GaitWear: Haptic Cues for In-the-Wild Gait Normalization of Users with Parkinson's Disease

Ana Filipa Lourenço de Oliveira

Thesis to obtain the Master of Science Degree in

Information Systems and Computer Engineering

Supervisor: Prof. Augusto Emanuel Abreu Esteves

Examination Committee

Chairperson: Prof. João António Madeiras Pereira
Supervisor: Prof. Augusto Emanuel Abreu Esteves
Member of the Committee: Prof. Hugo Miguel Aleixo Albuquerque Nicolau

January 2021

Acknowledgments

Primeiramente, gostaria de agradecer ao professor Augusto Esteves, por todo o apoio, orientação, confiança e paciência ao longo deste ano de trabalho. Obrigado por todos os constantes desafios e por cada vez que eu me sentia perdida, me ajudar a reencontrar um caminho. Foi sem dúvida uma figura preponderante em todo este trabalho que de seguida se apresenta. Gostaria também de agradecer ao Dr. Mohamed Khamis por toda a ajuda e feedback dado ao longo deste trabalho.

Seguidamente, gostaria de agradecer aos meus pais, porque sem eles nada disto seria possível. Obrigada por todo o amor, dedicação e pela oportunidade de completar mais este capítulo da minha vida, convosco sempre do meu lado.

À minha irmã Inês, que mesmo sem querer e saber foi das pessoas mais importantes em todo este processo. Obrigado por quereres ser como eu, fazendo com que eu queira ser constantemente uma pessoa melhor.

Aos meus avós Júlio e Idalina, por serem os melhores avós do mundo, e das pessoas que eu mais admiro neste mundo. Obrigado!

À minha Tia Elsa, Carolina e Julinho, por todo o carinho, apoio e força que me deram desde sempre.

Ao meu melhor amigo João, pelo constante apoio, disponibilidade e amizade, não só durante a realização deste trabalho, mas em quase todos os momentos da minha vida. Um muito obrigado! Tudo isto teria sido muito mais difícil sem ti.

Finalmente, gostaria de agradecer a todos os outros que de uma forma ou de outra tiveram impacto em mim durante a minha vida académica, principalmente, ao Paulo, Mariana, Regouga e Francisco, não só por todos os dias infindáveis no Lab 2 a trabalhar, mas também por todos os outros incontáveis momentos de brincadeira e de companheirismo.

Tudo isto soa a pouco e não faz juz ao quanto eu vos agradeço. E por isso este trabalho também é vosso.

Abstract

Parkinson's patient's gait is one of the most affected motor characteristics of this disorder. The reduced efficiency regarding gait normalization of traditional therapies has introduced the concept of cueing. Many studies have been performed in order to assess the impact of these cues on patients' gait's parameters, and although the results are quite significant, we had found three major limitations: the assessment of cues usage only inside a controlled environment; the limited usage of information especially on Haptic cues; and the lack of investigations of its effects behind gait. To clarify these aspects, we had conducted a Virtual Reality (VR) field study in order to safely assess the impact of visual and Haptic cues (with both temporal and spatial information) outside a laboratory, in participants' gait performance, usability, perceived cognitive load, and safety (i.e. awareness of their surroundings).

Due to Covid-19 pandemic and the major restrictions that were imposed, our study was performed by healthy participants (N=8). And although not suffering from any gait impairment, the results showed a positive effect of using haptic cues in regards to participants cadence, step length, and general awareness of their surroundings when compared to the visual cue. Other interesting outcome was the lack of significant difference between the usage of only temporal and temporal + spatial information in haptic cues. Besides this, in terms of usability and workload, haptic cues, were appointed to be participants' favourites and least demand, in contrast to visual cues.

Taking into account the results of this study, in addiction to the fact that many studies had observed long-term effects when using cues, we proposed an wearable app, that allowed participants' to display the best fit stimulus (Haptic 1P1W), whenever they felt the need to have it on.

Keywords

Parkinson's disease; Gait; Visual cues; Haptic cues; Virtual Field Study; Performance; Usability; Attention; Eye-tracking;

Resumo

A locomoção é um dos fatores mais afetados pela doença de Parkinson. A reduzida eficiência, das terapias tradicionais em relação à normalização deste factor, levou à introdução do conceito de pistas na forma de estímulos. Embora muitos estudos, com o objectivo de avaliar o impacto destes na locomoção dos pacientes, tenham obtido resultados significativos e importantes, três grandes limitações foram identificadas: a avaliação destas ajudas somente em ambientes controlados; a utilização de informação extremamente limitada, especialmente nas pistas hapticas; e a falta de investigação dos seus efeitos para além da locomoção. Para clarificar estes aspetos, foi realizado um Estudo de campo virtual de maneira a avaliar o impacto dos estímulos visuais e hapticos (com informação temporal e espacial), fora de um laboratório, na locomoção, usabilidade, exigência congnitiva e segurança de pacientes com Parkinson.

Devido ao Covid-19 e às restrições impostas, o nosso estudo foi realizado por participantes saudáveis (N=8). Embora estes não sofressem de nenhuma doença de locomoção, os resultados mostraram um efeito positivo aquando a utilização das pistas hapticas, em termos de cadência, largura da passada e consciência do ambiente envolvente, quando comparado com os mesmos resultados obtidos durante a utilização das pistas visuais. Outra observação interessante, foi a falta de uma diferença significativa entre o uso de apenas informações temporais e temporais + espaciais durante a utilização dos estímulos hapticos. Além disto, em termos de usabilidade e carga de trabalho, os estímulos hápticos foram apontados como sendo os favoritos dos participantes e os menos exigentes em termos cognitivos, contrastando com o estímulo visual. Tendo em conta os resultados deste estudo e o fato de que muitos dos estudos anteriormente realizados neste domínio observaram a presença de efeitos a longo prazo, aquando a utilização de determinados estímulos, foi proposto uma aplicação para smartwatch. Esta aplicação permite que os participantes utilizem o estímulo mais indicado (Haptic 1P1W), apenas quando sentirem necessidade de o fazer.

Palavras Chave

Doença de Parkinson; Locomoção; Pistas visuais; Pistas Hapticas; Estudo de Campo Virtual; Desempenho; Usabilidade; Atenção; Eye-tracking;

Contents

List of Figures

List of Tables

Acronyms

VR	Virtual Reality
WHO	World Health Organization
SUS	System Usability Scale
Nasa-TLX	Nasa Task Load Index
IPQ	Igroup Presence Questionnaire
ITQ	Immersive Tendencies Questionnaire
VE	Virtual Environment
OSC	Open Sound Control
HMD	Head-mounted display
CSV	Comma-Separated Values
HDR	High Dynamic Range
LDR	Low Dynamic Range
ANOVA	Analysis of Variance
SPSS	Statistical Package for the Social Sciences

1

Introduction

Contents

Gait disorders, which greatly contribute to a decrease in quality of life and increased mortality, are common and often devastating companions of the ageing process [7]. These disorders increase from around 10% between the ages of 60 and 69 years, to more than 60% in those over 80 years of age [8]. Age is not the only source of these impairments, as strokes, Parkinson's disease, myelopathy, or sensory ataxia are some of the most known and studied neurological conditions with repercussions in patients' gait [9].

Our work was primary motivated by Parkinson's disease, the second most common neurodegenerative disorder that affects over 10 million people all over the world [10]. As the disease progresses many are the effects in patients' ability to walk: their gait pattern becomes usually characterized by a shortened gait stride, their walking speed is reduced, their gait variance is increased, and they can be affected by what is known as festinating gait [11]. As there is no cure or treatment that completely addresses the effect of Parkinson's disease on gait, these symptoms can be minimized with lifestyle changes and physiotherapy. Another approach is what is known as *cueing*.

Cueing consists of sensory spatial and temporal stimulus that have been shown to minimize the effect of Parkinson's disease in users' gait [2, 12–15]. The usage of these stimulus in Parkinson patients has been investigated for quite some time, proving to be beneficial when the movement (gait) is concerned [2, 13, 16]. This concept has been applied to patients in vary different forms. In this work we will focus on the **Visual**, **Auditory** and **Haptic cueing** solutions for improving Parkinson's patients gait.

Firstly, regarding the **Visual Cues**, it has been quite explored the usage of lines and staircases, on the floor as a form of stimulus. These, were not only displayed as physical cues [2, 13, 17] (tape or paper on the floor), but it has also been used virtual reality [3] and augmented reality [4, 18] to provide the stimulus to the patient. The usage of these has proved to be effective in improving patients' gait parameters, in particularly **spatial parameters** (step and stride length) [2, 3, 5, 13, 17], not only during the usage of the cues but also after their removal (long-term effects).

Secondly, the usage of **Auditory Cues** is also quite common when assessing Parkinson's patients' gait. The fact that Rhythm and music when used as an auditory stimulus leads to a synchronization between the muscles and the sound pattern [19], is one factor that make these cues promising in this field. In fact, it is almost unanimous the effects of these stimulus in patients' gait parameters, especially in the **temporal metrics** (velocity and cadence) [13, 19–21]. Besides this, long-term effects were also observed [14, 15, 22].

Although these improvements while using visual and auditory cues are quite important, little research has been conducted regarding patients' **usability** and **workload** demands' factors when using these cues, specially outside a controlled environment (i.e. research laboratory), where patients are constantly submitted to external stimulus and need to engage in simple tasks such as walking through a crosswalk – a task that requires undivided attention and concentration [23]. Therefore, although improving gait, the usage of lines on the floor (forcing the patient to look down), or a constant sound on patients' ear, in addiction to other important events happening around the patient, may be too distractive for the patient to handle. These distractions and division of **attention** have been proven to be even more problematic and difficult for Parkinson's patients [24–26].

Thirdly, **Haptic Cues** are usually connected with vibration, pressure and shear sensation. Its applications in medicine [27], technology [28] and games [29] are undoubtedly positive. Similarly, this stimulus is quite promising in terms of its applications on Parkinson's patients' gait, mainly because it is easier to adapt to patients' life, being not as limited and conditioned to the laboratory environment as the visual and auditory cues. Some studies had investigated the usage of these in some of the gait's parameters, and besides the fact that there is a lack of agreement on its effects on each of that parameters, the type of information provided by the stimulus had been quite limited to the temporal one. Although this had produced some improvements in some cases, Gómez-jordana et al [3] study should also be considered. This study had used the two types of information together, in a virtual environment, observing an improvement in every gait's parameters (stride length, cadence, velocity and stride variability). Although, this study only considered Visual stimulation, there is no evidence that it had been studied the usage of these two types of information through Haptic stimulus.

Finally, additionally to all of these factors, there is still other issue that is important to discuss. The fact that all the described stimuli, in order to improve gait, are only considered to be "always on", may be too much and not needed for the patients. For instance, having a metronome beat constantly in the patients' ear is probably unbearable to deal during daily basis routine, in addition to, it has already been proven that, these type of stimuli produce **carryover** effects, being not always necessary. Therefore, finding the stimulus that most fit each patient needs without disturbance and having the patient choose when to have it on, may also beneficial.

1.1 Objectives

The aim of this thesis is to improve Parkinson's patients gait. In order to do that we will take into account three different ambitions:

- Firstly, we aim to assess the effect of **visual** and **haptic** cues not only in participants' gait performance, but the usability, perceived cognitive load, and safety of these types of systems. In particularly, we aim to study the usage of three distinct haptic cues against a visual baseline. These haptic cues were designed to not only provide the users' with temporal but also spatial information.

- Secondly, we aim to perform this assessment in the context of **in-the-wild locomotion**, where the user's attention may be split between the navigation task (e.g. checking for cars while crossing the street) and attending to the gait normalization cues.

- Thirdly, we aim to propose a **system** that displays participants' best fit stimulus (taking into account its effects on gait, usability and attention), whenever the participants feel the need to have it on.

1.2 Contributions

The final product of this thesis is the android Wearable app, **Gaitwear**. However, during our work we have also made other important contributions to the scientific community:

- Implementation of two novel **haptic cues** (Haptic 2P1W and Haptic 1P2W) that combine temporal and spatial information into a single cue.
- Implementation of a **virtual field study**, in order to reproduce a in-the-wild environment in a controlled environment.
- Quantitative and qualitative information regarding the effects of each of the studied stimulus in participants' **gait**, **usability** and **attention**.
- Quantitative information regarding participants' attention during a navigation task using **eye-tracking**.
- Submission and presentation of a paper to the **International Workshop on Cross-Reality (XR) Interaction, ACM ISS 2020** with the results of preliminary test sessions [30].
- Submission of an article to the XR Special Issue 2021 : Behaviour Information Technology Journal - XR In the Era of COVID-19 Pandemic. The results from this submission are still unknown.

1.3 Document Structure

This paper is divided into several sections and subsections for a better understanding of the work developed. In the next Chapter (2) we present a collection and reflection of the state of the art, in particularly, the current cueing techniques available to mitigate Parkinson's effects on mobility - Visual cues, Auditory cues and Haptic cues. After this, in Chapter 3 we present the objectives, reasons and the decisions behind the Virtual Reality (VR) field study implementation. In that chapter it is also explained and specified the implementation and the features of each component of the study. Following this, in Chapter 4 we present the methods and procedures that were followed during the performance of the study and the results that outcome from it. Chapter 5 is dedicated to the presentation of GaitWear. Finally, in Chapter 6 draw conclusions upon our work, and reflect about its limitations and future work.

2

Related Work

Contents

In this section we present the results from searching literature around Parkinson's patients' gait normalization, specifically when using cues. This research starts by a brief introduction to gait disorders. After this, we focused on the effects of Parkinson's disease on patients' mobility followed by an understanding on the available traditional and alternatives therapies. Regarding these last ones, this work had focused on three different types of stimuli: Visual, Auditory and Haptic. In order to be easier to analyse each of this stimulus, these three types of cues have been divided into three different sections where it is presented the results of previous studies regarding their immediate and long-term effect on patients' gait and a small elucidation of the mechanisms underlying the improvements.

2.1 Gait Disorders

Walking is normally assumed to be a simple, innate ability that we execute, seemingly effortless, every day. However, this does not match with reality, since walking is an extremely complex task that requires the whole nervous system to be functioning fully corrected. Making this ability quite sensitive to a number of neurological disorders [31].

Besides affecting directly patients' gait, these impairments contribute to a significant decrease in patients' **quality of life**, increased in the risk of falling [7], and increase of **mortality**. In fact, the sixth most common cause of elderly people's death, is accidental injuries, most of them caused by falls [32]. In addiction this, the fact that patients' suffering from these impairments are normally afraid of falling, leads to a reduction of patient's mobility and independence.

One important factor that greatly increases the probability of the appearance of these gait impairments, is **age**. In fact, it is observed an in increasing from around 10% between the ages of 60 and 69 years, to more than 60% in those over 80 years of age [8].

In addiction to this age factor, as explained before, many of these gait impairments' causes are related to neurological disorders. Strokes, **Parkinson's disease**, myelopathy, or sensory ataxia are some of the most known and studied conditions with repercussions in patients' gait [9]. Since those conditions, have different impacts on gait, we had focus particularly in one: Parkinson's' disease.

In the following sections and subsections we will be presenting and focusing on the effects of this disease in patients' gait, and the approaches that had been studied in order to mitigate those.

2.2 Parkinson's disease and its effects on mobility

Parkinson's disease was originally described by James Parkinson in his "Essay on the shaking palsy" from 1817 [33], and is now considered the second most common neurodegenerative disorder, after Alzheimer's disease. Over 10 million people all over the world have been diagnosed with this condition.

In terms of percentage, this disease affects approximately 1% of persons older than 60 years, and up to 4% of those older than 80 years [10]. This diagnose is made clinically, relying on the presence of 2 out of 3 cardinal Parkinson's features. *Bradykinesia*[1], rigidity, and rest tremor are the symptoms considered as cardinal signs of the disease, and in order to perform a diagnose, bradykinesia must be combined with one of the other two (rigidity and tremor) or both. Postural instability is also considered a cardinal feature, however, this symptom only appear generally in late stages of the disease [35].

When it comes to Parkinson's patients' gait, its pattern is normally characterized by a shortened stride length, increased stride variability, reduced walking speed and festinating gait [11]. These gait's factors are mainly influenced by *bradykinesia* and postural instability, although, all the symptoms mentioned before contribute in some way for that gait deterioration.

The cause of Parkinson's disease is still unknown in most of the cases. The degeneration of dopaminergic neurons in the midbrain is the most assigned reason for the disease. Genetic factors have been appointed to be the cause of this degeneration, leading to some cases of Parkinson's disease. Although it may seem to be quite rare, genetic factors are the cause of 5-10% of the cases diagnosed [36]. Besides these genetic factors, rural living, farming, drinking well water, and exposure to pesticides are environmental factors associated with an increased risk of developing Parkinson's disease [37]. Surprisingly on the other hand, cigarette smoking, alcohol and caffeine intake are proven to reduce that risk [38].

These causes are traditionally assessed by therapeutic interventions based on dopamine treatments, and although it has been successful in some aspects and symptoms of the disease, gait, and balance are resistance to it. In concrete, Blin et al [39] performed a study to observe the modification of gait parameters induced by L-Dopa (dopamine treatment). The results show that temporal gait parameters such as stride and swing duration gait variability were resistance to the treatment. The finding of a treatment is complicated by the fact that although Parkinson's patients may share some of the symptoms and lifestyles of Parkinson's disease, no two patients experience Parkinson's in the same way.

Therefore, in the next section it will be presented an effective alternative for traditional therapies in order to improve gait and balance.

2.3 Current techniques to mitigate Parkinson's effects on mobility

Per definition, cueing relays on the provision of sensory stimulus that can be categorized in two major types:

- **Spatial stimulus**, that provides the user with spatial information, used as a guide of where the

---

[1] *Bradykinesia* is defined as a reduction of speed when planning, initiating and executing a movement with a progressive reduction of its amplitude. This symptom affects almost all daily life activities since the type of movements more effected are the repetitive/rhythmic voluntary, such as gait, and the spontaneous ones, such as facial expression and blinking [34]

actions should be done

- **Temporal stimulus**, that provide temporal information used to inform the user about movement timing.

The usage of these stimulus in Parkinson patients has been investigated for quite some time, proving to be beneficial when the movement (gait) is concerned [2, 13, 16, 17, 19, 20].

The comparison and analysis of the effectiveness of these two types of stimuli on Parkinson's patients' gait rely on temporal and spatial distance measures. These have been proven to be a reliable and meaningful analysis of the gait of a neurological patient [40, 41]. Therefore, for temporal measures it is common to consider velocity, cadence, and stride time. Whereas, stride length [2] and step length[3] are considered as spatial distance measures.

2.3.1 Visual Cue

It was in the year of 1942 that Von Wilzenben first described cues as a facilitator in locomotor activities and encouraged Parkinson's patients to use visuals cues [42]. The first study regarding this influence on the gait of Parkinson's patients was carried out by Martin in 1967 [16]. Since that time, many were the studies regarding the effects of visual cueing on gait proving that gait's pattern in Parkinson's patients could be improved by its usage [2, 13, 17]. It was on Martin's work, in which it was investigated the type of visual stimulus that affected Parkinson patients' gait. He concluded that despite the beneficial effects showed while using brightly colored lines, obstacles with two to three inches of height produced the maximum favorable effect. Posterior studies confirmed these results [2, 43, 44].

Snijders et al. [44] assigned reasons in order to explain this effect. The first cause relies on the fact that, the addiction of a third-dimension results in a more powerful activation of the visual cortical areas. Secondly, the fact that the objects have an illusion of height, the patients' feet need to be lifted higher, with more knee flexion. This kind of movement is quite different when compared to the basic walking (where the foot does not need to be lifted higher), leading to a repetitive leg movement. This type of motion has been under research since Parkinson's patients showed significant preservation of this kind of movement, for example when cycling [1] (see Figure 2.1).

Baring that in mind, studies performed by Bagley [2], Meg E. Morris [17] and M. Suteerawattananon et al. [13] aimed to explore the effects of Parkinson's subjects' gait when exposed to visual cues. The visual cues used in these three different studies were quite similar, consisting in triangular tubes made from light cardboard (see Figure 2.2) , strips of cardboard and tape (respectively) placed on the floor along the walkway.

---

[2] Stride length is the distance between two consecutive heel strikes by the same foot.

[3] Step length is defined as the distance between two consecutive heel strikes.

(a) Parkinson's patient demonstrating severe difficulties to walk by himself.

(b) Parkinson's patient capable of riding a bike alone without any difficult.

Figure 2.1: Images from the Snijders' study [1], showing the differences of difficulties for a Parkinson's patient between walking and riding a bike (clear preservation of repetitive leg movement).

The results were unanimous showing that when compared with the baseline (before the visual cues), stride length and step length [2, 13, 17] suffered a considerable improvement. Cadence results were also consistent between the three studies, showing a reduction of the steps per minute [2, 13]. This means that the patient's strides were slower showing a reverse of the typical festinating gait pattern of a Parkinson's disease patient.

Regarding velocity, the results of the studies are not so similar as in the previous gait's parameters. Susan Bagley [2] found no significant difference between the baseline and cue phase, however, Meg E. Morris [17] and M. Suteerawattananon et al. [13] observed an improvement. These different opinions may be due to methodologies differences since Bagley's study [2] placed the cues 150% of the initial step length of each subject, Suteerawattananon et al. had used intervals of 40% of patients' height and, and Morris [17] had distanced them taking into account the step length value of patients' age-, sex- and height- matched control.

Therefore regarding these studies, we may say that they all have used lines on the floor as cues, and although that turn out to be beneficial, it did limited the type of information provided to the patient. It was only possible to display spatial information (distance between lines).

2.3.1.A Long-term Effect and Virtual Reality

This limitation was bypassed by the appearance of **virtual reality as a potential alternative to rehabilitation therapy**, due to the fact that it enables the creation of an environment with tasks favorable to each patient's needs. In addition, it offers the possibility of repetitive practice and feedback about

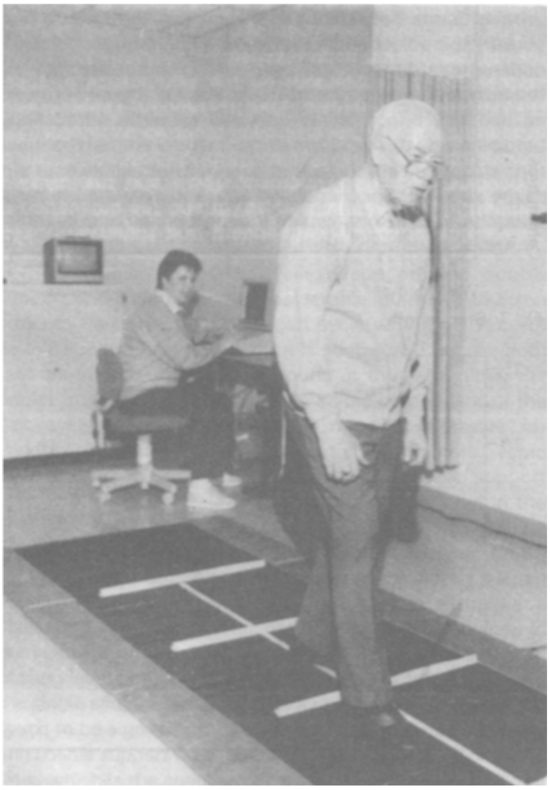


Figure 2.2: Triangular tubes made from light cardboard used as visual cues by Bagley et al [2].

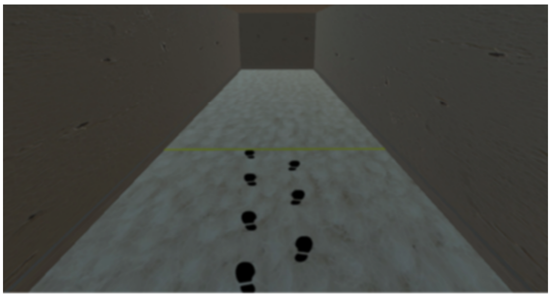


Figure 2.3: Virtual visual cues used by Luís Jordana et al [3].

performance [45].

Therefore, in order to understand the impact of both types of information on gait's parameters, Luis Jordana et al [3] performed a study presenting visual cues in a virtual reality environment via a virtual reality head-set (see figure 2.3). The cues consisted in footprints providing not only spatial cues (space between them) but also temporal cues (the footprints would change color from black to red in order to induce rhythmic). Thus, Jordana's results showed improvements in every gait parameter. In a more specific analysis, spatial cues improved step length and velocity and combining these with temporal cues it is also visible an improvement in step cadence and a notable reduction in gait variability.

All the studies referred before consisted in a single session of training, focusing their attention on the almost immediate effect of visual cues in Parkinson's patients' gait. However, in order to fully understand that effects, it is important to observe the carryover effect of using these cues.

It is in this field, where virtual reality has been mostly applied by providing specific games as training exercises [46–48]. Both commercial VR systems, such as Nintendo Wii [49] and Xbox Kinect [47], and personalized VR devices specifically designed to treat PD symptoms, were used with positive results, especially on balance, fall reduction and gait.

In specific, Ying-Yi Liao et al. [49] observed an improving on muscle strength, and walking abilities in patients with PD through 12 sessions in 6 weeks of VR Wii Fit exercises. The results show that the improvements, after all the sessions, when using VR are comparable to the ones when using traditional physical therapy. Although these results are quite important and interesting, this study has several limitations. The fact that this comparison (between the VR's results and the traditional physical therapy) is done based on the application of different exercises - VR study group had received 15 minutes of treadmill training every session that the other group had not received - makes it difficult to truly compare the results between the two groups. Besides this study constraint, an improvement in the patients' mobility is shown for **at least one month**.

Similarly, the usage of games was addressed by Mendes et al [50] in which they used 10 different *wii fit* games during 14 twice-weekly individual training sessions, in order to observe the learning, retention and transference of motor capabilities just by using different games with different physical and cognitive requirements. The results, besides a normal learning capacity, showed a transference capability of the patients when asked to performed similar tasks that were not on the training protocol. Besides, significant improvement were still observed after **60 days** succeeding the training process, showing carryover effects.

These long-term effects were not only observed when using virtual realities.

Bagleys et al [2] and Meg E. Morris [17], while using lines on the floor (as described before) also observed these effects. In particularly, Bagley et al [2], after following protocol A-B-A (no cue - cue - no cue) also observed that after walking with the cue, patients would still have a greater stride length while walking without help, when compared to the baseline values measured before the cue intervention. Similarly, Meg E. Morris [17], also prove that the training effect of visual cues was transferred to when walking without them, leading to a normalization of gait parameters, stride length, velocity, and cadence during for at least 2 h. In the same logic, Ben Sidaway [51] had observed that 30 days after the completion of the 4 weeks of training, step length and gait speed were still stabilized and improved from baseline (before training).

