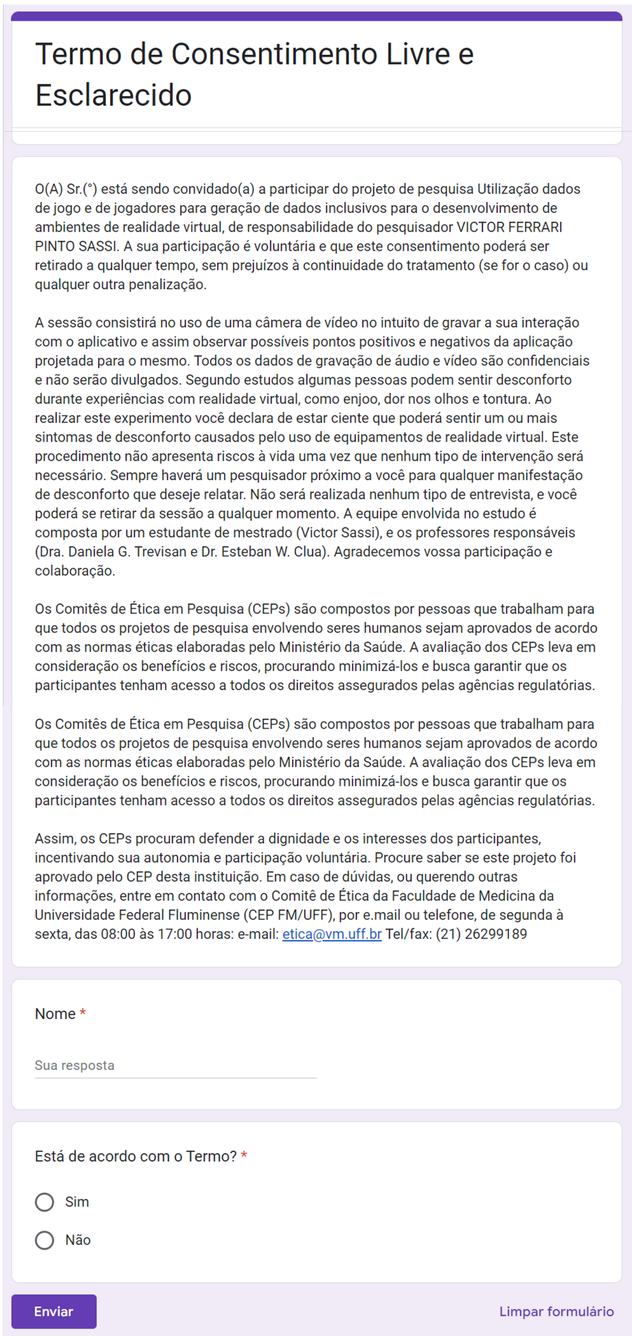
Não

Enviar

Limpar formulário

Figure D.1: Profile Questionnaire

APPENDIX E – Free Informed Consent Form



Termo de Consentimento Livre e Esclarecido

O(A) Sr.(°) está sendo convidado(a) a participar do projeto de pesquisa Utilização dados de jogo e de jogadores para geração de dados inclusivos para o desenvolvimento de ambientes de realidade virtual, de responsabilidade do pesquisador VICTOR FERRARI PINTO SASSI. A sua participação é voluntária e que este consentimento poderá ser retirado a qualquer tempo, sem prejuízos à continuidade do tratamento (se for o caso) ou qualquer outra penalização.

A sessão consistirá no uso de uma câmera de vídeo no intuito de gravar a sua interação com o aplicativo e assim observar possíveis pontos positivos e negativos da aplicação projetada para o mesmo. Todos os dados de gravação de áudio e vídeo são confidenciais e não serão divulgados. Segundo estudos algumas pessoas podem sentir desconforto durante experiências com realidade virtual, como enjoo, dor nos olhos e tontura. Ao realizar este experimento você declara de estar ciente que poderá sentir um ou mais sintomas de desconforto causados pelo uso de equipamentos de realidade virtual. Este procedimento não apresenta riscos à vida uma vez que nenhum tipo de intervenção será necessário. Sempre haverá um pesquisador próximo a você para qualquer manifestação de desconforto que deseje relatar. Não será realizada nenhum tipo de entrevista, e você poderá se retirar da sessão a qualquer momento. A equipe envolvida no estudo é composta por um estudante de mestrado (Victor Sassi), e os professores responsáveis (Dra. Daniela G. Trevisan e Dr. Esteban W. Clua). Agradecemos vossa participação e colaboração.

Os Comitês de Ética em Pesquisa (CEPs) são compostos por pessoas que trabalham para que todos os projetos de pesquisa envolvendo seres humanos sejam aprovados de acordo com as normas éticas elaboradas pelo Ministério da Saúde. A avaliação dos CEPs leva em consideração os benefícios e riscos, procurando minimizá-los e busca garantir que os participantes tenham acesso a todos os direitos assegurados pelas agências regulatórias.

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Assim, os CEPs procuram defender a dignidade e os interesses dos participantes, incentivando sua autonomia e participação voluntária. Procure saber se este projeto foi aprovado pelo CEP desta instituição. Em caso de dúvidas, ou querendo outras informações, entre em contato com o Comitê de Ética da Faculdade de Medicina da Universidade Federal Fluminense (CEP FM/UFF), por e.mail ou telefone, de segunda à sexta, das 08:00 às 17:00 horas: e-mail: etica@vm.uff.br Tel/fax: (21) 26299189

Nome *

Sua resposta

Está de acordo com o Termo? *

○ Sim

○ Não

Enviar

Limpar formulário

Figure E.1: Research consent form (free informed consent form (ICF))

APPENDIX F – Virtual Reality Sickness Questionnaire

VRSQ (Virtual Reality Sickness Questionnaire)

Indique seu número de teste. *

Sua resposta

Seu preenchimento está sendo realizado antes ou depois da experiência? *

- Antes
- Depois

Indique o resultado da sua experiência para cada um dos fatores abaixo. *

	Nenhum	Leve	Moderado	Severo
Desconforto geral	○	○	○	○
Fadiga (cansaço)	○	○	○	○
Fadiga (ocular)	○	○	○	○
Dificuldade de concentração	○	○	○	○
Dor de cabeça	○	○	○	○
Cabeça pesada	○	○	○	○
Visão embaçada	○	○	○	○
Tontura	○	○	○	○
Vertigem	○	○	○	○

Enviar

Limpar formulário

Figure F.1: Virtual Reality Sickness Questionnaire (VRSQ)