Although these results are encouraging, both virtual and traditional visual cues are limited and conditioned to a control environment. In other words, it is not easy nor it is safe for the patient to recreate these environments outside a laboratory and without a professional help. In addiction, the time (ranging from 4 to 7 weeks) and the physical effort required to accomplish such long-term improvements are other disadvantage of the usage of these cues in a daily basis.

This constraint to the laboratory environment was solved by the appearance of augmented reality.

2.3.1.B Augmented reality solutions

Augmented reality is defined as *"an interactive experience of a real-world environment where the objects that reside in the real world are enhanced by computer-generated perceptual information, sometimes across multiple sensory modalities"* [52]. Many studies using this technology had been performed in order to assess its influence on Parkinson's patients' gait. And in order for these studies to produce greater results, Janssen et al [4] pointed out some important features:

- Maximization of the involvement between the virtual cues and the real environment;
- Smart glasses light weighted and with a sufficiently wide field of view in order to have some periphery vision;
- Augmented visual cues should start near the body of the user.

Janssen [4] applied these features in order to investigated the effects of 3D augmented visual cues (staircase [53] and 3D bars) delivered by smart glasses in comparison to conventional transverse bars on the floor, on patients' gait parameters. The results show that stride length was significantly more increased during the usage of traditional floor cues rather than the augmented cues. Cadence was higher and gait variability was lower during augmented cues. This lack of significant improvements when using augmented cues can be explained by the User experience. Patients found the glasses **not comfortable**, **not aesthetic** and **with little field of view and stability** (see figure 2.4). These factors may have become a distraction for patients, leading to compromised results. With that in mind, Espay et al [18] after a two weeks of training and familiarization with the augmented device, observed significant improvement in gait velocity and stride length.

Therefore, we may recognize that although the usage of augmented reality is capable of producing improvements on gait's parameters, **usability factors** should be taking into account. It is not only important to understand the effectiveness of a cue condition in patients' gait's parameters, but also to understand what are the implications for them in order to obtain these results.

Other important issue, common to all the studies described in this work, is that visual cues are presented on the floor, forcing the patient to look downwards leading to neck and trunk flexion [5]. This condition is observed while using the "traditional lines on the floor", however, it is even more detected while using augmented realities due to the limited field of view provided by the devices.

These postural modifications were investigated by Wyke [54], who stated that head posture governs body posture and limb control, and that the mechanoreceptors in the cervical spine may influence patterns of walking. Abnormalities in the cervical spine, reduce the efficiency of postural control and contribute to the disorders of posture and gait.

Baring that in mind and assuming that the more straight the posture of the patient was, the more efficient would it be to control balance and equilibrium, Weissenborn performed a single subject study [5]

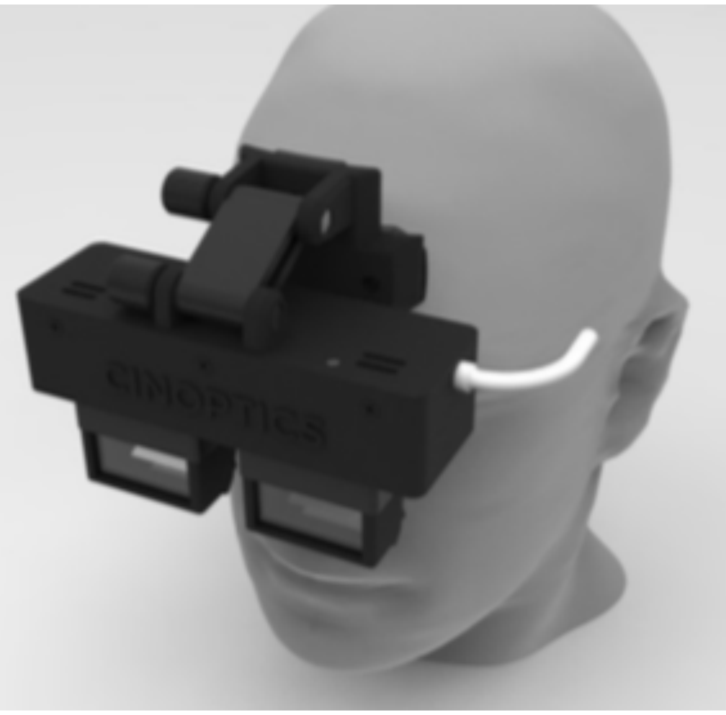
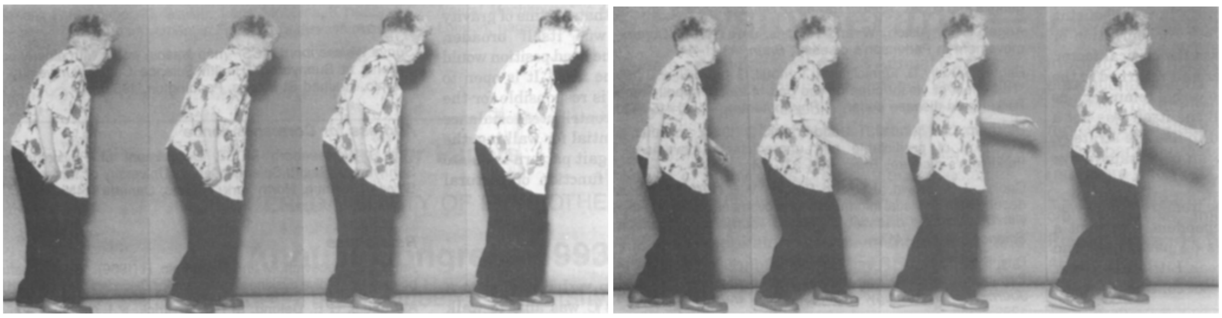


Figure 2.4: Glasses used by Janssen's study [4] described by the patients as not comfortable, not aesthetic and with little field of view and stability.

with the objective to observe the impact on the gait of Parkinson's patients of visual cues to a target above eye level. In order to do that, the subject was instructed to walk while looking on a visual target (a clock and a number over a doorway) above eye level. The results, not only showed an improvement on the gaits parameters (step length and velocity) like the previous studies, but it was also observed a re-integration of arm swing, rhythm, heel strike and a more erect posture (see figure 2.5). Beyond these impressive results in the laboratory environment, Weissenborn [5] affirmed that the patient was able to walk outdoors using street elements like trees and windows as visual targets.

This was quite an important observation, however, the fact that this study was performed by only one subject makes it hard to analyse and generalize the results. In addition to this study's limitation, the maintenance of balance and head up while walking demands a great amount of concentration - patients needed constant verbal reminders to focus on the visual targets - and effort. Therefore, it would be important to understand whether these postural and gait improvements are acceptable taking into account the amount of physical and mental effort for the patient.

Now that it has been shown different approaches and results regarding the usage of visual cues, it is important to understand the pathology reasons that enable gait's modifications in Parkinson's disease patients when using visual stimulus.



(a) Video clips of the patient performance without visual cues.

(b) Video clips of the patient performance with eye level visual target.

Figure 2.5: Video clips from the Weissenborn's study [5], showing a more erect posture, re-integration of arm swing and an increased of step length when using eye level targets as visual cues.

2.3.1.C Mechanism underlying visual cue improvements

The reasons behind the effectiveness of the visual cues on Parkinson's patients' gait are still uncertain [17], however, we found three possible explanations:

1. The fact that when the patient is walking, the stripes provoke a dynamic visual stimulus since the movement of the patient through them gives an illusion of downward movement in the visual field. This explanation is proven by the study performed by Azulay [55] with the objective to evaluate the influence of dynamic and static visual cues in Parkinson patients' gait. It compared gait performance using visual cues with normal lightning and with stroboscopic illumination, this type of illumination was used in order to suppress dynamic visual cues completely [56, 57]. The results showed that gait improvements were conditioned by the perception of motion of the stripes since patients were no longer able to improve gait's parameters by using the stripes when dynamic visual perception was suppressed. This dependence on visual information in order to control motor activity in Parkinson's disease patients is supported by previous studies, not only regarding patients' gait, but also in arm movement [58] and in movement preparation and initiation [59].

2. Azulay's [55] study also correlates the hypothesis that visual floor cues generate an optical flow that activates a cerebellar visual–motor pathway, as opposed to the cortical–motor pathway. The fact that visual stimuli allow the creation of a cerebellar circuit in order to bypass the damaged basal ganglia, makes it possible for patients to avoid their weakly functional basal ganglia [60–62].

3. Other explanation for the efficacy of these cues was proposed by the work of Mitchell Glickstein and John Stein [62] relying on the fact that the emotional stimulation provoked by the visual cues enabled the gathering of the remaining motor capabilities of the patient in order to produce normal movements, momentarily.

	Step Length	velocity	Cadence	Usability
Bagley [2]	+	–	+	
Meg E. Morris [17]	+	+	+	
M. Suteerawattananon [13]	+	+	+	
Luis Jordana [3]	+	+	+	
Janssen [4]	–		–	
Weissenborn [5]	+	+		
Espay [18]	+	+		

Table 2.1: Sum up of the studies used in this section and its impact and outcomes regarding step length, velocity, cadence and usability metrics. Key: **+** means significant improvement; **–** means not significant improvement; and the empty cells represent no information.

Finally, as it can been seen in Table 2.1, it has been proven that important improvements in gait's parameters are observed when visual cues are provided to Parkinson's patients. However, no attention has been paid regarding the demands, work load, usability metrics and attention of the patient while using this cues.

Traditional "on the floor" visual cues, virtual reality cues and augmented reality cues were the ones considered. For each of these, limitations, drawbacks and advantages were found and discussed. It is important to retain that both traditional and virtual reality cues are confined to a controlled environment, only the augmented reality makes it remotely possible and safe for the patient to recreate that condition in a daily basis.

In order to address this confinement to a controlled environment problem, auditory cues are other type that must be considered.

2.3.2 Auditory Cue

"Every disease is a musical problem; every cure is a musical solution" - Novalis

It is known that sound, music, and rhythm have been used throughout history and across cultures to stimulate and organize motor function [19, 63]. Parkinson's patients' gait is one example of that. Rhythm and music used as an auditory cue generates a stimulus on spinal motor neurons, enabling a synchronization between muscle activation and the beats in the sound pattern, which leads to a reduction of the amount of time required for the muscles to respond to a motor command [19]. This was partially observed in Palsev and Elner's work [64], since their results show a reduction of the reaction time on voluntary movements when the subjects were exposed to sounds.

Therefore, different auditory cueing techniques such as musical beats [15, 65], metronomes [13], rhythmic clapping or equivalent have been implemented as strategies for improving patients' gait.

These auditory cues have been associated with the temporal regulation of a movement, being clear its effects in velocity [13, 19–21], cadence [13, 19–21] and in some cases, stride length [19, 21]. And despite an almost unanimous opinion regarding gait velocity, the effects of auditory cues on stride length remain inconsistent. This can be explained by the fact that velocity is dependent on cadence (steps/min), stride length or both. This means that the increase of velocity may be due to an increase of cadence, stride length or both. Suteerawattananon's work [13] that, since stride length did not differ significantly from the no cue condition, when using the auditory cue. However, it was observed an increase of gait cadence leading to a rise of velocity. Another interesting study, regarding the variance of stride length, was performed by Howe et al [20], which studied the effect of increasing and decreasing subject's step frequency produced by a metronome. This frequency varied from 85% to 115%, leading to a decrease and increase of velocity (respectively), and maintenance of stride length. Contrary to these results, a similar study performed by McIntosh [19] in which the auditory cue was set to 10% faster than the patients' baseline cadence had observed an increase in velocity, cadence and stride length. However, this contrasts with Willems et al work [66], where auditory cues were administered at -10% and +10% of patients' baseline cadence, resulting in an increase and decrease (respectively) of patients' step length when comparing to baseline.

Therefore, we may say that there is no consensus regarding the effects of the auditory cues with different beats frequencies (above and below baseline cadence). These difference are explained by Howe [20] and suteerawattananon [13] as subtle methodologies difference regarding verbal instructions, tasks, calculations, and the state of medication.

It is easy to observe from the previous studies that the results differ a lot from each study depending on the type of cue used - metronome/music combined with different frequencies. This happens because cues can influence gait parameters differently, depending on the subject characteristic and on the study's methodology applied. And although music [67], in particularly, music that is familiar to the patient [68] is believed to produce a more significant improvement in gait velocity and stride variability, when compared to the usage of a metronome beat, it is still quite unknown the impact of both regarding the demands of having a **constant sound in a patient's ear**.

This issue was bypassed by a study performed by Pieter Ginis et al [69] that used an **intelligent system** which recognized when deviations from the normal cadence of steps occurred, and it would start the auditory cue. Therefore, the auditory stimuli were only turned on when the patient needed them. The outcomes of this study found a similar stabilizing effect on gait both using the "always on" and the smart system. Ironically, the amount of gait's deviations during the usage of the smart system was significantly reduced.

This study, similarly to the ones described before, paid attention to the almost immediate effect in Parkinson's patients gait of using auditory cues. However, in order to fully understand that effects, it is important to observe the carryover effect of using these cues.

	Step Length	**Velocity**	**Cadence**	**Usability**	**Long-term**
McIntosh [19]	+	+	+		NO
M. Suteerawattananon [13]	–	+	+		NO
Howe [20]	–	+			NO
Freedland [21]	+	+	+		NO
Hausdorff [14]	+	+	+		YES
Thaut [15]	+	+	+		YES
Kadivar [22]					YES

Table 2.2: Sum up of the studies used in this section and its impact and outcomes regarding step length, velocity, cadence, usability metrics and long-terms effects. Key: **+** means significant improvement; **–** means not significant improvement; and the empty cells represent no information

2.3.2.A Long-term effect

Therefore, Hausdorff et al [14], observed that after walking with the auditory stimulus (metronome) set both to 100% and 110% of the patient's comfortable step rate, the improvement of patients' gait parameters was still visible after 2mins and 15mins proving the existence of an immediate carryover effect.

Similarly, Thaut et al [15] and Kadivar et al [22] carried out a study in order to observe the effects on patients' gait's parameters after a period of training, 3 weeks and 6 weeks respectively. They both observed long-term effects, in particularly, Kadivar et al [22] concluded that gait and balance gains improvements over baseline lasted for at least 8 weeks after the training intervention. These results, similarly to the ones found in the Visual Cues section, become evidence that although the damage in motor function is quite evident, motor learning abilities are still maintained in Parkinson's patients [70].

As we can see in Table 2.2, although these studies' results are quite promising, the lack of information and research regarding the effects of these type of training sessions on an usability perspective for the patient are considered an issue.

2.3.2.B Visual vs. Auditory cues

It has already been proven that both visual and auditory stimuli may improve gait in Parkinson's patients. Since these two types of cues influence gait differently - visual cues have a greater impact in stride length whereas auditory cues influence velocity and cadence. It would be natural to speculate that by gathering these two cues, the effects would complement the improvements of each cue when presented individually. By this, we mean that the results of presenting the two cues would improve velocity, cadence and step length significantly. However, this is not the case. A study performed by suteerawattananon [13], concluded that although the cues were quite effective individually, the application of the two cues at the same time decreased the results accomplished when using just the visual cues. This can be explained by the fact that a division of attention between the two cues will increase the attentional demands of the task resulting in a deterioration of their walking performance.

However, once again, their confinement to a controlled (laboratory) environment is considered a disadvantage making it quite difficult for the patient to replicate those conditions in an environment outside the laboratory [71] where noise or lightning may not be the ideal.

In order to resolve some of these spatial constraints, Haptic cues in the form of rhythmic somatosensory stimulus using vibration is an interesting form of stimulus to take into consideration.

2.3.3 Haptic Cue

Haptic sensory also called "sense of touch" refers to the ability to extract object features such as shape, orientation, and texture by moving the hands or other body surfaces around it [72]. This is typically described as being divided into two categories: kinesthetic and tactile. Tactile sensations are going to be the ones focus on this work. This is usually synonymous with vibration feedback but it can also be in the form of pressure and shear sensation [73]. The applications of these stimuli have been present in different areas, such as medicine [27], technology [28] and games [29].

Taking into account the benefits of using haptic stimulus in those areas, vibration stimulus has been applied in rehabilitation techniques on Parkinson's disease patients. It is important to remember that as visual and auditory capabilities, haptic competences are affected by the ageing process [74]. Besides this, Parkinson's disease leads to an additional decrease in haptic sensitivity and acuity (the ability to differentiate between two haptic stimuli) [74]. For that, it would be expected that the lack of sensitivity to touch would be a barrier to the usage of this stimulus in Parkinson's patients. However, studies have provided evidence of the opposite, showing improvements regarding posture [75], balance [76] and gait normalization [77].

Regarding gait normalization, many studies had observed the influence of haptic feedback using footwear [12], belts, gloves [78], or even headbands [79], and although showing an improvement regarding patient's gait in many parameters, the usage of them outside the laboratory is quite limited. One solution for this, consists of wrist vibration stimulus.

Van Wegen et al [77] investigated whether patients could utilize that rhythmic vibrations on the wrist (using a miniature vibrating cylinder) in order to modulate their stride frequency (cadence), increasing stride length. In order to do that, they hypothesized that by using a slower vibration frequency (-10%) when compared to patients' preferred frequency, it would result in larger stride lengths. The results provided evidence of the ability of Parkinson's patients to modify their gait's patterns when exposed to haptic cues on the wrist. However, these modifications were only tested in cadence (frequency of steps), missing an observation of other important metrics such as stride variability and velocity. These additional metrics are important since as said before in auditory cues, it was observed an increase of stride variability, when lower cue frequencies from patients' baseline speed were set as stimuli [66].

Complementary, a study performed by Sejdic [78], show that tactile cues resulted in a decrease of

	Step Length	Velocity	Cadence	Usability	Long-term	Type of information
Van Wegen [77]	+		+		NO	Temporal
Sejdic [78]					NO	Temporal
Novak [12]	+	+	+		NO	Temporal

Table 2.3: Sum up of the studies used in this section and its impact and outcomes regarding step length, velocity, cadence, usability metrics and long-terms effects. Key: **+** means significant improvement; **–** means not significant improvement; and the empty cells represent no information

stride variability value when using the preferable step cadence of the patients, however, this improvement was not statistically significant. This fails to agree with a study performed by Novak et al [12] in which a vibration stimulation on the foot also synchronized with the step frequency of the patient resulted in an increase of walking speed, cadence and stride length and a decreased of stride variability. However, the fact that these two studies used different stimulus (one on the back of the hand other on the foot, respectively), in addition to the usage of different statistical metrics may have led to this disagreement.

Although all the studies presented above agree on the fact that haptic stimuli are one promissory approach to gait regulation, its effects on gait's parameters is still quite unspecified (see table 2.3) . Besides, the type of stimulus provided in these previous work constitute other limitation. In other words, it has only be applied temporal information through haptic stimulus (see table 2.3). Although, these stimuli had produced some improvements, there is no evidence of the usage of spatial and temporal information simultaneously as an haptic cue in Parkinson's patients' gait. The usage of these two types of information, as exposed before, had been used as visual cues in Gómez-jordana et al [3] work. In addition to this, their combination has also been used recently by Google in **Google maps** feature. This application uses haptic feedback in order to provide vibrations to let the user know not only when to turn (temporal information), but which direction to turn in: three vibrations for a left turn, two vibrations for a right turn (spatial information).

2.4 Discussion

This section gives an overview of the existing research literature regarding the influence of cues in Parkinson's patients. It starts by giving a little introduction regarding the disease, its symptoms, causes, cure, and diagnosis. After that, it is presented the definition of cues, and how they influence Parkinson's patients gait. In order to be more easy to understand and to read this section was divided in three subsections: Visual cues, Auditory cues and Haptic cues. In each of these, is briefly described the used cue in each study and a critic of the results obtained by the authors. In addition, it is also presented a neurological explanation in order to understand the effects of these cues in patient's gait.

Firstly, regarding **visual cues** most of the studies have used lines on the floor, made with different materials and placed at different positions and distance from each other. The usage of these cues, limited the type of information provided to the patient, being only possible to present spatial information (the distance between the lines). For that, it is unanimous that the most significantly improvements were observed in the spatial gait's parameters: stride length and step length [2, 13, 17]. These effects, were not only observed while using the visual cues but it has led to a normalization of these parameters for at least one month after training a significant amount of time (carryover effects) [51].

Although these improvements were quite significant and important, up to our knowledge, no attention has been payed, regarding usability and workload demands' factors when using these cues. These are quite important, in order to understand if those improvements are still that significant when comparing to its requirements.

Besides this, three other aspects regarding the usage of lines on the floor as visual cues, should also be taken into account. Firstly, its **spatial constraints**. The fact that it is quite impractical to have lines on the floor outside a laboratory or a house environment. One solution for this, is the usage of augmented reality. However, almost every found study regarding this issue had used augmented reality glasses [4, 18]. Which are yet very limited regarding its field of view and comfort especially for Parkinson's patients that have additional problems of dividing attention [26]. Secondly, the fact that the evaluation of these cues' improvements had only been performed **inside a controlled environment**, without other events that need patients' attention, is also considered a limitation. Thirdly, other important aspect to bare in mind when presenting visual cues to Parkinson's patients is the fact that the more the patient looks down, the more the **neck is flexed**, and the more the gait and posture of the patient are negatively affected [5, 54].

Improvements in velocity and cadence were also reported by some of the visual cues studies, however, these gait's parameters were most influenced when using **auditory cues**. These, similarly to the visual cues, were limited to only one type of information provided to the patients - temporal stimulus - leading to an unanimous improvements in velocity and cadence (temporal parameters) [13, 19–21]. Some of these improvements were still observed for at least 8 weeks [22], after a significant period of training (long-term effects). Besides this, other important thing to point out is that the studies approaching the auditory cues had used two different cues: music and metronome, which makes it normal for the results to differ from each other depending on the type of auditory stimulus used. And although music seemed to have a greater impact on patients' gait normalization [67, 68], once again, no attention is paid regarding the impact of both in relation to **usability metrics, workload nor attention**.

It would be natural to speculate that by using both visual and auditory cues at the same time, the effects on patients' gait would complement the improvements of each cue when presented individually. However, this is not the case. Using the two cues together has proved to decreased the results accomplished when using each individually [13]. On the other hand, the effects of using the two types of information - spatial and temporal - together in a virtual environment has proved to improve every gait's parameters (stride length, cadence, velocity and stride variability) [3].

Both visual and auditory cues can induce great improvements in Parkinson's patients' gait, however their usage outside the laboratory environment is quite limited and undetermined. Therefore, **haptic cues** are quite promissory in order to address this issue. And although it is considered to effect patients' posture, and balance positively while using complex devices like headbands [79], belts, gloves [78] and footwear [12], there are not much research and agreement regarding the utilization of simpler devices for that intention. Besides that, the type of information used through the Haptic cues' studies were only temporal. However, since, the usage of both types of information - spatial and temporal - in the visual field, has proven to produce improvements in every gait performance metric, more attention should be paid regarding the usage of both in Haptic cues. In addiction, similarly to the visual and auditory cues, little awareness regarding the impact of these stimuli on a usability perspective for the patient.

Finally, taking into account all the information gathered regarding the three cues described in this work, we may conclude that it is important that not only an analysis of the **gait performance** (taking into account stride and step length, velocity, cadence), but also an evaluation of **stimuli usability** and attention impact from the patient perspective when submitted to each cue. This is important due to the fact that a stimulus may produce improvements in a patient's gait, however the patient may find it too uncomfortable and too difficult to follow, and that should be taken into account.

Besides this individual analysis of each stimulus, an understanding on how Parkinson's patients' would react while using these cues **in-the-wild**, would also be interesting. In other words, examine the effect of using cues, on patients' gait parameters, attention and usability metrics, outside a control environment, such as a street, a supermarket or a public transport, where multiple external stimuli are constantly presented to the patient. Finally, since many previous works had observed carryover effects (highlighting the fact that cues are not always needed in order to produce improvements), a solution that enable patients' to turn the stimulus on and off depending on their needs and preference, would also be necessary and important.

3

VR Field Study – Cue Selection and Implementation

Contents

Before proposing a solution that aims to normalize users' gait in a comfortable and safe way out in-the-wild, we needed to assess what are the effects of various stimuli not only on participants' gait but also in terms of usability and gaze.

In order to understand those, we had developed a experimental study [80], in which we presented different types of cues to the participants and analysed how they would react to them.

In order to carefully design and implement this study, we had divided this process into three distinctive and important moments. First we needed to determine which questions did we want to answer through the study. After this, and taking into account those, we had to take into account the architecture and implementation that it should follow.

Therefore, in this chapter we focused firstly on the **questions** that we needed this study to answer. After we briefly analyzed and explained the **architecture** behind the study and then, we described and justified all the decisions supporting its **implementation**.

3.1 Questions to be answered

Taking into account all the previous research presented in Chapter 2, we were able to identify a concrete set of questions that were still not answered and therefore that we aimed to clarify.

1. What are the effects on **gait parameters** of patients with gait disorders (e.g. Parkinson's' Disease) when using Haptic cues, comparing to when not using any cue (baseline)? And comparing to when using Visual or Auditory cues? Did gait velocity/step length/cadence increase or decrease?
2. Is VR a viable research approach?
3. What are the gait 's effects of using Temporal + Spatial information in Haptic cues?
4. In terms of **usability**, what is the most preferable/comfortable/easiest stimulus? And the least?
5. In terms of **workload**, what are the stimuli that required higher and inferior levels?
6. Regarding patients' **security**, what is the safest stimulus for a patient to use in-the-wild? In other words, what is the stimulus that let the participants be more aware of the surrounding?

3.2 Architecture

The architecture of our study was quite simple and is represented in figure 3.1. As it can be seen, in order to accomplish the aims of this study, we had used three distinct components: **Mobile Application**, **Smartwatch Application** and **Unity Application**. Each of these components had specific functionalities

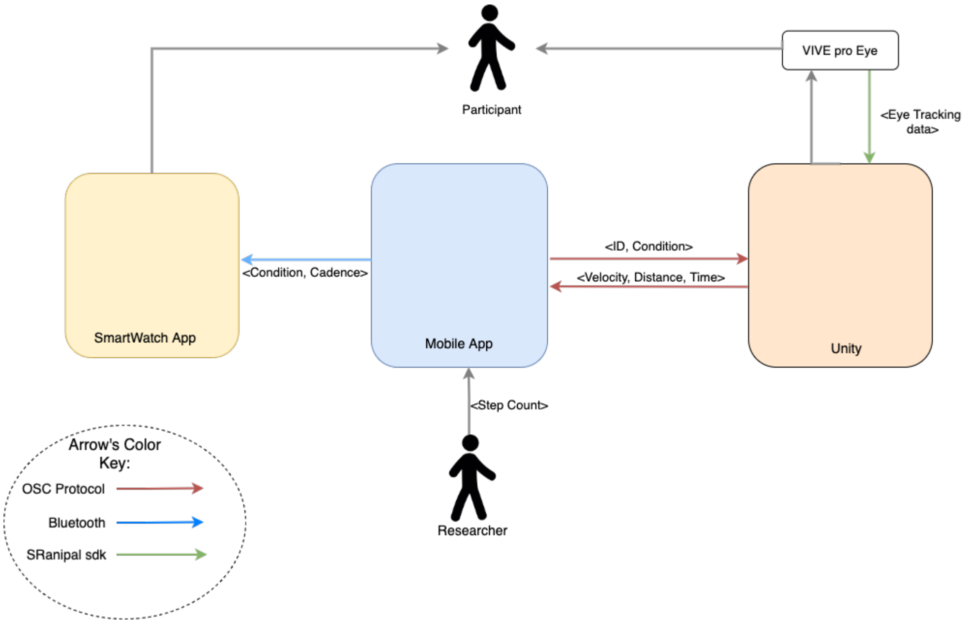


Figure 3.1: VR field study architecture.

- explained in the following sections (3.3.3, 3.3.4, 3.3.5) - and therefore specific target users. For that, and as it can be seen in figure 3.1, the mobile application belonged to the **researcher** in charge of the study, whereas the smartwatch and unity application were primarily used by the study's **participants**.

In addiction to this, the foundation of this study's architecture and design rely on the interaction and communication between each component.

Mobile application was the center of all these communications, meaning that it was the phone application that communicated with unity and with the smartwatches. In fact, we may identify three main communications paths: Mobile –> Unity; Unity –> Mobile; Mobile –> Smartwatch. In specific, communications and data exchanged between the unity app and the mobile app were achieved by using the **Open Sound Control (OSC) protocol**. This protocol enabled the communication between multiple devices (the phone and the PC) in almost real-time. On the other hand, communications between the mobile App and the smartwatches were accomplished through the usage of Bluetooth.

Besides these three main components, we still had to consider the VIVE Pro Eye Head-mounted display (HMD). This device, not only enabled the presentation of the unity simulation to participants, but also the detection and collection of eye tracking data (more details in section 3.3.5.C).

In the next sections, we explain how each component works and interact with the others, and their main functionalities.

3.3 Implementation

Now that we understood the architecture and objectives of this study, it is important to discuss the implementation of each component and the development process of the study.

Therefore, in this section we will start by specifying how we selected the Cues and Environment used in this study. These two decisions were quite important during the early stages, since they influenced all the implementation of the remaining components. After the explanation of these decisions, we will focus on the implementation and features of the mobile application; smartwatch application and unity application.

3.3.1 Cues

3.3.1.A Cues Selection

Taking into account the before-presented literature, we identified 3 different main types of cues: Visual, Auditory and Haptic.

After considering each of those cues, we knew that we wanted to explore **Haptic cues**.

These cues, were considered to be a promissory approach regarding gait normalization, not only because many previous studies had already observed positive effects on users' gait performance [12, 75, 76, 81], but also because these types of cues had been demonstrated to be less cognitively taxing than visual stimuli in navigation tasks. In addition to this, the fact that it could be provided to users in a **less distracting** and **more private** form (such as a smartwatch or fitness tracker) validated the potential ease of being used outside a controlled environment.

Besides these usability reflections, the fact that haptic cues had been **briefly explored** in the past, significantly less than the others two types of cues, allowed us to explore them in a more profound way (i.e. using different types of information presented – only temporal, temporal + spatial)

After choosing haptic cues as our main point of interest, we aimed to get a comparison between our future results and the state of the art. Therefore, besides haptic cues, we had chosen to use **Visual cues**, since they were appointed to be the most used and studied type when gait normalization is concerned, which made them a good representation of the state of the art.

Therefore, we may say that this choice was based on three different factors:

1. The need for new information. We aimed to research and investigate as many new information about the cues as possible.
2. The feasibility of using the cues outside the laboratory. We took into consideration, how easy or difficult it was for the users to produce the stimulus outside and how distracting were they.

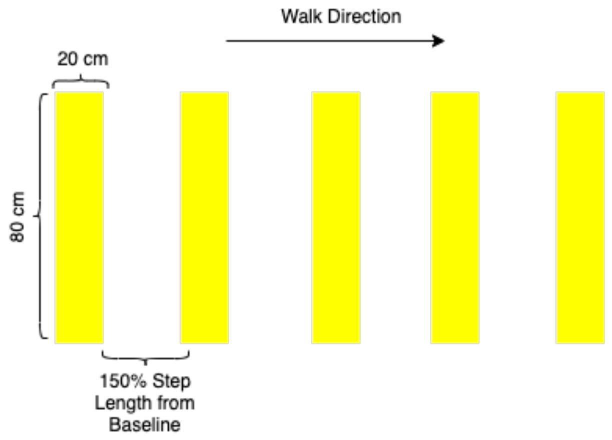


Figure 3.2: Visual cues Representation.

3. State of the art representation. We wanted to compare our results with previews studies which made it important to had a stimulus that had already been explored and used.

3.3.1.B Cues design

After selecting the type of cues that we wanted to use in our research we had to design them. In other words we had to decide how they were going to be presented to the users and what type of information they would transmit.

Visual Cues

Since the main purpose of using visual cues was to represent previous work, we had followed those works [2, 13, 17, 44, 53], where almost unanimously bright traverse bars on the floor were used as cues. For that, we had used bright yellow bars, on the floor, perpendiculars to the direction of the walk, as it can be seen in Figure 3.2. These bars measured in height 80cm and in width 20cm, however, taking into account the previous literature these measures were not homogeneous, meaning that almost each paper had different dimension for the visual bars.

Besides this, other important thing that we had to determine was the location of the cues, in other words, the distance from one bar to the next one. In order to make an inform decision about that, we took into account Knuttson's work [82], in which after analysing Parkinson's disease patients' gait it was observed that on average, the step length of these patients was half the step length of people of the same age without the disease. Apart from this reason, Bagley et al. [2] had also placed the bars apart from each other by 150% of the initial step length, observing improvements in the gait pattern of Parkinson's patients. Therefore, we had set the distance from each bar at 150% of the initial step length of each subject.

Haptic Cues

Regarding Haptic cues, since one of the main objective for using these cues in our study, was to explore this type of stimulus in different forms that had not been yet explored, firstly, we had to focus on which type of information did we want and need to represent through the stimulus.

As a reminder, temporal and spatial are the usual types of information used through cues. In the case of Haptic cues, Temporal information (only) had already been used through a simple vibration at specific intervals (cadence) [12, 77, 78]. On the other hand, up to our knowledge, temporal + spatial information had not been yet investigated when aiming to normalize gait.

Besides this, other important consideration that we had in mind was these **cues' usability** outside the lab, which means that the way they were presented to the user - in terms of portability, weight, size, privacy - was also an important factor. In order to consider that, we had decided to use **Smartwatches**.

With that in mind and in order to fill some of those information gaps, in our study, we had used three different haptic cues. They differ from one another in two aspects: the **pattern** of the vibration used and/or **the way they were provided to the users**. Besides these differences, all three cues had used the **vibration** as haptic stimulus.

Thus, in our study we had used the following three cues:

- **Haptic 1P1W (1 Pattern, 1 Watch)** – Similarly to the visual cues, this cue was used as a representation of previous work [12, 77, 78], using a single vibration (200 ms) on the participant's wrists and providing them with a rhythmic stimulus (see Figure 3.3(a)), informing the participant when to take the next step. The *temporal* property of this stimulus varied between participants, in order to correspond to -10% of their initial cadence.

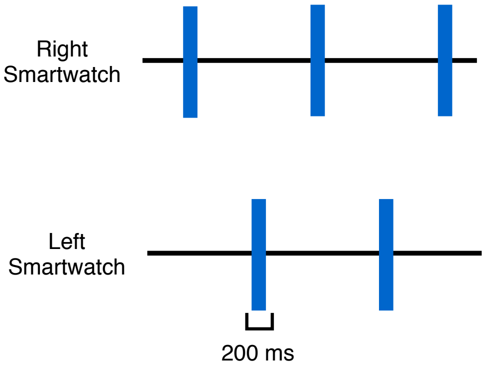
- **Haptic 2P1W (2 Patterns, 1 Watch)** (Novel) – In order to use the two types of information simultaneously in one cue, and inspired by Google's work in Google maps feature (usage of haptic feedback with the aim of guiding the user), we had developed two patterns of vibration (see figure 3.3(b)) - the first was composed by two short vibrations (100 ms each) and the second pattern consisted in one longer vibration (200 ms). Each of these patterns was mapped to a foot, meaning that each time a pattern was on, the participant knew which foot was supposed to take the step.

  As a clarification, the temporal and spatial property of this cue was presented by giving information to the participants regarding when to take a step (temporal) and which foot to use (spatial). Similarly to the previous explained cue, the *temporal* property of this stimulus varied between participants in order to correspond to -10% of their initial cadence.

- **Haptic 1P2W (1 Pattern, 2 Watches)** (Novel) – Similarly to Haptic 2P1W, we had developed other cue that presents the two types of information together, however, for this we were inspired by the simplicity of Haptic 1P1W's single pattern. Therefore, we had used also a single pattern with one

((a)) Haptic 1P1W representation

((b)) Haptic 2P1W representation



((c)) Haptic 1P2W representation

Figure 3.3: Representation of Haptic cues. Each vertical line corresponds to a vibration, the duration of that vibration is directly proportional to line's height, this means that the bigger the line, the longer the vibration.

simple vibration (200 ms) and two smartwatches (represented in figure 3.3(c)). This vibration was alternatively played between the two watches - placed on the left and right wrist of the participant - providing the users with a rhythm with temporal and spatial properties. In other words, every time the left watch vibrated, participants' knew that it was left foot turn to take the step, similarly to the right watch. Therefore, similarly to the Haptic 2P1W, we had given information to the participants about when to take a step (temporal information) and which foot to use (spatial information). Once again, the *temporal* property of this stimulus varied between participants in order to correspond to -10% of their initial cadence.

3.3.2 Environment

Now that we had explained the choice and design of the cues used in our study, we need to focus on how we had chosen the environment in which our study took place.

3.3.2.A Environment Selection

As said before, one of our main objectives was to examine the effects of cues in-the-wild, outside the laboratory controlled environment, where multiple distractions are constantly presented to the participant.

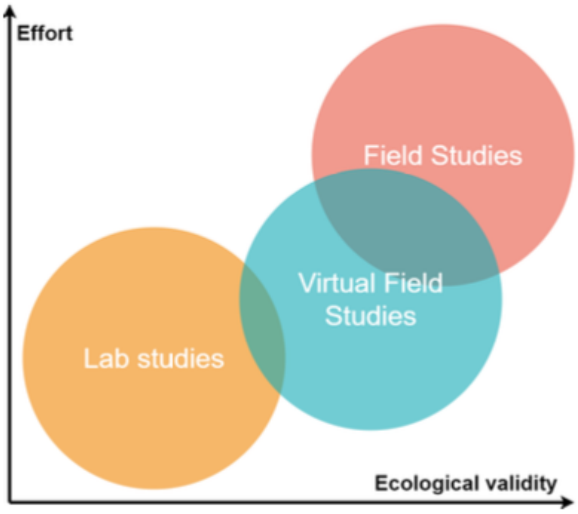


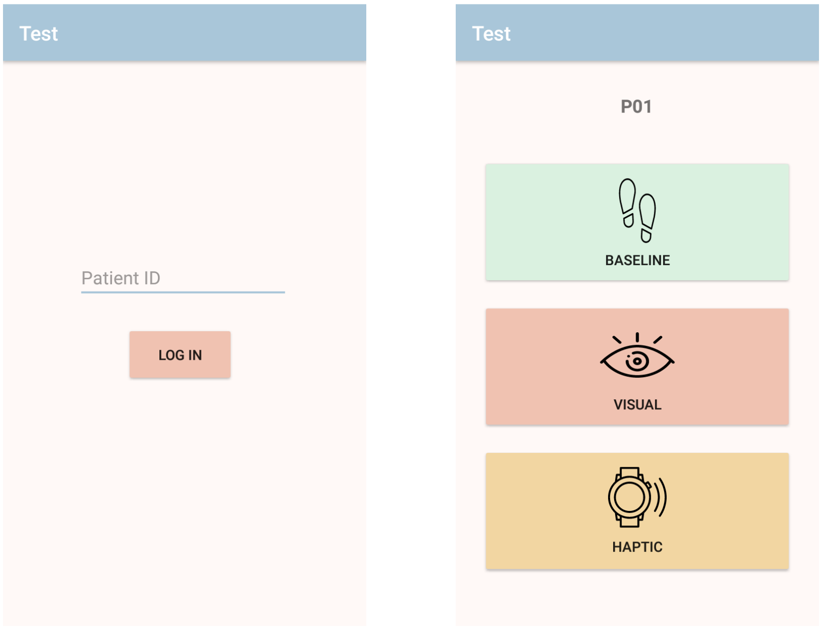
Figure 3.4: Ville Mäkelä et al. [6] comparison between VR Field Studies, Field Studies and Lab Studies.

The choice of the environment where the study would take place (street, supermarket, store, Shopping Center), was based on selecting the most **common** and **used** environment by people. Thus, we had chosen to use a **Street**. However, given the sensibility of patients with gait impairments, in specific Parkinson's patients, doing this study literally on a street was quite imprudent and dangerous, leading us to use **Virtual Reality**.

One concern that emerged with the decision of using VR was its feasibility as a research platform to evaluate real world scenarios. However, some prior work had already been performed aiming to compare users behave in VR against real-world scenarios. These investigations have been performed in the most diverse areas: Education [83], Evacuation Scenarios [84], Medicine [85–87], Locomotion [88, 89] and others, however, the results are quite unanimous, since participants' tended to adopt behaviours in VR similarly to the real world. Therefore, we may say that VR has became a feasible research platform to evaluate real world scenarios.

In addition to this, Ville Mäkelä et al. [6] when comparing Lab studies, Virtual Field Studies and Field Studies placed the VR filed studies between the lab studies and the real-world field studies, since in terms of ecological validity VR studies are closer to field studies and when concerning about the required effort, VR studies are closer to the lab studies (see Fig. 3.4).

Besides this, another important factor that led us to perform our study through the usage of VR was the fact that this technology enabled us to not only ensure participants' **security** but also to have a great level of **control** over the environment, e.g. researchers can easily transform and adapt the simulated situation/environment.



(a) Application screen where the researcher introduced the ID assigned to that participant.

(b) Application screen where the researcher chose the condition to be tested.

Figure 3.5: Screenshot from our Mobile Application.

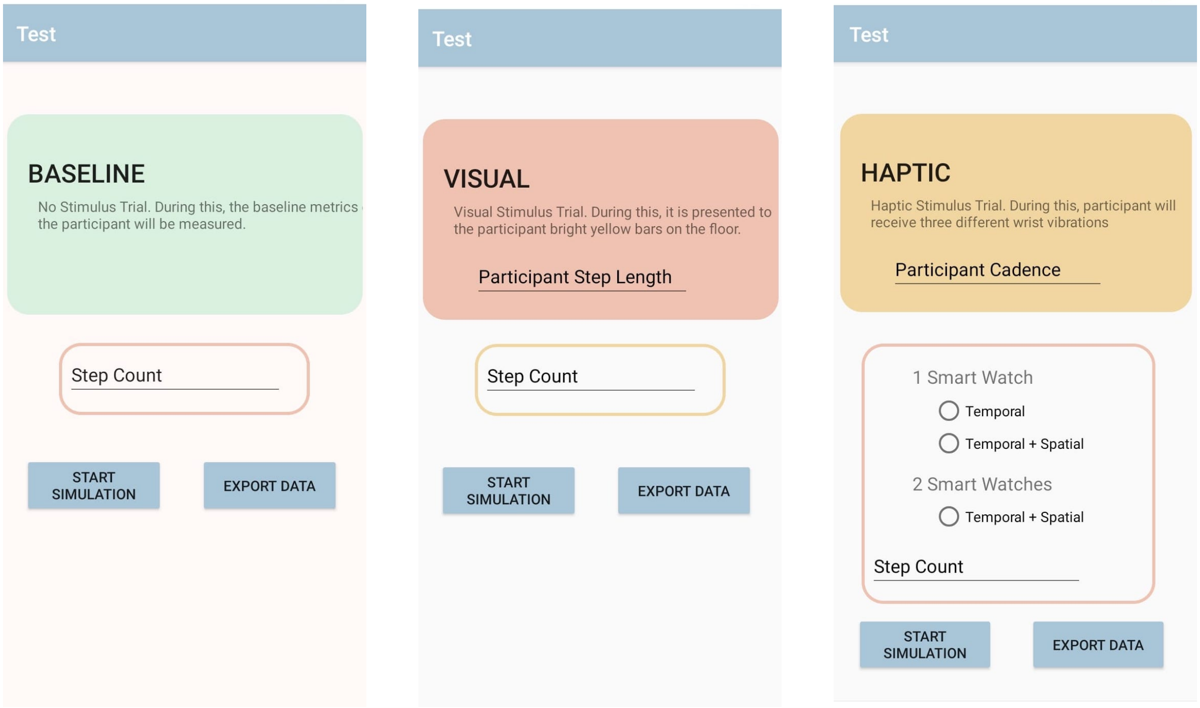
3.3.3 Mobile Application

The mobile application, that belonged to the researcher in charge of the study, was the center of all study. With this, we mean that it was the mobile application that communicated and controlled all the other components. This application had 3 major functionalities: **Register**, **Cues' Control** and **gather, calculation and store data**.

3.3.3.A Register

The register function simply aimed to facilitate the collection and organization of different types of data, and to agile data processing. For that, each participant had assigned an **ID** that was introduced and stored into the mobile application (through the screen that is shown in figure 3.5(a)), in order to make sure that all the data collected from that participant was always assigned to him/her.

The storage of the ID was done through *Android's Shared Preferences*, which allowed us to save and retrieve data in the form of <key,value> pair. Therefore, after the researcher introduced the ID of the participant (e.g. P01) , that pair stored by the shared preferences was <ID,P01>.



No Stimulus Trial. During this, the baseline metrics the participant will be measured.

Visual Stimulus Trial. During this, it is presented to the participant bright yellow bars on the floor.

Haptic Stimulus Trial. During this, participant will receive three different wrist vibrations

(a) Baseline application screen.

(b) Visual cue application screen.

(c) Haptic cues application screen.

Figure 3.6: Screenshots from our Mobile Application.

3.3.3.B Cues' Control

Other important functionality of this application relied on the fact that, it enabled the researcher, in charged with the study, to control all the different studied stimuli.

Therefore, after the participant was logged in, the Application showed to the researcher a menu with the three options of stimulus(see figure 3.5(b)): Baseline, Visual and Haptic. Each of these options were buttons, and when the researcher clicked on them, another screen was shown, as demonstrated respectively in figure 3.6(a), figure 3.6(b) and figure 3.6(c). It is important to note that all the three screens had: a Start Simulation button, a *Export Data* button, and a Step count input field. Besides this, Visual and Haptic Screens had also a field displaying, respectively, the step length and cadence measured during baseline trial.

Through the three screens, the researcher was able to start the Unity simulation and the correspondent stimulus, by clicking the "*Start Simulation*" button. What happened after that depended on the stimulus that was being tested:

- **Baseline** – When starting the baseline condition, this mobile application would communicate with unity, sending the **ID** of the participant and the name of the **condition** ("baseline", in this case), and the unity simulation would start.

- **Visual** – Similarly to Baseline, when starting the visual condition, the application would send to unity the **ID** of the participant, the name of the **condition** ("visual" in this case), in addition to the **step length** measured during baseline trials.
- **Haptic** – The process behind Haptic cues was slightly different than the other two, since when clicking on the *Start Simulation* button, not only the mobile application communicated with the unity application, but it also communicated with the smartwatch application. For the unity application it was sent the **ID** of the participant, and the name of the **condition** that was being tested and, therefore, selected from the haptic screen radio boxes (represented in figure 3.6(c)). For the smartwatch application it was sent an **ID** of the haptic condition (in order for the watches to produce the correspondent vibration) and the **cadence** measured during baseline.

3.3.3.C Gather, Calculation and Store data

During the simulation, the researcher had the important task of **counting the steps** taken by the participant in that trial, in order to, introduce that number of steps in the Input field "Step Count" (see figure 3.7), when the trial was over.

Besides this, when the participant reached the end of the trial and the unity application stopped, unity sent back to the mobile application some important data:

- The **time** that the participant took to perform the task
- The **distance** walked by the participant

With this information received from unity and the step count introduced by the researcher, our mobile application calculated the **average step length, cadence and velocity** during that condition. Therefore, when the unity application ended and the researcher had already introduced the number of steps, the *"Export data"* button can be pressed, in order for the application to **calculate** and **export those values** into a WalkData.csv file, that was stored in the mobile internal storage.

Besides this, if **Baseline** was the condition being tested, these values - cadence and step length - were used as **input** for the haptic and visual conditions, respectively.

3.3.4 Smartwatch Application

This application was developed as a wear OS app, being its main functionality to provide the Haptic stimulus to the user.

This provision would started after receiving information from the mobile application, regarding the haptic cue that should be presented and the baseline cadence of that participant. In order to receive

```java
public class ListenerService extends WearableListenerService {
    private static final String START_ACTIVITY = "/message";

    @Override
    public void onMessageReceived(MessageEvent messageEvent) {

        if( messageEvent.getPath().equals( START_ACTIVITY ) ) {
            final String message = new String(messageEvent.getData());

            Intent messageIntent = new Intent();
            messageIntent.setAction(Intent.ACTION_SEND);
            messageIntent.putExtra( name: "message", message);
            LocalBroadcastManager.getInstance(this).sendBroadcast(messageIntent);

        } else {
            super.onMessageReceived( messageEvent );
        }
    }
}
```

(a) Wearable Listening Service

```java
public void haptic1P1W(Long cadence) {

        timer = new Timer();
        double tempo = (60.0 / cadence) * 1000;
        double tempoReduc = tempo - (0.1 * tempo);
        Long finaltempo = (Double.valueOf(tempoReduc)).longValue();


        mTt1 = new TimerTask() {
            public void run() {
                mTimerHandler.post(new Runnable() {
                    public void run() {

                        long[] mVibratePattern = new long[]{0, 200, 0};
                        int[] amp = new int[]{0, 255, 0};
                        VibrationEffect effect = VibrationEffect.createWaveform(mVibratePattern, amp,  repeat: -1);
                        v.vibrate(effect);

                    }

                });
            }
        };

        timer.scheduleAtFixedRate(mTt1,  delay: 1, finaltempo);
    }
```

(b) Haptic 1P1W Implementation

Figure 3.7: Wearable Application Screenshots.

that information, we had developed a Listening Service that was always listening for new messages from the mobile application. This service was implemented, as it can been seen in figure 3.7(a), by using the *onMessageReceived* method from the *WearableListeningService* service. In this method we checked the path that was sent over the *MessageApi*, and then, if appropriate, we launched our main activity where the received data was analyzed and the haptic condition that should be displayed was selected.

In terms of implementation of the Haptic cues, as explained before in section 3.3.1.B, there were three different types of haptic stimuli (Haptic 1P1W, Haptic 2P1W, Haptic 1P2W), and although they were quite different from each other, their implementation was quite identical (Haptic 1P1W implementation can be seen in figure 3.7(b)). First within a new Task, from the baseline cadence value (steps per minute), received from the mobile application, we had calculated the time between each vibration (-10% of baseline cadence). Then, we had created a *VibrationEffect*, with a specific pattern and amplitude. This effect was repeated at a specific rate, being this rate the previous calculated time between vibrations. This repetition was accomplished by using *scheduleAtFixedRate*.

3.3.5 Unity Application

This application was implemented using Unity and deployed on a VR Headset. It had three major functionalities: the presentation of the VR environment to the participant, Visual cues presentation and the collection and storage of different types of information.

3.3.5.A VR Environment

Since one of the main purposes for this study to use VR technology was to understand the implications of visual and haptic cues outside the laboratory, the **reality** and **immersion** of the Street simulation were important requirements.

In order to accomplished reality, we had used as template a normal and common **crossroad**, repre-

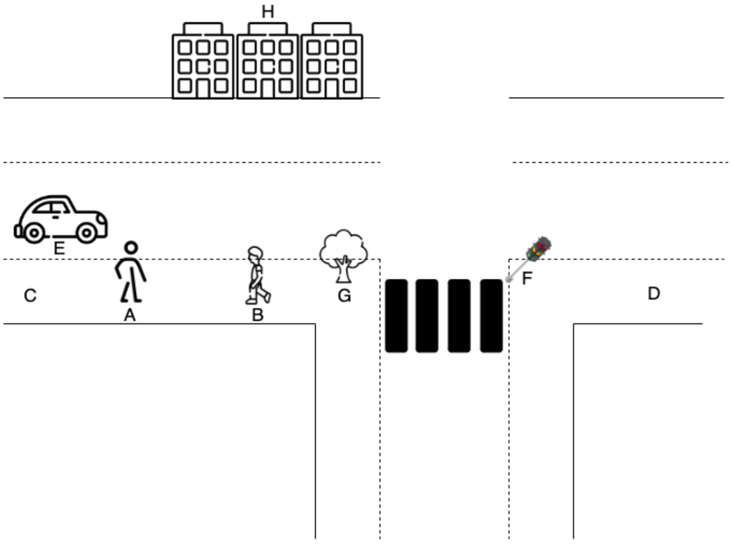


Figure 3.8: The virtual street structure. Key: A - Participant; B - Other pedestrian; C&D - Side Walk; E - Moving vehicle; F - Pedestrian traffic light; G - Tree; H - Buildings;

sented in figure 3.8. When deciding the structure and constitution of that street, we took into consideration two different types of elements:

- **Base Elements (Non-distractors)** – These were static elements that are normally presented in streets: side walks, crosswalk, trees, buildings, street benches, garbage cans. These were always presented in the simulation.
- **Distractors** – These were non-static elements, meaning that they changed or moved during the simulation. The distractors elements on our scene were: a **pedestrian** that was also walking (represented in fig.3.8 as B); a **pedestrians light** that changed colors from red to green(represented in fig.3.8 as F); and a **car** passing by (represented in fig.3.8 as E). These events took place after participants walked 2.5, 3.5 and 1.5m, respectively.

All of these elements were **positioned** and **scaled** in the most realistic way possible (see fig.3.9). The only restriction was that, during the simulation the participant performance should not be compromised by none of these elements. Meaning that they should not become an obstacle in the participants' path. Besides this, all of these elements were imported from the ***Unity Asset Store***, the link of each asset used in our scene is presented in 3.1.

After all the elements selected and positioned, we had focused on four factors that were essential when developing a truthful scene:

- **Lightning** – In terms of lightning there were two different aspects that we had to consider: the lights modes and the lights sources. Regarding the first one, since most of the objects in our scene were static, we had used *Baked lights*. In addition to this, in our scene we had used two different sources

Figure 3.9: Printscreen of the virtual street. Key: A - Pedestrian traffic light; B - Other pedestrian; C - Moving vehicle;

	Link
Characters	https://assetstore.unity.com/packages/3d/characters/humanoids/humans/character-pack-02-16577 https://assetstore.unity.com/packages/3d/characters/humanoids/humans/civilian-2-character-bundle-13036
Floor	https://assetstore.unity.com/packages/2d/textures-materials/floors/floor-materials-pack-v-1-140435
Sky	https://assetstore.unity.com/packages/2d/textures-materials/sky/wispy-skybox-21737
Buildings	https://assetstore.unity.com/packages/3d/environments/urban/city-low-poly-2455#content
Car	https://assetstore.unity.com/packages/3d/vehicles/land/low-poly-civilian-vehicle-5-124987
Nature	https://assetstore.unity.com/packages/3d/environments/nature-starter-kit-2-52977
Traffic elements	https://assetstore.unity.com/packages/3d/props/free-traffic-essentials-asset-pack-125092
Car sound	https://assetstore.unity.com/packages/audio/sound-fx/transportation/i6-german-free-engine-sound-pack-106037

Table 3.1: Unity Assets Links

of light, a **Directional Light** in order to represent the sun, and **Ambient Lightning** through the usage of a *Skybox*, simulating the sky.

- **High Dynamic Range (HDR)** – This defines how extremely bright or dark the colors are captured by the cameras in the scene. By default, unity's cameras use Low Dynamic Range (LDR). However, this technique does not reflect the way we perceive lights in real life, leading to unrealistic scenes, caused by its limited range of color values. On the other hand, when using HDR technique, the way pixels values are store, allow for a much larger range of values[1], leading to a more realistic representation of colors (more representative of the way we observe lights). For that, we had used HDR.

- **Rendering Path** – Rendering Paths consist on a series of operations related to lighting and shading. There are two major techniques of rendering: Forward Rendering and Deferred Shading. The first one is the unity's default render path, however, in this, real-time lights are considered to be quite expensive to process, whereas **Deferred shading** is appointed to be the most lighting and

---

[1] More information about HDR can be found in Unity's Documentation

shadow fidelity rendering path (between these two)[2]. Therefore we had used Deferred Shading as Rendering Path in our simulation.

- **Color Space** – This represents the math used by Unity when combining colors in lighting equations or when interpreting texture values, having a profound impact on the realism of the scene. Between the two types of color spaces (Linear and Gamma), and since we did not have any hardware constraints, it was used **Linear Color Space**. This is considered to be the preferred Color Space for realistic rendering [3].

In terms of **immersion**, we had used 2D and 3D sounds. City streets, normally have a characteristic background noise (normally associated with noise pollution), being always audible even if the source of it is not near to the listener (someone talking, constructions, beeping from cars). In our simulation we took that into consideration and we had used a 2D city sound clip that was always playing in the backgound of the simulation. Besides this, and since we had a car passing by, we also had used a 3D sound effect in order to made this sound vary depending on the position and distance of the listener to the car. To accomplished that volume variation we had used the *Rolloff Mode*.

3.3.5.B Visual Cues Presentation

It was at this Unity application where the visual cues (presented in section 3.3.1.B), were created and presented to the participant (see fig. 3.10).

When unity received from the mobile application a message with condition ID equals to "visual", the application created and displayed the yellow bars, on the floor. The generation of these, was done by replicating a *prefab*, previously designed and created by us, for 9 meters (starting at participants' position). Beyond the condition ID, as explained before, the mobile application also sent the **step length** of that participant, measured during the baseline trial. That value, was used by unity in order to calculate the distance between each yellow bar. These calculations were done taking into consideration 150% of that received value plus the height of the bars.

3.3.5.C Data Collection and Storage

During simulation, Unity Application collected data related to gate and to eye tracking.

As explained before in section 3.3.3.C, to complete the information needed by the mobile application to execute performance calculations (gate related), when unity's simulation ended, the amount of **time** the participant needed to complete the trial, and the walked **distance** were sent to the mobile application through OSC protocol.

---

[2] More information about Rendering Paths can be found in Unity's Documentation

[3] More information about Color Spaces can be found in Unity's Documentation

Figure 3.10: Printscreen of the virtual street when visual cues were presented.

Besides this gate related information, unity application was also in charge of the integration and collection of eye tracking data, in our case provided by HTC VIVE Pro Eye HMD. In order to access these data, we had used the *VIVE Eye Tracking SDK* also known as *SRanipal*[4] which allowed us to track and integrate users' eye movement. In addition to this, and in order to simplify the implementation of the process of collecting this data, we had also used *Tobii XR sdk*[5]. This Sdk, enabled us with a set of properties that helped us understand what was the object at which the participant was looking and for how long, in **every frame**

To accomplished that, every GameObject on the unity scene had a Collider and a script attached. It was through that script, that it was used the *Tobii XR SDK*'s GazeFocusChanged method from IGazeFocusable interface, in order to check if that object was in users' focus. If true, it was incremented and updated the number of times - **hits** - and the amount of time - **dwell time** - that object had been looked at during the simulation. In addition to this, every time the user changed the GameObject under focus, a Comma-Separated Values (CSV) file (*eye_data.csv*) was updated with the information regarding that gaze. In other words, after a gameObject lost users' focus, the name of that GameObject, the number of hits and the dwell time of that respective gaze, were exported to that CSV file. Being each line of that CSV file a description of a different look at a gameObject.

Besides this, and since that file could have many entries (every hit was an entry), when the unity application ended, it was created a new CSV file (*eye_data_resume.csv*), with a summary of every focused objects names and the correspondent number of hits and dwell time.

---

[4] More information about SRanipal Sdk can be found in VIVE developers' Documentation

[5] More information about Tobii XR SDK can be found in Tobii XR SDK's Documentation

4

VR Field Study

Contents

After completing the implementation and development described in the previous chapter, a set of participants had performed the study. In this section we explain the **methods** and **procedures** behind it, in addiction to the **results** that outcome from it.

Firstly, we start by introducing the preliminary user study that was conducted before the study's final version, and the comments and observations that were taking into account when designing the final version of it. Secondly, we present our User Study by explaining the process of participants selection, experimental setup, experimental design, metrics and procedure. Finally, we present and analyse the results from the performance of the study.

4.1 Preliminary User Study

Before reaching the final version of our user study, we performed a **first iteration** of the study, in which we made sure that all the study's components were correctly performing all their main functionalities (described in section 3.3) and that we were collecting all the needed metrics.

This study was performed by six patients without any gait impairments. Except for one, these were aged between 18 and 25 years of age (*M* = 27.0; *SD* = 11.52); and the majority were students (66.6%).

Even tho this was not the final version of our study, we aimed to get some feedback regarding the study procedures and the objectives motivating it, and for that, we had submitted a paper to the ***International Workshop on Cross-Reality (XR) Interaction, ACM ISS 2020*** with the results of these preliminary test sessions [30].

Apart from the fact that we found those results quite promissory, we realised that there were some lack of important information regarding usability and gaze. In fact, we found the following gaps:

- We were not measuring **workload** information, which was important in order to understand the impact of each used cue in terms of participants' Mental demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration.

- We were not evaluating how participants reacted to the VR simulation. In other words, there was lack of information regarding: the presence sense on the VR simulation, and how the participants felt during the simulation.

- Regarding the **stimulus**, there was lack of information regarding participants' personal opinion on each presented stimulus.

4.2 User Study

Taking into account all of those gaps found during the preliminary study, we will now present our final VR field study.

4.2.1 Participants Selection

This study was initially intended to be performed by participants with gait disorders, however due to Covid-19 restrictions, in addiction to the fact that as said before, gait disorders are more likely to be found in elderly people which according to the World Health Organization (WHO) are the most vulnerable and high risk group to contract the virus, the access to this group of people was very restricted and not recommended.

The hypothesis of having **healthy people** performing this study, had raised some questions regarding the validity of future results, since these were not our primarily participant, and as explained in the Related Work (Chapter 2), there were great differences between the gait of healthy people and gait of patients with gait disorders. However, previous works that aimed to evaluate the effects of cues on Parkinson's patients' gait had also used healthy participant mainly as a form of comparison, but also observing how cues affected their gait [13, 24, 55, 78, 90]. With that comparing in mind, Hanakawa [91] had observed that the right lateral pre-motor cortex, was triggered by visual transverse lines on the floor (visual cues) in Parkinson's disease patients to a greater degree than in age-matched healthy individuals. Thus, this might mean that, Parkinson's' patients have a greater predisposition to be positively affected by the visual cues than healthy participants.

However, a more recent work, performed by Arias et al. [90], while investigating the effects of visual and auditory cues on Parkinson's disease patients and healthy participants, had observed that sensory stimulation affected **similarly** Parkinson' patients and healthy participants' gait.

Therefore, we addressed this study to any person without gait impairments, regardless gender, age, or their experience with VR, who was available to participate.

Regarding the sample size of participants needed, it is important to understand the design implemented in our study (explained in section 4.2.3). Since we followed a within participants design counterbalanced using a Latin Square, we needed a minimum of 4 participants, in order to complete a Latin Square.

4.2.2 Experimental Setup

This study was performed in a IST's room, at TagusPark's campus, and since it consisted on having participants walking, some rearrangements had to be made, in specific, some tables and chairs were moved in order to free some space.

In that room we had a **PC**, in which the Unity application (detailed in section 3.3.5) was running. This computer was connected to the **HCT Vive Pro Eye** head-mounted display (combined resolution of 2880×1600 px, 615 PPI, 90Hz, 110° FoV) and eye-tracker (120Hz, 0.5° 1.1° accuracy), in which the application was deployed. This connection followed VIVE's tutorial [1] where every step, regarding this connection, was detailed.

After this, the two SteamVR **Base Station** 2.0 were placed and installed. These were the ones transmitting signals to the headset and the controllers, so their position and installation was considered to be an important step. For that, we had also followed VIVE's recommendations [2], and the base stations were mounted diagonally at opposite corners of the space, and adjusted so that the front panels were facing toward the center of the play area.

Following this hardware configuration, the **room-scale** play area was setup [3]. This was also an important procedure that ensured participants security and confidence during the simulation. So, when delimiting the play area we made sure that the floor was cleared, and that those boundaries were distanced from objects (i.e. walls, tables, chairs) for at least 0.5 meters.

Besides this, we had also used:

- Two Huawei Watch 2 with the Smartwatch application installed, more information about this can be found in section 3.3.4.
- A cell phone running Android 7 or later with the Mobile application installed, more information about this can be found in section 3.3.3.
- A PC with the questionnaires that the participant should fill during the session. These surveys are presented and explained in section 4.2.4.A.

4.2.3 Experimental Design

In this study we had followed a **within participants** design, meaning that each participant performed all the conditions of the study. However, with the implementation of this design two sides effects arised: participants' experience with the procedures was likely to grow (**practice effects**), and prior conditions may had an influence on later responses (**carryover effects**). So, in order to face this effects, we had also implemented a **partial counterbalanced design**. In partial counterbalancing there are four major requirements:

---

[1] Connecting the headset to your computer VIVE's tutorial can be found in https://www.vive.com/us/support/vive-pro-eye/category$_{h}owto/connecting-the-headset-to-your-computer.html$

[2] VIVE's instructions regarding the installation of the base station can be found in https://www.vive.com/us/support/vive-pro-eye/category$_{h}owto/installing-the-base-stations.html$

[3] VIVE's instructions regarding the Setup up of a room-scale play area can be found in https://www.vive.com/us/support/vive-pro-eye/category$_{h}owto/setting-up-room-scale-play-area.html$

1. A subset of all possible orders of conditions is included. The number of conditions' sequences, present in that subset, is the minimum number of sequences needed so that each condition occurs in each position at least once.
2. Each participant perform all conditions of the study.
3. Each condition is performed an equal number of times.
4. Each condition is performed an equal number of times in each order position.

To create a partially counterbalanced order we used a **Latin square**. This is a formalized partial counterbalancing procedure that ensures that each condition appears only once per line and per column (where each line represents the sequence of conditions performed by each participant, and the columns the order position of each condition).

So, in order to produce a Latin square we had to consider the number of cues' conditions presented on this study, and as presented and described before (in section 3.3.1), our study had 4 different conditions:

A – Visual – Bright transverse bars displayed on the floor.

B – Haptic 1P1W – Simple vibration pattern, played on participants' wrist at specific intervals, informing the participant when to take the next step (i.e. each vibration was mapped to a step).

C – Haptic 2P1W – Two distinct vibration patterns were played in sequence on a single smartwatch, and mapped to a foot. This means that each time a pattern was on, the participant knew which foot was supposed to take the step.

D – Haptic 1P2W – Simple Vibration pattern played alternatively over two smartwatches, placed on participants' left and right wrists, in order for the vibration to be mapped to the correspondent foot. So, every time the left watch vibrated, participants' knew that it was left foot turn to take the step, similarly to the right watch.

In order to generate that matrix, we had used an online tool[4]. The result is presented in table 4.1, where each row represents the sequence of conditions that the correspondent participant followed, and the letters refer to the correspondent cue condition.

---

[4] The online tool used to generate a Latin Square can be found in https://www.dcode.fr/latin-square

Participant ID	Sequence			
P01	A	B	C	D
P02	D	A	B	C
P03	B	C	D	A
P04	C	D	A	B

Table 4.1: Latin square used in our study. Each row represents the conditions' sequence used for each participant. Being each letter associate with a condition: **A** – Visual; **B** – Haptic 1P1W; **C** – Haptic 2P1W; **D** – Haptic 1P2W.

4.2.4 Metrics

In order to understand the effects of the cues on participants' gait and experience, during the study we had measured and analyse:

Performance. This included participants' cadence (steps per minute), step length (cm), and velocity (meters per second). This was calculated through the following three equations (4.1, 4.3, 4.2):

$$Step \quad length(cm) = \frac{\Delta x}{\#steps} \tag{4.1}$$

$$cadence(steps/min) = \frac{60 * \#steps}{\Delta t} \tag{4.2}$$

$$velocity(m/s) = \frac{cadence}{Step \quad length} \tag{4.3}$$

Where #steps corresponded to the amount of steps that each participant took in each trial. This number was calculated by the researcher as a result of visually counting the number of steps during a trial. Δt and Δx corresponded to the amount of time that each participant took to perform each trial, and the total distance walked by each participant in each trial (around five meters), respectively. These two values were calculated automatically by our VR simulation.

Usability. After each cue, participants completed the System Usability Scale (SUS) [92], a Raw Nasa Task Load Index (Nasa-TLX) [93] and a Stimulus usability questionnaire. In addition to this, and in order to have an overall perspective of the stimuli and experience, at the end of the study we asked the participants to fill a preference questionnaire, - where they had to pick and comment their favourite and least favourite cues - a Igroup Presence Questionnaire (IPQ) [94], and a simple questionnaire regarding their experience with our VR Scene.

Gaze. In order to assess participants' awareness of the three distractors and other objects included in the scene, we measured the number of **gaze hits** - the number of times the participant looked at the object - and **dwell time** - the amount of time spent looking at each object - across cue conditions.

4.2.4.A Questionnaires

As explained before, we had conducted various questionnaires in order to evaluate our some usability factors of our study, however these were performed in different moments of the testing session and with different objectives.

So, we will now focus on each questionnaire in order to understand how and why they were used.

All of the following questionnaires were created and presented to participants through Google Forms.

Demographic Survey. This questionnaire, presented in Appendix B, was divided into three parts with different objectives.

In the first part we asked participants demographic questions, in order to understand who were our participants. These questions were regarding their gender, nationality, age, height and occupation.

In the second part we asked participants' consent in order to use their results for scientific purposes in an anonymous way.

Finally, the last part of this survey focused on investigate how comfortable was the participant with VR and smartwatches.

Immersive Tendencies Questionnaire (ITQ) [95]. The ITQ was developed to measure the capability or tendency of individuals to be involved or immersed during regular activities. This was done through a twenty-nine questions with a seven-point Likert Scale format, as answers. This questionnaire, was quite important in order for us to understand how likely and easy it was for each participant to enter in our Virtual Environment (VE).

SUS [92]. This questionnaire is considered to be a reliable tool for measuring usability, consisting on a ten item questionnaire with five response options (from Strongly agree to Strongly disagree) in a Likert Scale format.

Raw Nasa-TLX [93]. This questionnaire is an adaptation of the original Nasa-TLX, where the amount of Mental demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration are assessed. Since we used the raw Nasa-TLX, we did not used the weighting process (second part of the Nasa-TLX), in order to make the survey simpler and yet still valid. Therefore, the questionnaire consisted on classifying each factor (Mental demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration) on a scale from 0 to 20. This means that for each cue, the participant evaluated how that cue influenced him/her in terms of mental demand, physical demand, temporal demand, Performance, Effort and Frustration.

Stimulus' Usability Survey In order to understand particularly how the participants felt about the stimulus, we had created a simple survey with 6 items regarding annoyance, comfort and ease of using the correspondent stimulus as cue (see Appendix C). Each of these items had five response options (from Strongly agree to Strongly disagree) in a Likert Scale format.

Ranking Survey. In order to know specifically what was participants favourite and least favorite stimulus, we had created this survey (presented in Appendix D). It is a simple form, where we ask the participant to order the stimulus by preference and to justify their choice regarding the most and least favourite stimulus. This ordering was done by assigning a number from 1 (least favourite) to 4 (most favourite) for each stimulus.

IPQ. [94] This questionnaire aims to understand the sense of presence of each participant during the virtual simulation, meaning, it aims to assess how much in the simulated street did the participant felt. This form consisted in a fourteen items questionnaire, each with seven response options (from Strongly agree to Strongly disagree), in a Likert Scale format.

VR Scene Questionnaire The main objective for this questionnaire was to assess what the participant felt about our VR simulation, in particularly, if they found it real, if they felt like themselves in there and if they were able to pay attention to the distractors. Therefore, we had created a simple form with six different items, each with five response options (from Strongly agree to Strongly disagree), in a Likert Scale format, and a open text field for they to leave any comments regarding the simulation. The used form can be found in Appendix E.

4.2.5 Procedure

This study had been performed by ten participants, which means that ten different testing sessions were held - one for each participant. Therefore, aiming to ensure uniformity and cohesion between each session, we had written a protocol guide, shown in Appendix A, in which all the interactions between the researcher and the participant, and each part of the session are detailed. Each session was divided into three different parts, which we will describe in the following subsections.

4.2.5.A Introduction and Pre-Study

After the participant arrival to the testing room, the researcher invited him/her to sit in front of the computer.

In order to comply with health and safety procedures it was asked to the participant to disinfect their hands properly with an alcohol solution with at least 70% alcohol, and to clean their face and wrists with disinfecting wipes. Besides this, it was required that the participant and the researcher wore a mask during the entire session.

Then, a brief introduction explaining the objectives of the study, and how the evaluation session was going to be conducted was presented to the user. After this, the user was asked to fill the Demographic Questionnaire and an Immersive Tendencies Questionnaire, both explained in section 4.2.4.A.

After collecting participants' information, we asked the participant to put on two smartwatches, one on each wrist, and to adjust them in order to be tight and comfortable to the wrist. Then, we introduced the participant to the headset, and helped him/her adjusting the equipment to their heads, and calibrating the eye-tracker.

Also, before the starting of the walks that were analyzed, it was allowed for the participant to have two moments of **familiarization** with the headset and the VE. Firstly, in the *VIVE Home*, which is the starting point environment for every experience, the participant was encouraged to walk freely and to notice the **boundaries** that became visible when the end of the play area was closer. After the participant was confident that it was safe to walk without hitting a wall or an object, we let them explore the VR street without any external stimulus, for a maximum of five minutes. Once again, it was shown, to the participant, that as soon as a real world object started to became near, a green boundary appeared in the simulation.

This was an important step, in order to minimize participants' fear of walking while using VR and to maximize the validity of our gathered data regarding gait.

4.2.5.B Walk Trials

After these firsts moments of data collection and familiarization with the study, we entered the core phase of this study in which the participant had to performed 5 different walks. The distant walked during each, was about 5 meters.

The study started by a trial with no stimulus, where baseline measures of participants' gait parameters were captured (i.e., cadence, step length, and velocity) and fed into the system for personalized stimuli.

Each of the following 4 trials had presented the previously described stimuli (in section 4.2.3) to the participant. Each of them had followed a specific protocol that was transversal to them all. First, the researcher presented the stimuli that was going to be used and gave time for any question that the participant may want to ask. Participants were then, asked to walk in a **straight line** towards the crossing light at the end of the scene (5 meters), and informed that the trial would stop when they were close to reaching it.

Then, in order to ensure the correctness of the gathered eye data, an **eye-tracking calibration** was performed.

After this, and if the participant was ready to start the trial, the researcher began the simulation and started counting the **number of steps** that the participant was taking, in order to introduce that number, after the simulation was ended, in the mobile application. During the simulation, **gait parameters** (i.e., cadence, step length, and velocity) and **eye-tracking data** (i.e. hits and dwell time) were captured.

Finally, after the participant had walked for 5 meters, and the simulation has ended, it was asked for the participant to remove the headset, put it on a table, and to sit in front of the computer in order to fill three different forms, that aimed to evaluate the experience with that respective stimulus. These were:

a **SUS**; a **Nasa-TLX**; and a **Stimulus' Usability Survey**. All of these were explained in section 4.2.4.A.

4.2.5.C Final Debrief and Session Closing

After the participant had finished performing the walks and filled the correspondent questionnaires, it was asked to answer 3 more questionnaires regarding the overall experience with the simulation and the stimuli. The first one was a **Ranking Survey**, followed by an **IPQ**, and a **VR scene questionnaire**. Once again, a more detailed explanation of these 3 forms can be found in section 4.2.4.A.

After the participant had completed all the final questionnaires, the researcher thanked the participant for the time spent and invited him/her to leave the room.

After the participant left the room, all the materials used during session (i.e. computer, smartwatches, headset, table and chairs) were **thoroughly disinfected**, with an alcohol solution with at least 70% alcohol.

4.3 Results

In this section we present and analyse the results obtained after the performance of the previously explained study.

We will start by characterizing the participants that performed the study. This will be followed by an analysis and interpretation of the results from each metrics, presented in section 4.2.4. Aiming to facilitate this analysis, we will divide it into 3 main subsections, where each of the metrics will be explore: Gait, Gaze and Usability Results.

4.3.1 Participants

Our study was performed by 10 different participants, however, only 8 of them were included in our analysis (the first 8). The reason behind this, relies on the fact that, as explained before, our study followed a balanced square design, needing 4 participants to complete one of these matrices. Therefore, in order to not leave a square half concluded, we had only used **8 participants**. From these, 6 had already been enrolled in our preliminary study.

Since all participants had given us **consent** to collect and use their data for scientific purposes, their profile is shown in table 4.2. This data was collected, as explained before, through a demographic questionnaire (presented in Appendix B), where demographic and other questions with interest to the study were asked.

Therefore, participants were all, except one, between 18 and 25 years old (*M* = 25.50; *SD* = 8,99); and the majority were students (75.0%). Using a 5-point Likert scale, participants reported being some-

ID	Age	Gender	Occupation	Height	Consent	Comfort with VR	VR Experience Context	Comfort with SmartWatch	ITQ
P01	22	Male	Student	183	YES	3	Games	4	95
P02	23	Female	Student	180	YES	4	University	3	120
P03	24	Male	Student	175	YES	3	Games	5	112
P04	18	Female	Student	163	YES	1	X	3	113
P05	50	Female	Worker	167	YES	1	X	2	100
P06	25	Male	Worker	177	YES	2	University	4	103
P07	21	Male	Student	165	YES	2	University	5	121
P08	21	Male	Student	180	YES	4	Other research	5	106
M	25,50			173,75		2,50		3,88	105,40
SD	8,99			7,69		1,20		1,13	8,47

Table 4.2: Participants' Characterization.

what comfortable with **VR technologies** (*M* = 2.50; *SD* = 1.20); only two (25%) of them did not feel comfortable with it, since they had never had any experience with this technology. In addiction, when asked about in what context had they previously interacted with VR, most of the participants (37.50%) stated that it was through University courses; 37.5% of them had already used it for entertainment/games purposes; Other researches was appointed by 12.50% of the participants as their source of prior interaction with VR.

Regarding, **smartwatches**, also using a 5-point Likert scale, participants reported being quite comfortable with these (*M* = 3.88; *SD* = 1.13).

Apart from this more personal information, as explained previously, before the start of the study, participants had also answered an ITQ (presented in Appendix **??**). The analysis of this was done, following Witmer and Singer [96] recommendations, as a single scale. This means that the score generated for each participant was the sum of the scale responses for each question item, except for items 19 and 24 ("Are you easily disturbed when working on a task?" and "To what extent have you dwelled on personal problems in the last 48 hours?", respectively) where the score required to be reverse – this was done by subtracting the score given by the participant from 8. In addiction to this, items 11 and 12 ("On average, how many books do you read for enjoyment in a month?" and "What kind of books do you read most frequently?", respectively) were not included in the results' analysis, since the type of data (categorical data) and information produced by them was not appropriate nor relevant for our research.

The results obtained from this questionnaire, are also presented in table 4.2. The bigger the value the more the patient had the tendency to be immersed. The scale (participants' answer to each question) had a satisfactory level of internal **consistency**, as determined by a ***Cronbach's alpha*** of 0.708.

4.3.2 Gait Results

In this section we present the results regarding gait. To facilitate their analysis, we had separated them by gait metrics (step length, cadence, velocity). For each of these metrics it was generated a boxplot

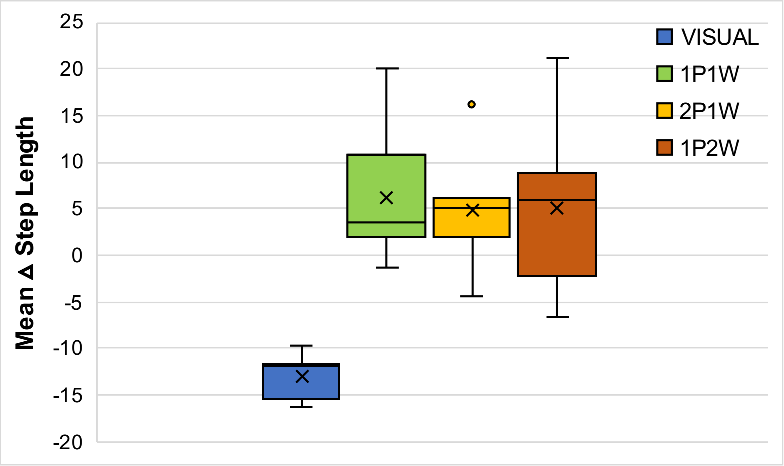


Figure 4.1: Step Length mean variation between baseline and each condition walks (ΔStep Length). Statistically significant changes from baseline were found during visual and Haptic 1P1W. One outlier (id = 2) in condition 2P1W was identified.

where the mean variation, between baseline and each condition walks, was compared.

In order to fully analyse them, each metric's result was evaluated in two different moments:

Firstly, it was performed a comparison between baseline and each metric's results, through the usage of **paired-samples t-test**, in order to understand whether the differences (increases and decreases from baseline, during the usage of each stimulus) observed in the boxplot were statistically significant.

Secondly, we had also performed a comparison between each cue condition. In other words, we had examined whether the variations from baseline between conditions were statistically significant. This analysis was performed though the usage of an **one-way repeated measures Analysis of Variance (ANOVA)**.

The first part of this test consisted on evaluating whether our data had any outliers and if it was normally distributed. Outliers were detected through the **boxplot**, and any data point that was more than 1.5 box-lengths from the edge of their box was classified as one. The way we dealt with this, rely on modifying the outlier by replacing its value with the next largest/smallest value instead.

To determine whether our data was normally distributed we had used **Shapiro-Wilk test of normality** [97].

Finally, we had run a **post hoc test** with a **Bonferroni** adjustment [98] to search for significant differences, when comparing all possible combinations of the tested conditions' variation.

All of this, was performed through the usage of Statistical Package for the Social Sciences (SPSS) software.

4.3.2.A Step Length

Step length results are presented in fig. 4.1, and as it can be seen, the mean step length **decreased** during the visual condition (M = -12,23 and SD = 0,03) and **increased** during the Haptic ones, when comparing to the baseline condition.

In order to understand whether these step length's differences from baseline were statistically significant, we had performed a **paired-samples t-test**. From this analysis, we examined a **statistically significant decrease** from baseline during visual condition (t(7) = 15.97, *p* = 0.003), and a statistical significant increase (t(7) = 2.527, *p* = 0.039) during Haptic 1P1W. Regarding the others Haptic conditions (Haptic 2P1W and Haptic 1P2W), although it was observed an increased of the mean step length from the baseline value during its usage in both cues, no significant differences were found.

In addiction to this, a one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in the participants' step length's variation between each tested condition. In other words we had compared **ΔStep length** (variation between Baseline and the correspondent walk) across conditions.

During this analysis, there was an identification of an outlier (figure 4.1) and the data was normally distributed (assessed by Shapiro-Wilk test ($p > .05$)). In addiction to this, from **Mauchly's test** of sphericity, we concluded that the assumption of sphericity was not violated, $\chi 2(2) = 3.01$, $p = 0.70$.

Regarding results' significance, we had examined that step length statistically significant changed between conditions, F(3, 21) = 19.20, $p < .0005$, partial $\eta 2 = 0.733$.

Finally, Post hoc analysis with a Bonferroni adjustment revealed that step length was statistically significantly decreased during visual condition when comparing to any of the Haptic cues. In fact, there were four significant comparisons that we had taken into account:

- **Visual – Haptic 1P1W**: When comparing, step length during visual cues and step length during Haptic 1P1W there was a decrease from 48.63 ± 2.31 cm to 29.51 ± 0.76 cm during visual, a statistically significant decrease of 19.12 (95% CI, 11.60 to 26.63) cm, $p < .001$.
- **Visual – Haptic 2P1W**: When comparing, step length during visual cues and step length during Haptic 2P1W there was a decrease from 47.43 ± 2.65 cm to 29.51 ± 0.76 cm during visual, a statistically significant decrease of 17.92 (95% CI, 9.87 to 25.96) cm, $p < .001$.
- **Visual – Haptic 1P2W**: When comparing, step length during visual cues and step length during Haptic 1P2W there was a decrease from 47.52 ± 3.10 cm to 29.51 ± 0.76 cm during visual, a statistically significant decrease of 18.01 (95% CI, 8.31 to 27.71) cm, $p = 0.002$.
- **Haptic – Haptic**: Any comparison between haptic cues, regarding step length, did not led to any statistically significant results, since *sig* > .05.

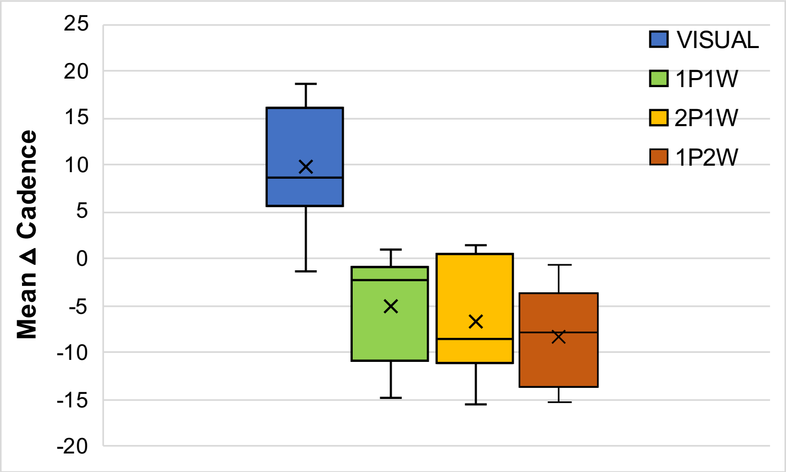


Figure 4.2: Cadence Mean variation between baseline and each condition walks. Statistical significant changes were found when comparing each condition to baseline. No outlier was identified.

4.3.2.B Cadence

Cadence results are presented in fig. 4.2, where cadence's mean variation between baseline and each stimuli walk is presented **(Δcadence)**.

In these, it can be seen that there was an increase in cadence during visual cues and a decrease during the haptic ones, when comparing to the baseline condition. In order to understand whether these cadence's differences from baseline were statistically significant, we had performed a **paired-samples t-test**. From this analysis, we examined a statistically significant **increase** during **visual condition**, t(7) = 4.135, p = 0.004, in contrast with a statistically significant decrease during every haptic trials (t(7) = 2.506, p = 0.041; t(7) = 3.055, p = 0.018; and t(7) = 4.482, p = 0.003; corresponding to Haptic 1P1W, Haptic 2P1W and Haptic 1P2W, respectively).

Similar to the analysis of step length, we had conducted a one-way repeated measures ANOVA, to investigate whether the variations of cadence between stimulus' conditions were statistically significant (Δcadence). During this analysis and before any conclusion regarding changes' significance, there were **no identified outliers** (as assessed by the boxplot in figure 4.2), and data was **normally distributed** (assessed by Shapiro-Wilk test (p > .05)). In addiction to this, from **Mauchly's test**, we concluded that the assumption of **sphericity was not violated**, $\chi 2(2) = 8.48$, p = 0.14.

After these, we had examined that cadences' variations between conditions were statistically significant, F(3, 21) = 39.79, p < .001, partial $\eta 2 = 0.85$.

Finally, **Post hoc analysis** with a Bonferroni adjustment revealed that cadence was statistically significantly increased during visual condition when comparing to any of the Haptic cues. In fact, there were four significant comparisons that we should take into account:

- **Visual – Haptic 1P1W**: When comparing cadence during visual and Haptic 1P1W, it was ob-

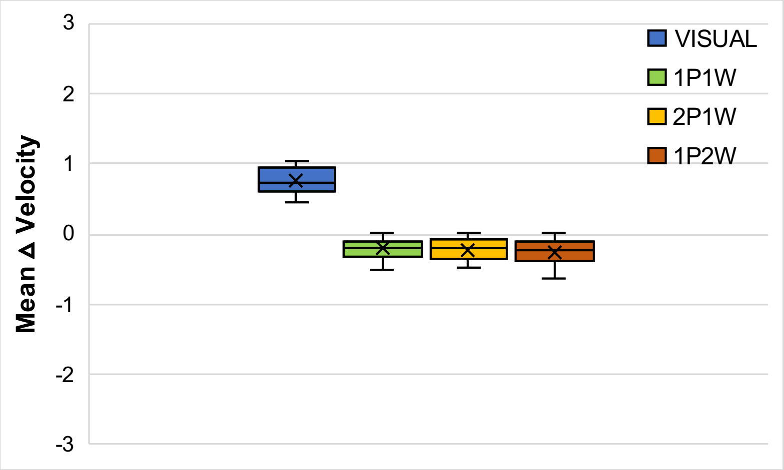


Figure 4.3: Velocity mean variation [m/s] between baseline and each condition walks. A significant increase during visual condition and significant decrease during Haptic conditions (1P1W, 2P1W, 1P2W) were observed. No outlier was identified.

served an increased from 34.79 ± 2.03 steps/s to 49.32 ± 1.48 steps/s during visual condition, a statistically significant increase of 14.56 (95% CI, 4.91 to 24.22) steps/s, $p = 0.006$.

- **Visual – Haptic 2P1W**: Regarding the comparison of cadence between visual condition and during Haptic 2P1W there was an increase from 33.17 ± 1.20 steps/s to 49.32 ± 1.48 steps/s during visual, a statistically significant increase of 16.15 (95% CI, 10.05 to 22.24) steps/s, $p < .001$.
- **Visual – Haptic 1P2W**: The comparison of these two resulted in the observation of an increase from 31.58 ± 1.14 steps/s to 49.32 ± 1.48 steps/s during visual condition, a statistically significant increase of 17.74 (95% CI, 10.11 to 25.35) steps/s, $p = < .001$.
- **Haptic – Haptic**: Any comparison between haptic cues, regarding cadence, did not led to any statistically significant results, since $sig > .05$.

4.3.2.C Velocity

The results regarding the variation of velocity between baseline and each condition tested, are presented in fig. 4.3.

It can be seen that there was an increase on velocity during visual conditions and a decrease during all Haptic conditions, when comparing to baseline values.

In order to understand weather these differences from baseline values were significant, we had conducted a **paired-samples t-test**.

From this test, it was observed a significant velocity increase during visual conditions ($t(7) = 10.478$, $p = 0.001$), in contrast to a significant decrease during Haptic 1P1W, Haptic 2P1W and Haptic 1P2W (respectively, $t(7) = -3.702$, $p < 0.001$; $t(7) = -3.82$, $p = 0.006$; $t(7) = -3.66$, $p = 0.009$).

Besides this analysis comparatively to the baseline, we had also compared participants' velocity variation (∆velocity) across conditions, through an **one-way repeated measures** ANOVA.

During this evaluation there were **no identified outliers** (as assessed by the boxplot in figure 4.3), and data was **normally distributed** (assessed by Shapiro-Wilk test ($p > .05$)). In addiction to this, from **Mauchly's test**, we concluded that the assumption of **sphericity was not violated**, $\chi 2(2) = 8.497$, $p = 0.136$.

Subsequently, we had examined if the Velocity's variations between conditions were statistically significantly different, F(3,21) = 77.54, $p < 0.001$, partial $\eta 2 = 0.917$.

In fact, from **post hoc analysis** there were four significant comparisons that we should take into account:

- **Visual – Haptic 1P1W**: When comparing the variation of velocity during visual and Haptic 1P1W, it was observed an increased from 0.73 ± 0.05 m/s to 1.69 ± 0.08 m/s during visual condition, a statistically significant increase of 0.97 (95% CI, 0.65 to 1.27) m/s, $p < 0.001$.
- **Visual – Haptic 2P1W**: During visual cues it was observed an increased from 0.72 ± 0.05 m/s to 1.69 ± 0.00 m/s, a statistically significant increase of 0.98 (95% CI, 0.69 to 1.26) m/s, $p < 0.001$.
- **Visual – Haptic 1P2W**: During visual cues it was observed an increased from 0.68 ± 0.05 m/s to 1.69 ± 0.00 m/s, a statistically significant increase of 1.01 (95% CI, 0.59 to 1.43) m/s, $p < 0.001$.
- **Haptic – Haptic**: Any comparison between haptic cues, regarding velocity, did not led to any statistically significant results, since *sig* > .05.

4.3.2.D Steps, Time and Distance

Beside these main metrics, we had also taken into account the amount of steps, distance and time required to perform each walk, since these factors were the ones influencing Step length, cadence and velocity.

The results regarding the mean variation of these factors between baseline and each tested condition, are presented in table 4.3. In this, we can see that the **distance** walked during all conditions and the **amount of time** needed to perform each of these walks, were quite similar, however, the total **amount of steps** taken during visual condition seem to had increased when comparing to any of the haptic cues.

Therefore, in order to understand whether these variations were statistically significant, we had performed an one way repeated measures ANOVA. From this, and as expected, there were no significant differences regarding the distance walked and the amount of time needed, between baseline and each condition, and between each condition.

	Visual	1P1W	1P2W	2P1W
Steps	4.25 (0.71)	-0.25 (1.67)	-0.625 (1.06)	-0.75 (1.28)
Distance [m]	-0.09 (0.28)	-0.14 (0.26)	0.21 (0.42)	0.19 (0.36)
Time [s]	1.71 (3.52)	1.87 (3.79)	1.89 (3.64)	2.52 (2.82)

Table 4.3: Mean variation of number of steps, walked distance and time, between baseline and each tested condition. Standard error is presented in brackets. Negative values represent a decrease from the mean baseline value.

On the other hand, the differences regarding the amount of steps taken during visual cues, were considered statistically significant when compared to baseline and all the haptic cues. In fact, this was an increase of 4.25 (95% CI, 3.24 to 5.25) steps/s, $p < 0.001$, from baseline condition; 4.5 (95% CI, 2.68 to 6.32) steps/s, $p < 0.0005$, from 1P1W condition; 4.88 (95% CI, 3.27 to 6.48) steps/s, $p < 0.0005$, from 2P1W condition; and 5.0 (95% CI, 3.06 to 6.94) steps/s, $p < 0.0005$, from 1P2W condition. In addiction to this, no significant difference was found when comparing haptic conditions.

Therefore, during Visual cues, participants tended to take more steps in order to walk the same distance in the same amount of time, which explain the decrease of step length and the increase of cadence during this condition.

4.3.3 Gaze Results

Gaze results can be seen in figs 4.4 and 4.5.

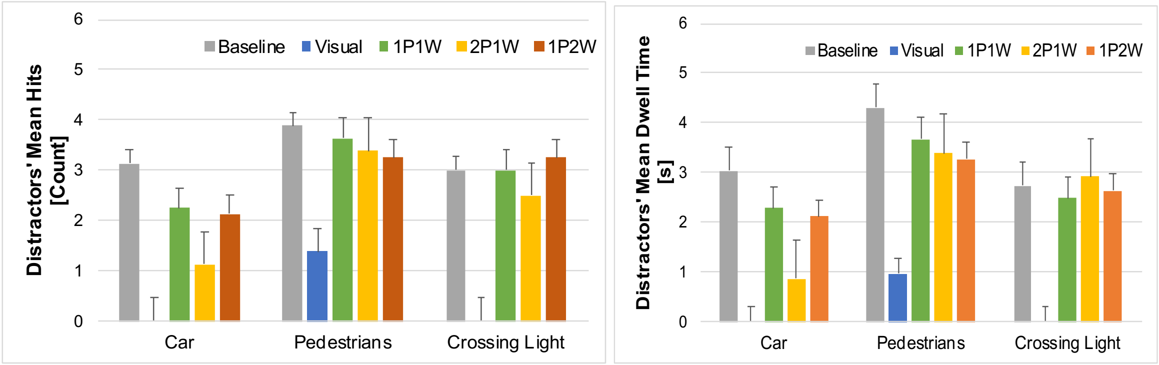
In order to present and analyse these, we had divided them into two different subsections, depending on the type of element to which it referred - **Distractors** or **Non-distractors**. As explained before, distractors elements were objects that had some kind of movement - a car passing by, another pedestrian walking and a crossing light changing. The non distractors elements were static elements that were always presented on the street - the floor, crosswalk, buildings and trees.

We had measured the number of hits and dwell time at each of those elements during the different conditions. And in order to determine whether these difference were statistically significant we had also used a one-way repeated measures ANOVA.

4.3.3.A Distractors

The results regarding the distractors elements' hits and dwell time are presented in fig. 4.4.

These results show that during visual condition it was not detected any look (hit) to the car nor to the pedestrian's crossing light, indicating that participants were not aware of these distractors at all. However, the other pedestrian was the element that was most looked at. These results are correlated with the ones presented in table 4.7, where participants stated that the car and traffic light were the elements that were least noticed, whereas the other pedestrian was more often looked at.



(a) Mean gaze hits across conditions for each of the distractors.

(b) Mean gaze dwell time across conditions for each of the distractors

Figure 4.4: Mean gaze results across conditions (and baseline) for each of the three distractors - Car, Pedestrians and Crossing Light.

Besides this more generic analysis, we had conducted one-way repeated measures ANOVA in order to understand whether the difference of the total numbers of hits and dwell time between conditions was statistically difference. We had performed the evaluation of these metrics individually (one ANOVA for hits and another for dwell time).

Firstly, regarding the number of **hits**, there were no outliers and the data was normally distributed, as assessed by boxplot and Shapiro-Wilk test (p > .05), respectively. The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity (χ2(9) = 8.20, p = .534). After these, we had observed that hits' variations between conditions were statistically significant, F(4, 28) = 14.80, *p* < .0005, partial η2 = 0.68. In addiction to this, Post hoc analysis with a Bonferroni adjustment revealed that the count of hits statistically **decreased from Baseline**, **Haptic 1P1W, Haptic 2P1W and Haptic 1P2W condition during visual condition** ((8.63 (95% CI, 6.11 to 11.14), p < .0005); (7.50 (95% CI, 2.87 to 12.40), p = .003); (5.63 (95% CI, 0.35 to 10.89), p = .036) and (7.25 (95% CI, 2.02 to 12.40), p = .008), respectively). In other words, participants, during visual conditions looked significantly less times to the distractors elements, when compared to baseline or when using any other stimulus. In addiction to this, no significant difference was found when comparing haptic conditions with baseline.

Regarding **dwell time**, there were also no outliers and the data was normally distributed, as assessed by boxplot and Shapiro-Wilk test (p > .05), respectively. The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity(χ2(9) = 4.07, p = .812). After these, we had examined that dwell time variations between conditions were statistically significant, F(4, 28) = 24.90, *p* < .0005, partial η2 = 0.78. Similarly to the hits analysis, Post hoc tests with a Bonferroni adjustment revealed that the count of dwell time at the distractors elements also statistically **decreased from Baseline**, **Haptic 1P1W, Haptic 2P1W and Haptic 1P2W condition during visual condition** ((9.14 (95% CI, 5.53 to

12.74), p < .0005); (7.48 (95% CI, 3.82 to 11.13), p < .0005); (6.22 (95% CI, 2.36 to 10.08), p = .003) and (7.06 (95% CI, 2.23 to 11.89), p = .006), respectively). In addiction to this, no significant difference was found when comparing haptic conditions with the baseline.

4.3.3.B Non-Distractors

The results regarding the non distractors elements' hits and dwell time are presented in fig 4.5.

Through those plots, it is observed that during visual cues, similarly to what happen with the distractors elements, participants did not noticed (i.e. looked) at some of these elements - buildings and trees. It was also quite noticed that floor's dwell time was much higher than the correspondent number of hits.

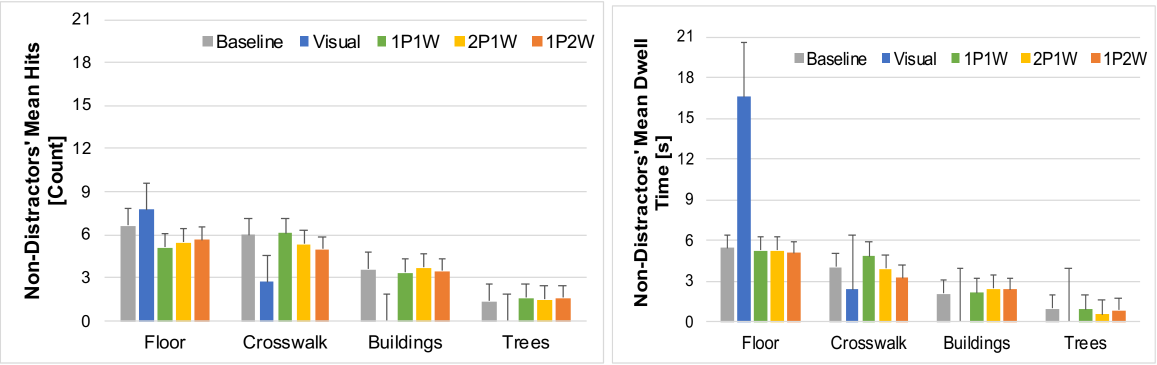
Besides these noticeable aspects, the others non-distractors elements seemed quite even across conditions, and for that, in order to understand whether the difference of the number of hits and dwell time between conditions was statistically different, we had conducted an one-way repeated measures ANOVA. Similarly to the distractors elements, the evaluation of these metrics was performed individually.

Regarding the number of **hits**, there were no outliers and data was normally distributed, as assessed by boxplot and Shapiro-Wilk test (p > .05), respectively. The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity ($\chi2(9) = 7.62$, p = .592). In addiction to this, Post hoc analysis with a Bonferroni adjustment revealed that the count of hits at the non distractors elements was statistically different across conditions, F(4, 28) = 4.90, *p* = .004, partial $\eta2 = 0.41$. In specific, hits' mean number had significant **decreased** from Baseline and Haptic 2P1W during visual condition, (8.88(95% CI, 0.11 to 17.64); 7.37(95% CI, 2.81 to 11.94), respectively). Besides this, no other significant differences were found, specifically regarding the comparison between haptic cues and baseline.

Regarding the **dwell time**, once again there were no outliers and data was normally distributed, as assessed by boxplot and Shapiro-Wilk test (p > .05), respectively. The assumption of sphericity was not violated, as assessed by Mauchly's test of sphericity ($\chi2(9) = 4.64$, p = .872). Post hoc tests with a Bonferroni adjustment revealed that the dwell time at the non distractors elements was statistically different across conditions, F(4, 28) = 9.73, *p* < .0005, partial $\eta2 = 0.58$. In fact, the mean dwell time had significant **increase** during visual cues when comparing to Baseline, Haptic 2P1W and Haptic 1P2W (6.60(95% CI, 0.16 to 13.04), 6.91(95% CI, 0.26 to 13.55), 7.47(95% CI, 1.88 to 13.05), respectively). Once again, it is important to highlight that no other significant differences were found, specifically regarding haptic cues and baseline.

4.3.4 Usability Results

Besides these quantitative metrics, as explained before (see section 4.2.4.A), during the study, we had also conducted some questionnaires, regarding usability, usage and workload of VR and the selected stimulus. In the following subsections, the result of those are presented.



(a) Mean gaze hits across conditions for each of the non distractors elements.

(b) Mean gaze dwell time across conditions for each of the non distractors elements

Figure 4.5: Mean gaze results across conditions (and baseline) for the non distractors elements - Floor, Crosswalk, Buildings and Tree.

4.3.4.A Usability

SUS' results are presented in table 4.4. As a reminder, this questionnaire consisted on a 10-item questionnaire scored on a 5-point Likert scale from 0 (strongly disagree) to 5 (strongly agree). For that, in table 4.4, we present the mean answer and standard deviation for each item during the different conditions.

Before any deeper analysis regarding this data, we had conducted a **Cronbach's alpha** test in order to measure the internal consistency and reliability of this data. For that, firstly we had to arranged participants' answers to contribute in the same manner for the scale. In other words, since the items of this questionnaire alternate between a positive and a negative tone, we had reverse the questions' answer codes of items 2, 4, 6, 8, and 10 so all scales had 1 as the negative and 5 as the positive. This Cronbach's alpha test was performed for each tested condition, which had resulted in the observation of an alpha higher than 0.700, as recommended by DeVellis [99], across all conditions. Specifically, visual, Haptic 1P1W, Haptic 2P1W, Haptic 1P2W had resulted on alpha values of 0.702, 0.806, 0.746, 0.770, respectively.

Regarding SUS Final Score, presented in the bottom of table 4.4, there was a clear preference for the haptic cues relying on a simple vibration pattern played over one or two smartwatches - 1P1W and 1P2W - (well above the average SUS score of 68). On the other hand, Visual cues and Haptic 2P1W's scores indicated the existence of an usability issue. In order to understand whether this differences were statistically significantly, we had conducted a **Friedman test**, which had identified this differences as significant, $\chi 2(3) = 21.911$, $p < .0005$.

In addiction to this, pairwise comparisons were performed with a Bonferroni correction for multiple comparisons. SUS final score was statistically significantly different between visual and haptic 1P1W

	Visual	Haptic 1P1W	Haptic 2P1W	Haptic 1P2W
I think that I would like to use this system frequently.	2,25 (0,71)	4,13 (0,35)	3,25 (0,71)	3,50 (0,53)
I found the system unnecessarily complex.	3,88 (0,64)	1,75 (0,46)	2,25 (0,71)	1,25 (0,46)
I thought the system was easy to use.	2,25 (0,71)	4,25 (0,71)	3,63 (0,74)	4,38 (0,52)
I think that I would need the support of a technical person to be able to use this system.	3,5 (0,53)	1,50 (0,53)	2,50 (0,76)	1,25 (0,46)
I found the various functions in this system were well integrated.	3,25 (0,53)	4,25 (0,46)	3,63 (0,52)	4,25 (0,46)
I thought there was too much inconsistency in this system.	2,13 (0,83)	1,75 (0,71)	1,88 (0,83)	1,75 (0,71)
I would imagine that most people would learn to use this system very quickly.	2,13(0,83)	3,88 (0,83)	3,38 (0,52)	4,13 (0,35)
I found the system very cumbersome (clumsy) to use.	3,75 (0,46)	1,88 (0,76)	2,88 (0,64)	1,75 (0,46)
I felt very confident using the system.	1,75 (0,46)	4,00 (0,76)	3,13 (0,83)	4,00 (0,53)
I needed to learn a lot of things before I could get going with this system.	2,38 (0,74)	1,50 (0,53)	3,63 (0,52)	1,5 (0,53)

Cronbach's alpha	0,702	0,806	0,746	0,770
Final SUS Score	40,00 (4,81)	80,31 (3,88)	58,75 (5,51)	81,88 (3,20)

Table 4.4: SUS results. Each row correspond to the mean answer for each question. In the bottom of the table it is presented the SUS final score and the Cronbach's alpha regarding each condition.The correspondent standard deviation is in brackets

	Visual	Haptic 1P1W	Haptic 2P1W	Haptic 1P2W
I found the stimulus easy to use.	2,65 (0,74)	4,38 (0,52)	3,75 (0,71)	4,50 (0,53)
I felt comfortable while using the stimulus.	2,62 (0,52)	4,63 (0,52)	3,88 (0,99)	4,50 (0,53)
I felt annoyed while using the stimulus.	3,25 (0,71)	1,25 (0,46)	1,88 (0,83)	2,38 (1,06)
I found the stimulus simple and easy to understand.	3,5 (0,93)	4,50 (0,53)	4,13 (0,64)	5,00 (0,00)
I found the stimulus useful.	2,75 (0,71)	4,13 (0,64)	3,75 (0,88)	3,88 (0,83)
I felt distracted by the stimulus.	4,00 (0,76)	1,63 (0,52)	2,63 (1,19)	1,75 (0,71)

Table 4.5: Stimulus' Usability results. Participants' mean answers for each question are presented, the correspondent standard error is in brackets. As a reminder, each of these questions had five response options (from 1 to 5, where 1 - strongly disagree and 5 - strongly agree).

(p = 0.001) and visual to haptic 1P2W ($p < 0.0005$). However, once again there were no statistically significant differences between haptic conditions.

These results were further corroborated by the results from the stimulus' usability questionnaire, presented in table 4.5. In this, we found some reasons for the discrepancies regarding SUS Final Score, in terms of annoyance, comfort, usage ease, simplicity and usability.

- About **stimulus' usage ease**, after conducting a Friedman test we had observed a statistically significantly difference between conditions ($\chi2(3)$ = 15.806, p = 0.001). In fact, it was observed a significant preference for Haptic 1P1W and Haptic 1P2W when comparing to visual condition (p = 0.016 and p = 0.008, respectively). Although during Haptic 2P1W condition, the mean score was also bellow Haptic 1P1W and Haptic 1P2W, the difference between them was not significant. Besides, it is important to highlight that no significance was found between Haptic cues.
- When asked about how **comfortable** did they felt while using the stimulus, participants tended to give higher classification to Haptic 1P1W and Haptic 1P2W. In fact, when performing the Friedman test we had observed a statistically significant difference between conditions ($\chi2(3)$ = 17.274, $p < 0.005$), specifically a significantly increase when comparing the results from Haptic 1P1W and 1P2W to the results from Visual condition (p = 0.016 and p = 0.006, respectively). Regarding Haptic 2P1W, its comparison with the others, did not led to any statistically significance result. Besides, it is important to highlight that no significant differences were found between Haptic cues.
- Regarding **annoyance**, after conducting a Friedman test we had observed a statistically significantly difference between conditions ($\chi2(3)$ = 18.409, $p < 0.005$). In fact, participants felt significantly more bothered by visual stimulus, than by Haptic 1P1W and Haptic 2P1W (p = 0.001 and p = 0.030, respectively). Despite the fact that Haptic 1P2W's score, regarding annoyance, was also lower than visual's, it did not led to a statistically significant difference. Besides, it is also important to highlight that no significant differences were found between Haptic cues.
- Concerning the **ease of understanding** each stimulus, after the performance of the Friedman test, it was observed a statistically significantly difference between conditions ($\chi2(3)$ = 14.455, p = 0.002). In fact, Haptic 1P2W was the stimulus appointed by the participants as the most easy to understand, and visual as the hardest to understand. The difference between these two was considered as statistically significant (p = 0.012). Regarding the others conditions (Haptic 1P1W and Haptic 2P1W), although they were considered to be more easy to understand than the visual cues, its differences were not considered to be significant. Besides, it is also important to highlight that no significant differences were found between Haptic cues.
- When inquired about how **useful** did participants found each stimulus, after performing a Friedman test, it was observed a statistically significantly difference between conditions ($\chi2(3)$ = 14.474, p

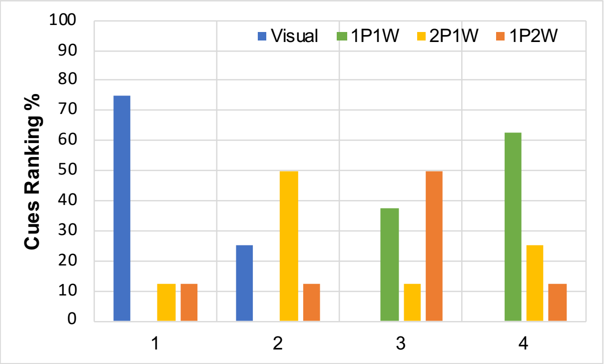


Figure 4.6: Cues Ranking results where the percentage of participants for each preference rank per condition is represented. **Key:** 1 - least favourite; 4 - most favourite.

= 0.002). In fact, participants significantly found Haptic 1P1W more useful than visual cues (*p* = 0.012). Besides this, no other comparison was considered significant.

- Finally, concerning how **distracted** did participants felt while using each stimulus, participants assigned a higher classification to visual cues (M = 4.00, meaning that they felt quite distracted by it), and lower score to the Haptic stimulus, in particularly to Haptic 1P1W (M = 1.63) and Haptic 1P2W (M = 1.75). After performing a Friedman test, we had observed a statistically significantly difference between conditions ($\chi 2(3)$ = 17.031, $p < 0.005$). In fact, participants felt significantly more distracted by visual cues than by Haptic 1P1W (*p* = 0.008) and visual to Haptic 1P2W (*p* = 0.008). Besides this, no other comparison was considered significant.

In addiction to this, these results were also in agreement with the conclusions taken from the preference rankings (through the rank questionnaire) presented in figure 4.6, where 75% of the participants had considered **visual** cues as their **least favourite**. In order to justify their answers, participants had made the following affirmations: "Distrai demasiado, estava mais preocupado em pisar as linhas do que a sentir que estava a andar." (It distract too much, i was more worried in stepping the lines, rather than feeling that i was walking), "Só vi o chão." (I only saw the floor), "Foi preciso pensar mais" (I needed more brain power), "Foi, para mim, o menos natural" (It was the least natural, for me).

On the other hand, the **most favourite** cue was assigned to the **Haptic 1P1W**, by 62,5% of the participants. To explain their choice, the following statements were made: "Muito intuitivo e simple" (Very intuitive and simples), "aprende-se rápido e quase que parecia natural" (It was easy to learn, and felt natural).

4.3.4.B Workload

Regarding the **workload** experienced by the participants during the usage of each stimulus, the results are presented in table 4.6. From these, it was observed an **higher level** of needed workload, during

	Visual	**Haptic 1P1W**	**Haptic 2P1W**	**Haptic 1P2W**
Mental Demand	63,13 (10,67)	18,75 (6,40)	36,88 (4,58)	16,25 (5,18)
Teporal Demand	18,15 (7,99)	10,63 (4,17)	10,00 (4,62)	10,63(4,17)
Physical Demand	17,50 (6,55)	10,00 (4,63)	10,00 (3,78)	11,88 (8,43)
Performance	66,88 (10,67)	11,88 (5,94)	15,00 (7,56)	13,13 (4,58)
Effort	58,75 (8,35)	13,13 (7,04)	23,75 (5,18)	11,25 (4,43)
Frustation	27,50 (7,56)	6,25 (2,31)	18,13 (5,30)	13,13 (5,30)
Mean Workload	41,98 (1,69)	11,77 (4,13)	18,96 (10,21)	12,71 (2,00)

Table 4.6: Raw Nasa-TLX results where it is presented the means, standard deviation (in brackets) for each workload factor across the different stimuli. The last raw exhibit the total amount of workload needed during the usage of each stimulus.

visual condition (M = 41.98; SD = 1.69), and an **inferior value** during haptic cues, in particularly, during **Haptic 1P1W** and **Haptic 1P2W** (M = 11.77; SD = 4.13, and M = 12.71; SD = 2.00, respectively). In fact, when comparing the results from these two Haptic conditions with visual, through the usage of **Friedman test**, there was a statistically significant increase during the last one ($p = 0.001$ and $p = 0.012$, respectively). In order to understand these changes, we should take into account each evaluated factor individually:

- **Mental Demand**. This factor evaluated how much mental and perceptual activity was required by the participants in order to perform the walk, while using each condition. The results showed a significant increase of this factor during visual condition (M = 63.13; SD = 10.67), when comparing to Haptic 1P1W (M = 18.75; SD = 6.40; $p = 0.001$) and to Haptic 1P2W (M = 16.25; SD = 5.18; $p = 0.001$). Haptic 2P1W's value (M = 36.88; SD = 4.58) was also quite higher than the others two haptic conditions, however, this difference was not significant ($p > 0.05$). Besides, no significant differences were found when performing comparisons between haptic cues.

- **Temporal Demand**. This factor evaluated how much time pressure did participants felt during each walk trial. The results were quite similar, across conditions and no significant comparison between them was found ($p > 0.05$, in every comparison).

- **Physical Demand**. This factor evaluated how much physical activity was required in order to perform each walk. Similarly to the results from temporal demand, these were also quite similar, across conditions and no significant comparison between the conditions was found ($p > 0.05$, in every comparison).

- **Performance**. This factor examined how successful did the participants felt during each walk with the stimulus (higher response's values correspond to a more deficient performance). The results revealed significant higher values during visual condition (M = 66.88; SD = 10.67), when comparing

	Mean Score (1 to 5)	Std. Dev	Mode
I found the experience of walking on the virtual street real.	3,38	0,74	3
I found the street real.	3,63	0,52	4
During the simulation, I felt that my body belonged to me.	4,75	0,46	5
How often did you notice the car passing by you?	2,75	1,04	3
How often did you notice the other pedestrian?	4,5	0,53	5
How often did you notice the pedestrian's traffic light turning red to green?	2,25	1,16	2

Table 4.7: VR usability results where participants opinion regarding the VR simulation is presented.

to any of the Haptics (p = 0.006; p = 0.03; p = 0.008, corresponding to Haptic 1P1W, Haptic 2P1W and Haptic 1P2W). Regarding Haptic comparisons, the results were quite similar, leading to no significant differences.

- **Effort**. This factor evaluated how hard did the participant had to work (physically and mentally) in order to accomplish the level of performance. Regarding the results, similarly to the Mental demand factor, it was observed a significant increase of effort during visual cues (M = 58.75; SD = 8.35) when compared with the same value during Haptic 1P1W (M = 13.13; SD = 8.35) and Haptic 1P2W (M = 11.25; SD = 4.43; p = 0.001, in both of the comparisons). Haptic 2P1W's value was also higher than the others two haptic conditions, however, this difference was not significant (p > 0.05).

- **Frustration**. This factor assessed how irritated, stressed, and annoyed were the participants while performing the walk with each stimulus. These results were quite low for every tested condition, however, it was observed a significant higher value during visual condition (M = 27.50; SD = 7.56) when compared to Haptic 1P1W (M = 6.25; SD = 2.31; p < 0.005). No other significant difference, across conditions, was found.

4.3.4.C VR and Presence

Regarding the usage of **VR**, we had collected participants' opinions about it, through the questions presented in table 4.7. As a result, we found out that, on a scale from 1 to 5 (where 1 is totally disagree and 5 is totally agree), participants found the street (M = 3.38; SD = 0.74) and the experience of walking in it (M = 3.63; SD = 0.52) quite real. Besides this, participants were more often aware of the other pedestrian, than the other two distractors - Car (M = 2.75; SD = 1.04) and the changes on the traffic light (M = 2.25; SD = 1.16).

In addiction to these usability results, other factor that is related to the usage of VR, is the sense of **presence** in the VE. This feeling was measured through the IPQ, resulting on a mean feeling of presence of 62.25 (SD = 7.07). These results were evaluated by the **Cronbach's alpha** test, in order to test the internal consistency and reliability of the data, resulting on an high internal consisting, α= 0.800.

Besides this individual analysis of the IPQ, we had run a **Pearson's product-moment** correlation to assess the relationship between ITQ and IPQ results. Although preliminary analyses showed the relationship to be linear with both variables normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$), there was no statistically significant correlation between them, $r(6) = 0.092$, $p = 0.829$.

4.3.5 Results' Discussion

From the performance of our VR field study we had evaluated the effects of different visual and haptic stimuli on participants' gait, attention and usability metrics. The sum up of these results is represented in table 4.8. However, in order to understand those, we had compared them with similar previous works and, analyse and justify them in an auto-critical way. We will start with the gait results, followed by the attention results, and finalizing with the usability results.

4.3.5.A Gait

During gait analysis we had evaluated the effects of using the different cues in participants' step length, cadence and velocity, across conditions.

A – Visual Cues

During **visual condition** it was observed a significant decrease of **step length**, and a significant increase of cadence, when compared to the baseline walk, contrary to what was observed in previous works [2, 13, 17, 100]. On the other hand, it was observed a significant increase of velocity, similarly to what demonstrated in previous works [17, 55, 100]. Although all of these metrics are important in order to understand the impact of the cues, we should bare in mind that form the state of the art, visual cues, were appointed to be effective in improving patients' gait parameters in particularly the spatial ones (step and stride length). Therefore, although our cadence's results are quite important, we should particularly focus on the step length discrepancies observed.

In order to understand the reason behind this decrease we should take under consideration the formula that was used to compute this metric: $StepLength = distance/\#steps$. From the previous presented analysis we had observed that although the distance walked during visual cues was quite similar to the baseline walk, the **number of steps** taken in order to perform the walk did **significantly increase**. In fact, it was quite notorious during the conduction of the study that participants seemed to take more and shorter steps during the usage of visual cues. Therefore, this increase of the number of steps was the direct cause for this step length decrease.

With the purpose of presenting explanations for this increase regarding the number of steps taken during visual condition, we took into account 2 different factors:

1. **Healthy participants and VR**. From the fact that our participants did not had any gait disorder (i.e. Parkinson's disease), would make it easy to hypothesize that they would maintain their gait stability and performance when submitted to VR, in an almost effortless way. However, this was not the case. From previous studies, it was observed that gait instability and gait deterioration is prevalent in the VR environment when examining healthy people gait's effects to this technology [101–103]. On the other hand, and surprisingly, previous studies regarding gait normalization in Parkinson's patients had resulted in improvements in walking abilities when using VR [3, 104, 105]. Therefore, the usage of VR in healthy participants instead of patients with gait disorders (i.e.Parkinson's' patients) may had had an influence regarding the decrease of step length during visual cues.

2. The fact that during simulation participants were **not able to see their feet**, may had also had some influence regarding the increase of the number of steps. However, this hypothesis was considered to be improbable since, Parkinson's patients from previous studies, that had used this technology without an avatar (participant representation in the VE) were still able to significant improvement gait and balance [3, 105].

Besides this deterioration of step length, **cadence** had also been negatively effected (i.e. increased) during the usage of visual cues, which was once again not expected when taking into consideration previous works related to Parkinson's' disease [2, 13]. In order to understand this, we should also take into account the formula that was used to calculate this value: $Cadence = 60 * \#steps/\Delta time$. Taking into account this equation, and the analysis presented in section 4.3.2.D, where it was observed that the time needed to perform the visual trial was quite similar to the baseline (no significant difference), in addiction to a significant increase in terms of # steps taken during visual condition, we may conclude that, once again, it was the increase of the number of steps that had influenced cadence's value (increasing it).

Hypothetical reasons for this increase regarding #steps during visual cues, had already been presented when discussing the effects on step length.

Regarding **velocity**, a significant increase (i.e. improve) was detected between visual condition and baseline, similarly to what demonstrated in previous works [17, 55, 100]. This metric is closely related to step length and cadence variation, in fact from the used formula ($velocity = Cadence/StepLength$) we can observe that velocity is positively correlated with cadence and negatively correlated with step length. Thus, since in our study it was observed a decrease of step length and an increase of cadence, this velocity increase was expected. In addiction to this, it is also important to reinforce the fact that no significant differences were observed regarding the time needed to perform the trial and the walked distance.

Taking all of this into account, and since one of our main objective for using visual cues was to have some kind of related work representation and comparison, we may conclude that, that was not accomplished. However, it is important to bare in mind that our study had diverged from previous ones in many factors: the participants (i.e. healthy), the usage of VR with different elements in it (different from the typical hallway from previous works), the usage of VR bars on the floor (opposed to the typical cardboard bars on the floor), and the distance between visual cues. These factors (one or more) may had had an influence in the performance of participants while using the visual cues.

B – Haptic Cues

Regarding **Haptic cues**, and before getting into any explanation and analysis regarding these results, we should remind that, up to our knowledge, the usage of haptic cues with the objective of gait regulation, had been **little explored** in the past, which makes it hard to find similar studies in order to compare results.

During this study, it was observed significant improvements regarding **step length** (i.e. increase) and **cadence** (i.e. decrease), when compared to baseline.

Firstly, regarding cadences' significant improvements (i.e. decrease), since we had used vibrations played at **-10% of participants' baseline** cadence, it was expected a decrease of this metric, similarly to what observed in previous literature [12, 81]. Besides this, we may also conclude that participants were able to match and adapt their cadence to the one presented by the smartwatches.

Besides this, participants' **step length** had also been improved through the usage of this haptic stimulus, significantly during Haptic 1P1W. Which is also in concordance with previous works [12, 81]. During the others two haptic cues (Haptic 2P1W and Haptic 1P2W), although it was also observed an improvement, it was not considered significant.

Finally, regarding **velocity**, it was detected a significant decrease between all haptic conditions and baseline, which was expected due to the decrease of step frequency, imposed by us [20]. Besides this, we should also take into account two different aspects: firstly, it is important to refer that participants had walked similar distances within the same amount of time (no significant differences). Secondly, since, as explained before, this metric is closely related to cadence and step length, which means that with cadence's decrease and step length's increasing, it would be expected that velocity would decrease too.

C – Gait and VR Field study

One important contribution of this study was the usage of a VR Field study approach. Taking into account all of these previously presented results, and the observed similarities and contrasts with the previous literature, we may infer that although it was quite successfully its usage during haptic cues, this approach may have had an impact on the perception of **visual cues**. This fact, may explain why participants had such a poor performance when comparing to similar state of the art studies.

On the other hand, little difference was noticed when using this study approach with **haptic cues**, when comparing to previous studies. In fact, as explained before, Haptic 1P1W did behave as expected (similarly to the previous works). Which lead us to conclude that in this case, the VR field study was successfully used.

This contrast between the success while using haptic and visual cues, and the uncertainty regarding what was the cause of the gait deterioration during visual cues, makes it quite difficult and unfair to establish a comparison between the obtained results during these two conditions. For that, we did not took into account comparisons between haptic and visual cues (only Haptic – Haptic, Haptic – Baseline and Visual – Baseline).

D – Temporal and Spatial Information

Before the start of this study we had hypothesize that the usage of **spatial and temporal** information together in Haptic stimuli, would have a positive impact in almost every gait parameter, as observed by a previous work in the visual field [3]. However, this was not observed (Haptic 2P1W and 1P2W had not significantly improved step length nor velocity). In addiction to this, none of the comparisons regarding the two types of stimulus, (only temporal (i.e. Haptic 1P1W) and temporal + spatial (i.e. Haptic 1P2W and Haptic 2P1W), had led to significant differences, when gait regulation is concern.

Which may lead us to conclude that the impact on gait's parameters of the usage of an haptic stimulus with spatial and temporal information, does not differ from using only temporal information.

4.3.5.B Attention

After this gait analysis, we should also take into account how did the stimuli influenced participants' **attention and awareness**, especially regarding the surroundings. For that we had used in our VR scene two different types of elements: distractors and non distractors, and measured the number of hits and dwell time at each of those elements.

During **visual cues** it was observed a significant decrease in the number of hits and dwell time at **distractors** elements, when comparing to baseline. In fact, it was not detected any look (hit) to the car nor to the pedestrian's crossing light, which indicates that participants were not aware of these distractors at all. In order to explain this decrease, we had appointed two main reasons. Firstly, the fact that as explained before, participants had some **struggles** coping with this cues, may had led to some extra focus on the visual stimulus. Secondly, the fact that, this cues were presented on the floor, forcing the participants to look down (to the floor), may had also led to a neglection of others events that were happen around them.

Consequently, since participants' attention was mainly directed towards the floor, **non-distractors**' mean dwell time had significantly increased, when comparing to baseline. However, the number of hits had decreased. Meaning that participants had looked less but longer times at the non-distractors elements (i.e. the floor).

	Gait			**Gaze**		**Usability**	
	Step length	Cadence	Velocity	Distractors	Non-distractors	Usability	Workload
Visual	– *	+ *	+ *	– *	+ *	–	+
Haptic 1P1W	+ *	– *	– *	–	–	+	–
Haptic 2P1W	+	– *	– *	–	–	+	–
Haptic 1P2W	+	– *	– *	–	–	+	–

Table 4.8: Sum up of study's results. **Gait and Attention Key:** + means improvement from baseline; – means deterioration from baseline; * means statistically significant difference from baseline; **Usability Key:** + means higher levels when comparing to the the other type of cue (visual/haptic) (not baseline); – means lower levels when comparing to the other type of cue (visual/haptic) (not baseline);

Contrasting to this, during **Haptic cues** no significant differences were found, regarding participants' hits and dwell time at the **distractors** and **non distractors** elements, when comparing to baseline. Meaning that **no evidence** was found about an effect of haptic cues in participants' gaze and attention.

4.3.5.C Usability

Finally, we also took into account the **usability** and **preference** of participants regarding each stimulus.

Although we had used several different questionnaires with the aim of evaluating participants' opinions, the answers were quite consistent when preferring the usage of **Haptic cues**, in particularly 1P1W stimulus, in contrast to the use of **visual cues**. These last ones were appointed by participants as their **least favourite**, difficult to use, difficult to understand, least comfortable, more annoying and distracting.

In addiction to this, regarding the **workload** needed by the participants' when using each stimulus, it was observed the requirement of **higher levels during visual cues** in contrast when using Haptic cues,in particularly, Haptic 1P1W and 1P2W. From this workload evaluation, we had identified that Mental Demand, Performance, Effort and Frustration were the factors that led to this increased during visual cues. Once again, it is important to highlight that participants had some struggles during the usage of visual cues, which may had led to a decrease in terms of usability, preference and an increase of the required workload.

Finally, we had also taken into account how participants felt about the **usage of the VR street**. As an overall, participants' found the street and the experience of walking on it quite real, and felt present in the VE. Regarding this sense of presence, we did not found a correlation between that and the participants' tendency to be immersed (from the ITQ). One reason that can be appointed in order to justify this lack of significance, is the fact that the versions of these used questionnaires (ITQ and IPQ) were different. The ITQ's used version was the second one (with 29 items [95]), however, the IPQ used was a short version of the second version (with only 14 items).

Thus, although there were some clear problems regarding the usage of visual cues, we may conclude that the usage of haptic cues, in particularly Haptic 1P1W, did improve participants' gait while not deteriorating their attention and usability.

5

GaitWear

After the performance of the VR field study, and understanding the effects of each of the studied cues in patients' gait, usability and attention, we had developed a **singleton android wear app** - GaitWear (Figure 5.1(a)). The main reasons for this, relied on two different aspects. Firstly, as explained before, the fact that from previous works it was commonly observed a carryover (long-term) effect after the usage of the cues for a certain amount of time [2, 11, 15, 17, 22, 49–51], showing that in order to produce improvements in patients' gait, it is not necessary to have the cues always on.

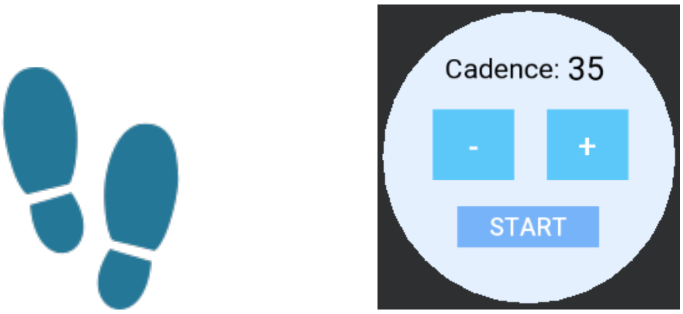
Secondly, the fact that the usage of cues is normally just associated with controlled environments (i.e. laboratory, home), represents other aspect that we aimed to address with this application. In other words, although the results from the laboratory environments are quite important, the fact that when the effects from previous cues' usage disappear, patients need to go back there in order to reimprove gait, it is considered as a limitation. Besides this, since the amount of time that the effects efficiently last is quite uncertain - being observed effects from 15 minutes to 60 days - patients' become afraid to go out and to leave controlled environments, leading to a reduction of patients' mobility, independence and quality of life.

Therefore, this application aims to be like a "**pill**" that patients with gait impairments (i.e Parkinson's disease) can use, whenever they feel the need to, in order to safely and easily continue to perform their daily routine, as normal as possible. For that, the application has three main functionalities:

1. **Stimulus Presentation**. From the previous VR field study, we had identified Haptic 1P1W as the stimulus that most improved participants' gait without deteriorating their attention or usability. In fact, regarding gait, from the previous results we had observed that Haptic 1P1W, was the only stimulus that was able to significantly change (i.e. improve) participants step length and cadence. In addiction to this, this stimulus was considered to be participants' favourite one, and the least demanding in terms of workload. Besides this, it is important to highlight that since we aim for this app to be used outside controlled environments, the fact that this stimulus (Haptic 1P1W) did not influence participants' attention to the surroundings, was an important factor for us to ensure users' safety while out in-the-wild.

   Therefore, taking into account all of these factors, that was the stimulus that was used in our application.

   - **Implementation:** The stimulus implementation was quite similar to the one explained in section 3.3.4. However, since the application run without the support of a mobile application, and there was no baseline value of cadence to be used to calculate the vibration frequency for each participant, we had established a default value for it. This value corresponded to less 10% of the mean cadence during our VR field study baseline walk. Therefore, since the cadence's mean value during baseline was 39 steps per minute, the used value as default was 35 steps per minute.



Cadence: 35

(a) GaitWear Logo

(b) Screenshot from GaitWear application

Figure 5.1: GaitWear

2. **Stimulus' Frequency Regulation.** In order to allow users to adapt the vibrations frequency to their needs or preference, we had enabled the stimulus' frequency regulation. In other words, depending on the situation or the users' needs, the cadence imposed by the stimulus can be changed at any time.

    - **Implementation:** This feature implementation was accomplished trough the usage of two buttons (one to increase 1 unit, other to decrease 1 unit of the cadence value – represented in figure 5.1(b) as + and -). This regulation can be done at anytime, just by clicking on the correspondent button.

3. **Start/Stop Stimulus.** Besides regulating the stimulus, the application allows users to start and stop the stimulus at anytime. This was an important feature, since as explained before, users may not always need the stimulus on, in order to have an improved gait. Other important reason behind this feature, was the fact that depending on users' daily routine and the different situations and scenarios that are part of it, users' may want to turn the stimulus off/on depending on those.

    - **Implementation:** This was accomplished through two different ways. Firstly, users could start/stop the vibration through the usage of a simple button, that could be pressed at anytime (*Start Button* presented in figure 5.1(b)). Secondly, and in order to introduce a different and simple type of input that did not need an interaction with the application screen, we had used a **flick wrist gesture** to toggle the stimulus' presentation. The choice of this gesture, relied on the fact that this is considered to be uncommon in daily life, quick and easy to execute and easily and reliably detectable [106].

6

Conclusion

Contents

6.1 Conclusions

Parkinson's patient's gait is one the most affected motor characteristics of this disorder. As the disease progresses, patient's gait becomes usually characterized by shortened step length, lower walking speed, increase gait variance and festinating gait. The unavailability of a cure and the reduced efficiency regarding gait normalization of traditional therapies have introduce the concept of cueing. Many studies have been performed in order to assess the impact of these cues on patients' gait's parameters, however, the little evaluation of these cues regarding patients' usability factors, especially outside a controlled environment, in addiction to the limited exploration of different type of stimuli, particularly on Haptic cues, were the principal reasons behind this work.

Therefore, this Thesis explored popular (i.e. Visual) and new stimuli (i.e. Haptic) to normalize users' gait in the context of a VR Field Study. The latter was employed so that we could explore the impact of these cues while walking in a simulated sidewalk; allowing us to start to assess not only the impact of these cues in the overall user experience, but their safety outside of a controlled laboratory environment (measured via gaze and awareness of several events).

In section 3.1, we had identified six different questions that were still not answered and that we aimed to clarify with the performance of this study. In order to understand whether those questions were answered or not, we will take into account all the previous presented and discussed results.

1. **Question:** *What are the effects on **gait parameters** of patients with gait disorders (e.g. Parkinson's' Disease) when using Haptic cues, comparing to when not using any cue (baseline)? And comparing to when using Visual or Auditory cues? Did gait velocity/step length/cadence increase or decrease?*

   - **Answer:** Although our participants did not have any gait disorder, haptic cues were able to significantly improve step length (i.e. increase) and cadence (i.e. decrease), when comparing to baseline values. Regarding velocity, it was observed a decrease while using these cues, which was quite expected due to the vibration frequency imposed by us (-10% of baseline). On the other hand, when using visual cues, it was observed a significant reduced in step length, and an increase of cadence and velocity, when comparing to baseline trial. When comparing Haptic and visual cues' results, it was observed a step length and cadence's significant improvement during all Haptic cues. This contrasts with velocity's results, where existed a significant improvement during visual cues usage, when compared to haptic stimuli.

2. **Question:** *Is VR a viable research approach?*

   - **Answer:** In order to answer this question in a more precise way, it is necessary further evaluations. However, comparing our results with previous works, it was notorious a significant contrast regarding what was expected when using visual cues, particularly regarding the step length results. This may lead us to conclude that the usage of VR field study might have had some impact regarding participants perception of the cues (visual cues). On the other hand, the usage of this VR approach while using haptic stimuli, led to expectable results. Therefore, we may say that the usage of the VR field study approach was viable while using Haptic cues, but not during visual trials.

3. **Question:** *What are the gait 's effects of using Temporal + Spatial information in Haptic cues? Were they different from using only Temporal information?*

   - **Answer:** Before the start of this study we had hypothesize that the usage of **spatial and temporal** information together in Haptic stimuli, would have a positive impact in almost every gait parameter, as observed by a previous work in the visual field [3]. However, this was not observed (Haptic 2P1W and 1P2W had not significantly improved step length nor velocity). In addiction to this, none of the comparisons regarding the two types of stimulus, (only temporal (i.e. Haptic 1P1W) and temporal + spatial (i.e. Haptic 1P2W and Haptic 2P1W), had led to significant differences, when gait regulation is concern.

     Which may lead us to conclude that the impact on gait's parameters of the usage of an haptic stimulus with spatial and temporal information, does not differ from using only temporal information.

4. **Question:** *In terms of usability, what is the most preferable/comfortable/easiest stimulus? And the least?*

   - **Answer:** Regarding usability, participants' found the usage of Haptic cues, in particularly, Haptic 1P1W and Haptic 1P2W more comfortable, easy to understand, easy to use and less distractives. Besides this, when asked about their **most favourite** stimulus, participants' majority had answered with **Haptic 1P1W**. On the other hand, **Visual cues** were considered to be participants' **least favourite**, being not comfortable, not useful, not easy to understand nor to use. Visual cues were also appointed as distractives and annoying.

5. **Question:** *In terms of workload, what are the stimuli that required higher and inferior levels?*

   - **Answer:** Regarding the Workload required by the participants when using the different stimuli, it was observed that during the usage of **visual cues**, higher levels of workload were needed, especially in terms of mental demand, performance, effort and frustration. On the other hand, Haptic cues, in particularly Haptic 1P1W, were considered to be significantly less demanding for the participants.

6. **Question:** *Regarding patients' security, what is the safest stimulus for a patient to use in-the-wild? In other words, what is the stimulus that let the participants be more aware of the surrounding?*

    - **Answer:** As expected, participants' were much more **less aware** of their surrounding while using **visual cues**. The fact that these cues were presented on the floor, forced participants to look down which had made them unconscious and unaware of important events that were happening around them, such as a car passing by or a traffic light turning red. This may have been even more noticed, because of the previously explained participants' struggles while using these cues.

      In contrast to this, **Haptic cues did not had a significant impact regarding participants' attention and gaze**. In other words, the comparison of the number of looks and the amount of time looking at the distractors' and non distractors' elements, between haptic cues and baseline were quite similar, not leading to any significant differences. Meaning that **no evidence** was found about an effect of haptic cues in participants' gaze and attention.

After the performance of this study, and taken into account its results, we had proposed a smartwatch application: **GaitWear**. This application represents a form to face the fact that patients not always need the presence of stimulus in order to improve gait (due to Carryover effects). Therefore, GaitWear aims to be like a "pill" that users can use whenever they feel the need to. In order to do that, GaitWear enables the display and users' control of Haptic 1P1W stimulus – the stimulus that led to more improvements during the performance of the VR field study.

6.2 System Limitations and Future Work

Our immediate future work includes expanding the number of participants in our VR field study, and following-up with participants with some form of gait impairment (particularly participants with Parkinson's disease) – the ultimate stakeholders of such a system. Secondly, an evaluation of the usage of GaitWear also with participants with some gait impairments, would also be interesting and important. Finally, we suggest a replication of our study via a standard field study in order to compare findings. This would enable us to further validate virtual field studies as a novel research paradigm, particularly in the context of locomotion and mobility tasks.

Bibliography

[1] A. H. Snijders and B. R. Bloem, “Cycling for Freezing of Gait,” *New England Journal of Medicine*, vol. 362, no. 13, p. e46, Apr. 2010. [Online]. Available: http://www.nejm.org/doi/abs/10.1056/NEJMicm0810287

[2] S. Bagley, B. Kelly, N. Tunnicliffe, G. I. Turnbull, and J. M. Walker, “The Effect of Visual Cues on the Gait of Independently Mobile Parkinson’s Disease Patients,” *Physiotherapy*, vol. 77, no. 6, pp. 415–420, Jun. 1991. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0031940610620354

[3] L. I. Gómez-Jordana, J. Stafford, C. L. E. Peper, and C. M. Craig, “Virtual Footprints Can Improve Walking Performance in People With Parkinson’s Disease,” *Frontiers in Neurology*, vol. 9, 2018. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fneur.2018.00681/full?report=reader

[4] S. Janssen, B. Bolte, J. Nonnekes, M. Bittner, B. R. Bloem, T. Heida, Y. Zhao, and R. J. A. van Wezel, “Usability of Three-dimensional Augmented Visual Cues Delivered by Smart Glasses on (Freezing of) Gait in Parkinson’s Disease,” *Frontiers in Neurology*, vol. 8, 2017. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fneur.2017.00279/full

[5] S. Weissenborn, “The Effect of Using a Two-step Verbal Cue to a Visual Target Above Eye Level on the Parkinsonian gait: A case study,” *Physiotherapy*, vol. 79, no. 1, pp. 26–31, Jan. 1993. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0031940610605378

[6] V. Mäkelä, R. Radiah, S. Alsherif, M. Khamis, C. Xiao, L. Borchert, A. Schmidt, and F. Alt, “Virtual field studies: Conducting studies on public displays in virtual reality,” in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–15.

[7] B. R. Bloem, J. Haan, A. M. Lagaay, W. v. Beek, A. R. Wintzen, and R. A. C. Roos, “Investigation of Gait in Elderly Subjects Over 88 Years of Age:,” *Topics in geriatrics*, Sep. 2016, publisher: SAGE PublicationsSage CA: Los Angeles, CA. [Online]. Available: https://journals.sagepub.com/doi/10.1177/002383099200500204

[8] P. Mahlknecht, S. Kiechl, B. R. Bloem, J. Willeit, C. Scherfler, A. Gasperi, G. Rungger, W. Poewe, and K. Seppi, "Prevalence and burden of gait disorders in elderly men and women aged 60-97 years: a population-based study," *PloS One*, vol. 8, no. 7, p. e69627, 2013.

[9] W. Pirker and R. Katzenschlager, "Gait disorders in adults and the elderly," *Wiener klinische Wochenschrift*, vol. 129, no. 3, pp. 81–95, Feb. 2017. [Online]. Available: https://doi.org/10.1007/s00508-016-1096-4

[10] S. V. Sarma, M. L. Cheng, U. T. Eden, Z. Williams, E. N. Brown, and E. Eskandar, "The effects of cues on neurons in the basal ganglia in Parkinson's disease," *Frontiers in Integrative Neuroscience*, vol. 6, 2012. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fnint.2012.00040/full

[11] J. M. Hausdorff, M. E. Cudkowicz, R. Firtion, J. Y. Wei, and A. L. Goldberger, "Gait variability and basal ganglia disorders: Stride-to-stride variations of gait cycle timing in parkinson's disease and Huntington's disease," *Movement Disorders*, vol. 13, no. 3, pp. 428–437, 1998. [Online]. Available: https://www.onlinelibrary.wiley.com/doi/abs/10.1002/mds.870130310

[12] P. Novak and V. Novak, "Effect of step-synchronized vibration stimulation of soles on gait in Parkinson's disease: a pilot study," *Journal of NeuroEngineering and Rehabilitation*, vol. 3, no. 1, p. 9, May 2006. [Online]. Available: https://doi.org/10.1186/1743-0003-3-9

[13] M. Suteerawattananon, G. Morris, B. Etnyre, J. Jankovic, and E. Protas, "Effects of visual and auditory cues on gait in individuals with Parkinson's disease," *Journal of the Neurological Sciences*, vol. 219, no. 1-2, pp. 63–69, Apr. 2004. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0022510X03003812

[14] J. M. Hausdorff, J. Lowenthal, T. Herman, L. Gruendlinger, C. Peretz, and N. Giladi, "Rhythmic auditory stimulation modulates gait variability in Parkinson's disease," *European Journal of Neuroscience*, vol. 26, no. 8, pp. 2369–2375, 2007. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1460-9568.2007.05810.x

[15] M. H. Thaut, G. C. McIntosh, R. R. Rice, R. A. Miller, J. Rathbun, and J. M. Brault, "Rhythmic auditory stimulation in gait training for Parkinson's disease patients," *Movement Disorders*, vol. 11, no. 2, pp. 193–200, 1996. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/mds.870110213

[16] J. P. Martin, *The basal ganglia and posture*. Lippincott, 1967.

[17] M. E. Morris, R. Iansek, T. A. Matyas, and J. J. Summers, "Stride length regulation in Parkinson's disease: Normalization strategies and underlying mechanisms," *Brain*, vol. 119, no. 2, pp.

551–568, 1996. [Online]. Available: https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/119.2.551

[18] A. J. Espay, Y. Baram, A. K. Dwivedi, R. Shukla, M. Gartner, L. Gaines, A. P. Duker, and F. J. Revilla, “At-home training with closed-loop augmented-reality cueing device for improving gait in patients with Parkinson disease,” *The Journal of Rehabilitation Research and Development*, vol. 47, no. 6, p. 573, 2010. [Online]. Available: http://www.rehab.research.va.gov/jour/10/476/pdf/espay.pdf

[19] G. C. McIntosh, S. H. Brown, R. R. Rice, and M. H. Thaut, “Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson’s disease.” *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 62, no. 1, pp. 22–26, Jan. 1997. [Online]. Available: http://jnnp.bmj.com/cgi/doi/10.1136/jnnp.62.1.22

[20] T. E. Howe, B. Lövgreen, F. W. Cody, V. J. Ashton, and J. A. Oldham, “Auditory cues can modify the gait of persons with early-stage Parkinson’s disease: a method for enhancing parkinsonian walking performance?” *Clinical Rehabilitation*, vol. 17, no. 4, pp. 363–367, Jun. 2003. [Online]. Available: http://journals.sagepub.com/doi/10.1191/0269215503cr621oa

[21] R. L. Freedland, C. Festa, M. Sealy, A. McBean, P. Elghazaly, A. Capan, L. Brozycki, A. J. Nelson, and J. Rothman, “The effects of pulsed auditory stimulation on various gait measurements in persons with Parkinson’s Disease,” p. 7.

[22] Z. Kadivar, D. M. Corcos, J. Foto, and J. M. Hondzinski, “Effect of Step Training and Rhythmic Auditory Stimulation on Functional Performance in Parkinson Patients,” *Neurorehabilitation and Neural Repair*, vol. 25, no. 7, pp. 626–635, Sep. 2011. [Online]. Available: http://journals.sagepub.com/doi/10.1177/1545968311401627

[23] A. Sobhani and B. Farooq, “Impact of smartphone distraction on pedestrians’ crossing behaviour: An application of head-mounted immersive virtual reality,” *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 58, pp. 228–241, Oct. 2018. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1369847818300998

[24] M. Morris, R. Iansek, F. Smithson, and F. Huxham, “Postural instability in Parkinson’s disease: a comparison with and without a concurrent task,” *Gait & Posture*, vol. 12, no. 3, pp. 205–216, Dec. 2000. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S096663620000076X

[25] M. H. Sharpe, “Is There a Divided Attention Deficit in Patients with Early Parkinson’s Disease?” *Cortex*, vol. 32, no. 4, pp. 747–753, Dec. 1996. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S001094529680044X

[26] J.-P. Azulay, S. Mesure, and O. Blin, “Influence of visual cues on gait in Parkinson’s disease: Contribution to attention or sensory dependence?” *Journal of the Neurological Sciences*, vol. 248, no. 1-2, pp. 192–195, Oct. 2006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0022510X06001961

[27] C. Basdogan, C.-H. Ho, and M. Srinivasan, “Virtual environments for medical training: graphical and haptic simulation of laparoscopic common bile duct exploration,” *IEEE/ASME Transactions on Mechatronics*, vol. 6, no. 3, pp. 269–285, Sep. 2001. [Online]. Available: http://ieeexplore.ieee.org/document/951365/

[28] A. Chang, “Audio-haptic feedback in mobile phones,” in *In CHI ’05 Extended Abstracts. ACM Press*. ACM Press, 2005, pp. 1264–1267.

[29] M. Faust and Y.-H. Yoo, “Haptic Feedback in Pervasive Games,” p. 8.

[30] A. de Oliveira, M. Khamis, and A. Esteves, “Using a vr field study to assess the effects of visual and haptic cues in" in-the-wild" locomotion.”

[31] A. Fasano and B. R. Bloem, “Gait disorders,” *CONTINUUM: Lifelong Learning in Neurology*, vol. 19, no. 5, pp. 1344–1382, 2013.

[32] S. P. Baker and A. H. Harvey, “Fall injuries in the elderly,” *Clinics in geriatric medicine*, vol. 1, no. 3, pp. 501–512, 1985.

[33] J. Parkinson, “An Essay on the Shaking Palsy,” *The Journal of Neuropsychiatry and Clinical Neurosciences*, vol. 14, no. 2, pp. 223–236, May 2002. [Online]. Available: https://neuro.psychiatryonline.org/doi/full/10.1176/jnp.14.2.223

[34] J. Jankovic, “Parkinson’s disease: clinical features and diagnosis,” *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 79, no. 4, pp. 368–376, Apr. 2008. [Online]. Available: http://jnnp.bmj.com/cgi/doi/10.1136/jnnp.2007.131045

[35] O.-B. Tysnes and A. Storstein, “Epidemiology of Parkinson’s disease,” *Journal of Neural Transmission*, vol. 124, no. 8, pp. 901–905, Aug. 2017. [Online]. Available: https://doi.org/10.1007/s00702-017-1686-y

[36] C. M. Lill, “Genetics of Parkinson’s disease,” *Molecular and Cellular Probes*, vol. 30, no. 6, pp. 386–396, Dec. 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0890850816301037

[37] A. Priyadarshi, S. A. Khuder, E. A. Schaub, and S. S. Priyadarshi, “Environmental Risk Factors and Parkinson’s Disease: A Metaanalysis,” *Environmental Research*, vol. 86, no. 2, pp. 122–127, Jun. 2001. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0013935101942641

[38] M. Kasten, A. Chade, and C. M. Tanner, “Epidemiology of Parkinson’s disease.” vol. 83, pp. 129–51, 1999.

[39] O. Blin, A. Ferrandez, J. Pailhous, and G. Serratrice, “Dopa-sensitive and Dopa-resistant gait parameters in Parkinson’s disease,” *Journal of the Neurological Sciences*, vol. 103, no. 1, pp. 51–54, May 1991. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/0022510X9190283D

[40] J. C. Wall and A. Ashburn, “Assessment of gait disability in hemiplegics. Hemiplegic gait,” *Scandinavian Journal of Rehabilitation Medicine*, vol. 11, no. 3, pp. 95–103, 1979.

[41] M. K. Holden, K. M. Gill, M. R. Magliozzi, J. Nathan, and L. Piehl-Baker, “Clinical Gait Assessment in the Neurologically ImpairedReliability and Meaningfulness,” *Physical Therapy*, vol. 64, no. 1, pp. 35–40, Jan. 1984. [Online]. Available: https://academic.oup.com/ptj/article/64/1/35/2727634

[42] V. Wilzenben HD, “Locomotion in the treatment of post encephalitic Parkinson’s disease.” 1942.

[43] S. Janssen, M. Soneji, J. Nonnekes, and B. R. Bloem, “A painted staircase illusion to alleviate freezing of gait in Parkinson’s disease,” *Journal of Neurology*, vol. 263, no. 8, pp. 1661–1662, Aug. 2016. [Online]. Available: http://link.springer.com/10.1007/s00415-016-8195-z

[44] A. H. Snijders, P. Jeene, M. J. Nijkrake, W. F. Abdo, and B. R. Bloem, “Cueing for Freezing of Gait: A Need for 3-Dimensional Cues?” *The Neurologist*, vol. 18, no. 6, p. 404, Nov. 2012. [Online]. Available: https://journals.lww.com/theneurologist/Abstract/2012/11000/Cueing_for_Freezing_of_Gait__A_Need_for.13.aspx#print-article-link

[45] M. A. Liebert, M. K. Holden, and P. D, *Virtual Environments for Motor Rehabilitation: Review*.

[46] A. P. C. Loureiro, C. G. Ribas, T. G. G. Zotz, R. Chen, and F. Ribas, “Feasibility of virtual therapy in rehabilitation of Parkinson’s disease patients: pilot study,” *Fisioterapia em Movimento*, vol. 25, no. 3, pp. 659–666, Sep. 2012. [Online]. Available: http://www.scielo.br/scielo.php?script=sci_abstract&pid=S0103-51502012000300021&lng=en&nrm=iso&tlng=en

[47] F. A. d. S. Mendes, L. Arduini, A. Botelho, M. B. d. Cruz, C. C. Santos-Couto-Paz, S. M. A. A. Pompeu, M. E. P. Piemonte, and J. E. Pompeu, “Pacientes com a Doença de Parkinson são capazes de melhorar seu desempenho em tarefas virtuais do Xbox Kinect®: [U+0093]uma série de casos[U+0094],” *Motricidade*, vol. 11, no. 3, pp. 68–80, Sep. 2015. [Online]. Available: http://www.scielo.mec.pt/scielo.php?script=sci_abstract&pid=S1646-107X2015000300008&lng=pt&nrm=iso&tlng=pt

[48] M. I. R. Severiano, B. S. Zeigelboim, H. A. G. Teive, G. J. B. Santos, and V. R. Fonseca, “Effect of virtual reality in Parkinson’s disease: a prospective observational study,” *Arquivos*

de Neuro-Psiquiatria, vol. 76, no. 2, pp. 78–84, Feb. 2018. [Online]. Available: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0004-282X2018000200078&lng=en&tlng=en

[49] Y.-Y. Liao, Y.-R. Yang, Y.-R. Wu, and R.-Y. Wang, “Virtual Reality-Based Wii Fit Training in Improving Muscle Strength, Sensory Integration Ability, and Walking Abilities in Patients with Parkinson’s Disease: A Randomized Control Trial,” *International Journal of Gerontology*, vol. 9, no. 4, pp. 190–195, Dec. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S187395981500099X

[50] F. A. d. S. Mendes, J. E. Pompeu, A. M. Lobo, K. G. da Silva, T. d. P. Oliveira, A. P. Zomignani, and M. E. P. Piemonte, “Motor learning, retention and transfer after virtual-reality-based training in Parkinson’s disease – effect of motor and cognitive demands of games: a longitudinal, controlled clinical study,” *Physiotherapy*, vol. 98, no. 3, pp. 217–223, Sep. 2012. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S003194061200051X

[51] B. Sidaway, J. Anderson, G. Danielson, L. Martin, and G. Smith, “Effects of Long-Term Gait Training Using Visual Cues in an Individual With Parkinson Disease,” *Physical Therapy*, vol. 86, no. 2, pp. 186–194, Feb. 2006. [Online]. Available: https://academic.oup.com/ptj/article/86/2/186/2805060

[52] “Augmented reality,” Dec. 2019, page Version ID: 929427095. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Augmented_reality&oldid=929427095

[53] S. Janssen, M. Soneji, J. Nonnekes, and B. R. Bloem, “A painted staircase illusion to alleviate freezing of gait in Parkinson’s disease,” *Journal of Neurology*, vol. 263, no. 8, pp. 1661–1662, Aug. 2016. [Online]. Available: https://doi.org/10.1007/s00415-016-8195-z

[54] B. Wyke, *Conference on the Ageing Brain* Cervical Articular Contributions to Posture and Gait: Their Relation to Senile Disequilibrium*.

[55] J.-P. Azulay, S. Mesure, B. Amblard, O. Blin, I. Sangla, and J. Pouget, “Visual control of locomotion in Parkinson’s disease,” *Brain*, vol. 122, no. 1, pp. 111–120, Jan. 1999. [Online]. Available: https://academic.oup.com/brain/article/122/1/111/330308

[56] B. Amblard, J. Cr[U+FFFD]mieux, A. Marchand, and A. Carblanc, “Lateral orientation and stabilization of human stance: static versus dynamic visual cues,” *Experimental Brain Research*, vol. 61, no. 1, Dec. 1985. [Online]. Available: http://link.springer.com/10.1007/BF00235617

[57] C. Assaiante, A. R. Marchand, and B. Amblard, “Discrete Visual Samples May Control Locomotor Equilibrium and Foot Positioning in Man,” *Journal of Motor Behavior*, vol. 21, no. 1, pp. 72–91, Mar. 1989. [Online]. Available: https://doi.org/10.1080/00222895.1989.10735466

[58] J. D. Cooke, J. D. Brown, and V. B. Brooks, “Increased Dependence on Visual Information for Movement Control in Patients with Parkinson’s disease,” *Canadian Journal of Neurological Sciences*, vol. 5, no. 4, pp. 413–415, Nov. 1978. [Online]. Available: https://www.cambridge.org/core/journals/canadian-journal-of-neurological-sciences/article/increased-dependence-on-visual-information-for-movement-control-in-patients-with-parkinsons-disease/DE32F2498C26632C5C7073CACB6C65A8

[59] P. Praamstra, “Reliance on external cues for movement initiation in Parkinson’s disease. Evidence from movement-related potentials,” *Brain*, vol. 121, no. 1, pp. 167–177, Jan. 1998. [Online]. Available: https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/121.1.167

[60] O. Rascol, “The ipsilateral cerebellar hemisphere is overactive during hand movements in akinetic parkinsonian patients,” *Brain*, vol. 120, no. 1, pp. 103–110, Jan. 1997. [Online]. Available: https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/120.1.103

[61] C. D. Marsden and J. A. Obeso, “The functions of the basal ganglia and the paradox of stereotaxic surgery in Parkinson’s disease,” *Brain*, vol. 117, no. 4, pp. 877–897, Aug. 1994. [Online]. Available: https://academic.oup.com/brain/article/117/4/877/285651

[62] M. Glickstein and J. Stein, “Paradoxical movement in Parkinson’s disease,” *Trends in Neurosciences*, vol. 14, no. 11, pp. 480–482, Nov. 1991. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/016622369190055Y

[63] M. H. Thaut, “The Future of Music in Therapy and Medicine,” *Annals of the New York Academy of Sciences*, vol. 1060, no. 1, pp. 303–308, Dec. 2005. [Online]. Available: http://doi.wiley.com/10.1196/annals.1360.023

[64] Y. PALTSEV, “Change in the functional state of the segmental apparatus of the spinal cord under the influence of sound stimuli and its role in voluntary movement,” *Biophysics*, vol. 12, pp. 1219–1226, 1967. [Online]. Available: https://ci.nii.ac.jp/naid/20000627244/

[65] M. H. Thaut, G. C. McIntosh, and R. R. Rice, “Rhythmic facilitation of gait training in hemiparetic stroke rehabilitation,” p. 6, 1997.

[66] A. M. Willems, A. Nieuwboer, F. Chavret, K. Desloovere, R. Dom, L. Rochester, D. Jones, G. Kwakkel, and E. Van Wegen, “The use of rhythmic auditory cues to influence gait in patients with Parkinson’s disease, the differential effect for freezers and non-freezers, an explorative study,” *Disability and Rehabilitation*, vol. 28, no. 11, pp. 721–728, Jan. 2006. [Online]. Available: http://www.tandfonline.com/doi/full/10.1080/09638280500386569

[67] J. E. Wittwer, K. E. Webster, and K. Hill, “Music and metronome cues produce different effects on gait spatiotemporal measures but not gait variability in healthy older adults,” *Gait & Posture*, vol. 37, no. 2, pp. 219–222, Feb. 2013. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0966636212002767

[68] N. de Bruin, J. B. Doan, G. Turnbull, O. Suchowersky, S. Bonfield, B. Hu, and L. A. Brown, “Walking with Music Is a Safe and Viable Tool for Gait Training in Parkinson’s Disease: The Effect of a 13-Week Feasibility Study on Single and Dual Task Walking,” *Parkinson’s Disease*, vol. 2010, pp. 1–9, 2010. [Online]. Available: http://www.hindawi.com/journals/pd/2010/483530/

[69] P. Ginis, E. Heremans, A. Ferrari, K. Dockx, C. G. Canning, and A. Nieuwboer, “Prolonged walking with a wearable system providing intelligent auditory input in people with parkinson’s disease,” *Frontiers in Neurology*, vol. 8, p. 128, 2017. [Online]. Available: https://www.frontiersin.org/article/10.3389/fneur.2017.00128

[70] L. Rochester, K. Baker, V. Hetherington, D. Jones, A.-M. Willems, G. Kwakkel, E. Van Wegen, I. Lim, and A. Nieuwboer, “Evidence for motor learning in Parkinson’s disease: Acquisition, automaticity and retention of cued gait performance after training with external rhythmical cues,” *Brain Research*, vol. 1319, pp. 103–111, Mar. 2010. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0006899310000041

[71] W. R. Young, M. W. M. Rodger, and C. M. Craig, “Auditory observation of stepping actions can cue both spatial and temporal components of gait in Parkinson[U+05F3]s disease patients,” *Neuropsychologia*, vol. 57, pp. 140–153, May 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0028393214000943

[72] Gibson and J. Jerome, “The senses considered as perceptual systems.” 1966.

[73] H. Culbertson, S. B. Schorr, and A. M. Okamura, “Haptics: The Present and Future of Artificial Touch Sensation,” vol. 1, pp. 385–409, 2018. [Online]. Available: https://doi.org/10.1146/annurev-control-060117-105043

[74] J. Konczak, A. Sciutti, L. Avanzino, V. Squeri, M. Gori, L. Masia, G. Abbruzzese, and G. Sandini, “Parkinson’s disease accelerates age-related decline in haptic perception by altering somatosensory integration,” *Brain*, vol. 135, no. 11, pp. 3371–3379, Nov. 2012. [Online]. Available: https://academic.oup.com/brain/article/135/11/3371/272843

[75] Y. Zheng and J. B. Morrell, “A vibrotactile feedback approach to posture guidance,” in *2010 IEEE Haptics Symposium*, Mar. 2010, pp. 351–358, iSSN: 2324-7347, 2324-7355.

[76] E. Rabin, J. Chen, L. Muratori, J. DiFrancisco-Donoghue, and W. G. Werner, “Haptic feedback from manual contact improves balance control in people with Parkinson’s disease,” *Gait & posture*, vol. 38, no. 3, pp. 373–379, Jul. 2013. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3664138/

[77] E. van Wegen, C. de Goede, I. Lim, M. Rietberg, A. Nieuwboer, A. Willems, D. Jones, L. Rochester, V. Hetherington, H. Berendse, J. Zijlmans, E. Wolters, and G. Kwakkel, “The effect of rhythmic somatosensory cueing on gait in patients with Parkinson’s disease,” *Journal of the Neurological Sciences*, vol. 248, no. 1-2, pp. 210–214, Oct. 2006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0022510X06002309

[78] E. Sejdić, Y. Fu, A. Pak, J. A. Fairley, and T. Chau, “The Effects of Rhythmic Sensory Cues on the Temporal Dynamics of Human Gait,” *PLOS ONE*, vol. 7, no. 8, p. e43104, Aug. 2012. [Online]. Available: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0043104

[79] W. Nanhoe-Mahabier, J. H. Allum, E. P. Pasman, S. Overeem, and B. R. Bloem, “The effects of vibrotactile biofeedback training on trunk sway in Parkinson’s disease patients,” *Parkinsonism & Related Disorders*, vol. 18, no. 9, pp. 1017–1021, Nov. 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1353802012002064

[80] S. Šipetić Grujičić, *Experimental StudiesExperimental studies*. Dordrecht: Springer Netherlands, 2008, pp. 421–424. [Online]. Available: https://doi.org/10.1007/978-1-4020-5614-7_1092

[81] E. v. Wegen, I. Lim, C. d. Goede, A. Nieuwboer, A. Willems, D. Jones, L. Rochester, V. Hetherington, H. Berendse, J. Zijlmans, E. Wolters, and G. Kwakkel, “The effects of visual rhythms and optic flow on stride patterns of patients with Parkinson’s disease,” *Parkinsonism & Related Disorders*, vol. 12, no. 1, pp. 21–27, Jan. 2006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1353802005001410

[82] E. Knutsson, “AN ANALYSIS OF PARKINSONIAN GAIT,” *Brain*, vol. 95, no. 3, pp. 475–486, Jan. 1972. [Online]. Available: https://academic.oup.com/brain/article/95/3/475/315945

[83] J. Parong and R. E. Mayer, “Learning science in immersive virtual reality,” *Journal of Educational Psychology*, vol. 110, no. 6, pp. 785–797, 2018, place: US Publisher: American Psychological Association.

[84] M. Moussaıd, M. Kapadia, T. Thrash, R. W. Sumner, M. Gross, D. Helbing, and C. Holscher, “Crowd behaviour during high-stress evacuations in an immersive virtual environment,” p. 8.

[85] H. G. Hoffman, D. R. Patterson, and G. J. Carrougher, “Use of Virtual Reality for Adjunctive Treatment of Adult Burn Pain During Physical Therapy: A Controlled Study,” *The Clinical Journal*

of Pain, vol. 16, no. 3, pp. 244–250, Sep. 2000. [Online]. Available: https://journals.lww.com/clinicalpain/Abstract/2000/09000/Use_of_Virtual_Reality_for_Adjunctive_Treatment_of.10.aspx

[86] A. A. Rendon, E. B. Lohman, D. Thorpe, E. G. Johnson, E. Medina, and B. Bradley, "The effect of virtual reality gaming on dynamic balance in older adults," *Age and Ageing*, vol. 41, no. 4, pp. 549–552, Jul. 2012, publisher: Oxford Academic. [Online]. Available: https://academic.oup.com/ageing/article/41/4/549/47286

[87] L. Li, F. Yu, D. Shi, J. Shi, Z. Tian, J. Yang, X. Wang, and Q. Jiang, "Application of virtual reality technology in clinical medicine," *American Journal of Translational Research*, vol. 9, no. 9, pp. 3867–3880, Sep. 2017. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5622235/

[88] P. Agethen, V. S. Sekar, F. Gaisbauer, T. Pfeiffer, M. Otto, and E. Rukzio, "Behavior Analysis of Human Locomotion in the Real World and Virtual Reality for the Manufacturing Industry," *ACM Transactions on Applied Perception*, vol. 15, no. 3, pp. 1–19, Aug. 2018. [Online]. Available: https://dl.acm.org/doi/10.1145/3230648

[89] S. Deb, D. Carruth, R. Sween, L. Strawderman, and T. Garrison, "Efficacy of virtual reality in pedestrian safety research," *Applied ergonomics*, vol. 65, Nov. 2017.

[90] P. Arias and J. Cudeiro, "Effects of rhythmic sensory stimulation (auditory, visual) on gait in Parkinson's disease patients," *Experimental Brain Research*, vol. 186, no. 4, pp. 589–601, Apr. 2008. [Online]. Available: https://doi.org/10.1007/s00221-007-1263-y

[91] T. Hanakawa, H. Fukuyama, Y. Katsumi, M. Honda, and H. Shibasaki, "Enhanced lateral premotor activity during paradoxical gait in parkinson's disease," *Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society*, vol. 45, no. 3, pp. 329–336, 1999.

[92] J. Brooke, "Sus: a "quick and dirty'usability," *Usability evaluation in industry*, p. 189, 1996.

[93] S. G. Hart, "Nasa-task load index (nasa-tlx); 20 years later," in *Proceedings of the human factors and ergonomics society annual meeting*, vol. 50, no. 9. Sage publications Sage CA: Los Angeles, CA, 2006, pp. 904–908.

[94] T. Schubert, F. Friedmann, and H. Regenbrecht, "The experience of presence: Factor analytic insights," *Presence: Teleoperators & Virtual Environments*, vol. 10, no. 3, pp. 266–281, 2001.

[95] B. G. Witmer and M. J. Singer, "Measuring presence in virtual environments: A presence questionnaire," *Presence*, vol. 7, no. 3, pp. 225–240, 1998.

[96] B. G. Witmer and M. F. Singer, “Measuring presence in virtual environments,” ARMY RESEARCH INST FOR THE BEHAVIORAL AND SOCIAL SCIENCES ALEXANDRIA VA, Tech. Rep., 1994.

[97] N. M. Razali, Y. B. Wah *et al.*, “Power comparisons of shapiro-wilk, kolmogorov-smirnov, lilliefors and anderson-darling tests,” *Journal of statistical modeling and analytics*, vol. 2, no. 1, pp. 21–33, 2011.

[98] S. E. Maxwell, H. D. Delaney, and K. Kelley, *Designing experiments and analyzing data: A model comparison perspective*. Routledge, 2017.

[99] R. F. DeVellis, *Scale development: Theory and applications*. Sage publications, 2016, vol. 26.

[100] G. N. Lewis, “Stride length regulation in Parkinson’s disease: the use of extrinsic, visual cues,” *Brain*, vol. 123, no. 10, pp. 2077–2090, Oct. 2000. [Online]. Available: https://academic.oup.com/brain/article-lookup/doi/10.1093/brain/123.10.2077

[101] J. H. Hollman, R. H. Brey, R. A. Robb, T. J. Bang, and K. R. Kaufman, “Spatiotemporal gait deviations in a virtual reality environment,” *Gait & posture*, vol. 23, no. 4, pp. 441–444, 2006.

[102] M. Schellenbach, M. Lövdén, J. Verrel, A. Krüger, and U. Lindenberger, “Adult age differences in familiarization to treadmill walking within virtual environments,” *Gait & posture*, vol. 31, no. 3, pp. 295–299, 2010.

[103] M. A. Sheik-Nainar and D. B. Kaber, “The utility of a virtual reality locomotion interface for studying gait behavior,” *Human factors*, vol. 49, no. 4, pp. 696–709, 2007.

[104] S. Badarny, J. Aharon-Peretz, Z. Susel, G. Habib, and Y. Baram, “Virtual reality feedback cues for improvement of gait in patients with parkinson’s disease,” *Tremor and Other Hyperkinetic Movements*, vol. 4, 2014.

[105] A. Lheureux, J. Lebleu, C. Frisque, C. Sion, G. Stoquart, T. Warlop, C. Detrembleur, and T. Lejeune, “Immersive virtual reality to restore natural long-range autocorrelations in parkinson’s disease patients’ gait during treadmill walking,” *Frontiers in physiology*, vol. 11, p. 1207, 2020.

[106] F. Kerber, P. Schardt, and M. Löchtefeld, “Wristrotate: a personalized motion gesture delimiter for wrist-worn devices,” in *Proceedings of the 14th international conference on mobile and ubiquitous multimedia*, 2015, pp. 218–222.

A

Usability Testing — Guide Protocol

At this appendix, we present the protocol followed during the VR field study.

GaitWear

Using a VR Field Study to Assess the Effects of Visual and Haptic Cues in "In-the-Wild" Locomotion

Usability Testing — Guide & Protocol

I. Material

In order to conduct this study, it is required:

- Mobile phone running Android 7 or later with the "GaitWear: Study" application pre-installed (to be used by the researcher);
- Two Smartwatches (to be used by the user);
- PC/laptop with the questionnaires for the user to fill and Unity Game engine pre-installed;
- VR headset with eye tracking;
- Notebook / sheets for taking notes (to be used by the researcher);
- Two chairs for the participant and the researcher to sit;
- Cleaning material (hand and face sanitizer and disinfectant spray, in order to comply with heath and safety procedures).

II. User Selection

There will be no criteria for selecting or restricting users to perform the tests.

III. Presentation

After the participant arrives, the researcher should invite him/her to sit in front of the computer.

In order to comply with health and safety procedures it should be asked the participant to **disinfect their hands** properly with an alcohol solution with at least 70% alcohol, and to **clean their face and wrists** with disinfecting wipes.

Then, it should be presented to the user the following brief introduction to the system and evaluation session:

> **"**Olá e, desde já, muito obrigado pela sua participação.
>
> O meu nome é Ana Oliveira e estou neste momento a terminar a dissertação de mestrado em Engenharia Informática e de Computadores no Instituto Superior Técnico.
> A minha tese de mestrado tem como principal objetivo diminuir os efeitos da doença de Parkinson na mobilidade dos pacientes.
> Esta normalização acontecerá através da presença de um estímulo que auxiliará o paciente na sua locomoção.
> De maneira a descobrir que estimulo será o mais benéfico tendo em conta não só as melhorias na locomoção, mas também a facilidade e segurança durante a sua utilização, iremos nesta sessão apresentar-lhe um conjunto de estímulos que serão objeto de estudo e análise.

Este é um estudo realizado com recurso a Realidade virtual e, portanto, antes do início da sessão terá uns minutos para se familiarizar com esta tecnologia e com o estudo em si.

Para além disto, antes de ser submetido a qualquer um dos estímulos, será feita uma pequena descrição sobre o mesmo.

Estaremos a observar e a tomar anotações sobre as suas ações, porém, não se sinta pressionado, pois o objeto de teste são os estímulos, e não o participante.

Esta sessão terá uma duração de cerca de 35 minutos, mas caso, em algum momento da sessão quiser abandonar ou parar, é livre de o fazer.

Novamente, muito obrigado pela sua participação**.”**

IV. Pre Study

1. Questionnaires

Before the start of the session, It will be asked to the participant to fill a simple survey in order to collect some **demographic information** and consent to the study and data collection: https://forms.gle/ggbVyEGaWPgbqm1Q6.

Besides this questionnaire, it will also be asked to the participant to fill a questionnaire regarding his/her **immersive tendencies**: https://forms.gle/43XfYhfr3zTFmZ8r8. This questionnaire will enable us to understand how involved and present the participant usual gets when submitted to external stimuli and experiences.

2. Smartwatches and Headset

After collecting participants’ information, we will ask the participant to **put on two smartwatches**, one on each wrist, and to adjust them in order to be tight and comfortable to the wrist
Then we will introduce the participant to the headset, for that, we will **adjust the VR headset** to their heads, and **calibrate the eye-tracker**.

3. User training

Also, before the starting of the walks that will be analyzed, it will be allowed to the participant to explore the Virtual Reality street without any external stimulus, for a maximum of five minutes.
It will be demonstrated to the participant that as soon as he/she starts to be near an object of the real world (wall, table), green boundaries will appear in the simulation.

V. Walk Trials

The participant will be performing 5 different walks.

The first walk will always be the **baseline** one. During this trial the participant will walk without any stimulus and the following introduction will be conducted:

> **“**Assim que a simulação começar, e se vir numa rua, caminhe em frente, em direção à passadeira, como se numa rua real se tratasse. Pare junto à passadeira, sem nunca a atravessar. Se por algum motivo se estiver a aproximar de um objeto do mundo real (parede, mesa, cadeira, ...) na simulação irá aparecer um retângulo que lhe indica qual a área segura à sua volta. Portanto peço-lhe que tente andar o mais normal possível e sem medo!**”**

The other 4 walks, with external stimulus, will be ordered following the balanced Latin square design (in order to minimize carryover effects):

1 2 4 3
2 3 1 4
3 4 2 1
4 1 3 2

Corresponding to:

1- **Visual**. Bright transverse bars will be displayed below participants’ feet, over the simulated sidewalk. When using this stimulus, the following introduction will be conducted:

> **“**Mais uma vez, assim que a simulação começar, e se vir numa rua, caminhe em frente, em direção à passadeira, **tentado pisar as barras amarelas que estão no chão**. Pare junto à passadeira, sem nunca a atravessar. Se por algum motivo se estiver a aproximar de um objeto do mundo real (parede, mesa, cadeira, ...) na simulação irá aparecer um retângulo que lhe indica qual a área segura à sua volta. Portanto peço-lhe que tente andar o mais normal possível e sem medo**”**

2- **Haptic 1P1W.** A simple vibration will play on the participant’s smartwatch, providing them with a rhythmic stimulus. When using this stimulus, the following introduction will be conducted:

> **“**Mais uma vez, assim que a simulação começar, e se vir numa rua, caminhe em frente, em direção à passadeira, **tentado coordenar o seu passo seu com a vibração no seu pulso**. Pare junto à passadeira, sem nunca a atravessar. Se por algum motivo se estiver a aproximar de um objeto do mundo real (parede, mesa, cadeira, ...) na simulação irá aparecer um retângulo que lhe indica qual a área segura à sua volta. Portanto peço-lhe que tente andar o mais normal possível e sem medo**”**

3- **Haptic 2P1W.** Two different vibration patterns will play in sequence on a single smartwatch, which again can be mapped to left and right steps. When using this stimulus, the following introduction will be conducted:

> “Mais uma vez, assim que a simulação começar, e se vir numa rua, caminhe em frente, em direção à passadeira, **tentado coordenar o seu passo seu com a vibração no seu pulso**. Esta vibração será composta por dois padrões, um será mapeado para o seu pé direito e outro para o seu pé esquerdo. Pare junto à passadeira, sem nunca a atravessar. Se por algum motivo se estiver a aproximar de um objeto do mundo real (parede, mesa, cadeira, ...) na simulação irá aparecer um retângulo que lhe indica qual a área segura à sua volta. Portanto peço-lhe que tente andar o mais normal possível e sem medo”

4- **Haptic 1P2W.** A simple vibration will play alternatively between the participant’s left and right smartwatches, providing them with a rhythmic stimulus that can be mapped to left and right steps. When using this stimulus, the following introduction will be conducted:

> “Mais uma vez, assim que a simulação começar, e se vir numa rua, caminhe em frente, em direção à passadeira, **tentado coordenar o seu passo seu com a vibração em cada pulso**. Pare junto à passadeira, sem nunca a atravessar. Se por algum motivo se estiver a aproximar de um objeto do mundo real (parede, mesa, cadeira, ...) na simulação irá aparecer um retângulo que lhe indica qual a área segura à sua volta. Portanto peço-lhe que tente andar o mais normal possível e sem medo”

VI. Trials Protocol

1. Introduction

After presenting each walk and the stimulus, the user will be given a short period to clarify any questions that it might have with the task. After such period, and if the user consents to be ready to proceed, the user with the help of the researcher may begin the eye tracking calibration.

2. Eye Tracking Calibration

The researcher must help the participant with this task.

3. Performing the Walk

4. Post-walk questionnaire

After each walk with external stimulus, the participant will be asked to fill 3 questionnaires:

- **NASA Task Load Index** (https://forms.gle/1Yg8GuiMrM6FMn2S6) – In order to assess the workload associated with that stimulus
- **SUS** (https://forms.gle/borHc7kqVGAyQKf76) – Aiming to evaluate the stimulus’ usability.
- **Stimulus’s usability** (https://forms.gle/Yi8Xn7wizebAHS9K8) – To analyze in a more detailed and personalized way the stimulus’ usability.

VII. Final Debrief

After the participant has finished performing the walks, it will be asked the participant to fill out 3 questionnaires regarding the participant's overall experience with the simulation and the stimuli:

- **Rank Preference** (https://forms.gle/FGvAA6f8nrYMRFm39) – This questionnaire will ask the participant to order the stimuli by preference, and to justify his/her answer.
- **Igroup Presence Questionnaire** (https://forms.gle/V7DxVNvSGwBRty5s9) – This questionnaire aims to analyze the presence, involvement and the realism of the experience.
- **VR Scene** (https://forms.gle/yXnxF7v1ttu9BTYf6) – This questionnaire will ask some questions about how the participant felt during the simulation

VIII. Session Closing

After the participant has completed all the final questionnaires, the researcher should thank the participant for the dispended time and invite him/her to leave the room.

After the participant leaves the room, the researcher should disinfect thoroughly all the material used in the session, with an alcohol solution with at least 70% alcohol.

B

Demographic Questionnaire

At this appendix, we present the demographic questionnaire conducted during VR field study. This survey was conducted using Google Forms tool.

Demographic Information

This questionnaire aims to collect some data about our study's participants' background - Gender, Nationality, Age, Height, Occupation, and Virtual Reality and Smartwatches' previous experience - and to get consent in order to use participants' data for scientific purposes in an anonymous way.

*Obrigatório

1. Participant ID (filled by the researcher) *

Marcar apenas uma oval.

○ P01
○ P02
○ P03
○ P04
○ P05
○ P6
○ P7
○ P8
○ P9
○ P10
○ P11
○ P12

2. Gender: *

Marcar apenas uma oval.

○ Female
○ Male
○ Non Binary
○ Prefer not to disclose
○ Outra: ______________________

3. Nationality *

___

4. Age *

___

5. Height (cm) *

___

6. Occupation *

Marcar apenas uma oval.

○ Student
○ Worker
○ Researcher
○ Unemployed
○ Retired
○ Outra: ___

7. I consent that the data collected (demographic data, eye tracking data, data related to mobility, and personal preferences) can be used for scientific purposes in an anonymous way. *

Marcar apenas uma oval.

○ Agree

Realidade Virtual

8. How comfortable are you with Virtual Reality? *

Marcar apenas uma oval.

	1	2	3	4	5	
Not Comfortable	○	○	○	○	○	Very Comfortable

9. In which context have you been in touch with Virtual Reality?

Marcar tudo o que for aplicável.

☐ For fun (games, entertainment, ...)

☐ For work (Conference calls, training simulations, design conceptualization, ...)

☐ Through University (Virtual reality classes, ...)

☐ Other scientific researches

☐ Medicine (pain treatment, phobias treatment, surgical treatment, ...)

☐ Others

Smartwatches

10. How comfortable are you with Smartwatches? *

Marcar apenas uma oval.

	1	2	3	4	5	
Not Comfortable	○	○	○	○	○	Very Comfortable

C

Stimulus' Usability Survey

At this appendix, we present the form used during VR field study to evaluate each used stimulus. This survey was conducted using Google Forms tool.

Stimulus's Usability

This questionnaire aims to evaluate how the participant felt about each presented stimulus. Therefore, for each sentence, select the answer option that most represents how you felt about the stimulus.

*Obrigatório

1. Participant ID (filled by the researcher) *

Marcar apenas uma oval.

○ P01
○ P02
○ P03
○ P04
○ P05
○ P6
○ P7
○ P8
○ P9
○ P10
○ P11
○ P12

2. Condition *

Marcar apenas uma oval.

○ Visual
○ 1P1W (Simple vibration in one smartwatch)
○ 1P2W (Simple vibration in two smartwatches)
○ 2P1W (Complex vibration in one smartwatch)

3. I found the stimulus easy to use. *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

4. I felt comfortable while using the stimulus. *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

5. I felt annoyed while using the stimulus. *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

6. I found the stimulus simple and easy to understand. *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

7. I found the stimulus useful. *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

8. I felt distracted by the stimulus. *

Marcar apenas uma oval.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

D

Ranking Cues

At this appendix, we present the form used during VR field study to assess participants' cues' order of preference. This survey was conducted using Google Forms tool.

Rank cues

This questionnaire aims to understand what was the most and least favorite stimulus for each participant, and why.

*Obrigatório

1. Participant ID (filled by the researcher) *

Marcar apenas uma oval.

○ P01
○ P02
○ P03
○ P04
○ P05
○ P6
○ P7
○ P8
○ P9
○ P10
○ P11
○ P12

2. Order the stimuli in order of preference (1 - your least favorite; 4 - your most favorite). *

Marcar apenas uma oval por linha.

	1	2	3	4
Visual	○	○	○	○
Haptico com uma simples vibração num pulso	○	○	○	○
Haptico com vibração complexa num pulso	○	○	○	○
Haptico com vibração simples nos dois pulsos	○	○	○	○

3. What were the reasons that led you to choose the stimulus as your favorite? *

4. What were the reasons that led you to choose the stimulus as your least favorite? *

5. During which condition(s) did you felt more aware of your surroundings? *

Marcar tudo o que for aplicável.

☐ Visual
☐ Haptic 1P1W (one simple vibration in one smartwatch)
☐ Haptic 1P2W (one simple vibration in two smartwatches)
☐ Haptic 2P1W (complex vibration in one smartwatch)

6. During which condition(s) did you felt less aware of your surroundings? *

Marcar tudo o que for aplicável.

☐ Visual
☐ Haptic 1P1W (one simple vibration in one smartwatch)
☐ Haptic 1P2W (one simple vibration in two smartwatches)
☐ Haptic 2P1W (complex vibration in one smartwatch)

7. You may leave here a comment on the stimuli that were used.

E

VR Scene Questionnaire

At this appendix, we present the form used during VR field study to evaluate participants' experience with the Virtual Environment. This survey was conducted using Google Forms tool.

VR Scene

This questionnaire aims to understand how the participant felt about the VR Scene.

*Obrigatório

1. Participante ID (preenchido pelo investigador) *

Marcar apenas uma oval.

○ P01
○ P02
○ P03
○ P04
○ P05
○ P6
○ P7
○ P8
○ P9
○ P10
○ P11
○ P12

2. I found the experience of walking on the virtual street real. *

Marcar apenas uma oval.

	1	2	3	4	5	
Totally Disagree	○	○	○	○	○	Totally Agree

3. I found the street real. *

Marcar apenas uma oval.

	1	2	3	4	5	
Totally Disagree	○	○	○	○	○	Totally Agree

4. During the simulation, I felt that my body belonged to me. *

Marcar apenas uma oval.

	1	2	3	4	5	
Totally Disagree	○	○	○	○	○	Totally Agree

5. How often did you notice the car passing by you? *

Marcar apenas uma oval.

	1	2	3	4	5	
Never	○	○	○	○	○	Often

6. How often did you notice the other pedestrian? *

Marcar apenas uma oval.

	1	2	3	4	5	
Never	○	○	○	○	○	Often

7. How often did you notice the pedestrian's traffic light turning red to green? *

Marcar apenas uma oval.

	1	2	3	4	5	
Never	○	○	○	○	○	Often

8. You may leave here a comment on the VR simulation that was used.