



Towards user-adapted navigation techniques in virtual environments : study of factors influencing users behavior in virtual reality

Hugo Brument

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THÈSE DE DOCTORAT DE

L'UNIVERSITÉ DE RENNES 1

ÉCOLE DOCTORALE N° 601
*Mathématiques et Sciences et Technologies
de l'Information et de la Communication*
Spécialité : *Informatique*

Par

Hugo Brument

Towards User-Adapted Navigation Techniques in Virtual Environments : Study of Factors Influencing Users Behavior in Virtual Reality

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Rapporteurs avant soutenance :

Jean-Rémy Chardonnet	Maître de Conférences, Institut Arts et Métiers de Chalon-sur-Saône
Frank Steinicke	Professeur, Université de Hambourg

Composition du Jury :

Président :	Guillaume Moreau	Professeur, IMT Atlantique Brest
Examineurs :	Jean-Rémy Chardonnet	Maître de Conférences, Institut Arts et Métiers de Chalon-sur-Saône
	Joaquim Jorge	Professeur, Institut Technique Supérieur de Lisbonne
	Anouk Lamontagne	Professeure agrégée, Université McGill
	Frank Steinicke	Professeur, Université de Hambourg
Dir. de thèse :	Ferran Argelaguet	Chargé de Recherche, Inria Rennes
Co-Dir. de thèse :	Maud Marchal	Professeure, INSA de Rennes
Co-encadrante de thèse :	Anne-Hélène Olivier	Maître de Conférences, Université Rennes 2

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List of Publications

Journal

- **Brument, H.**, Bruder, G., Marchal, M., Olivier, A. H., & Argelaguet, F. (2021). Understanding, Modeling and Simulating Unintended Positional Drift during Repetitive Steering Navigation Tasks in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics*, 27(11), 4300-4310.

International Conferences

- **Brument, H.**, Podkosova, I., Kaufmann, H., Olivier, A. H., & Argelaguet, F. (2019, March). Virtual vs. physical navigation in vr: Study of gaze and body segments temporal reorientation behaviour. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)
- **Brument, H.**, Olivier, A. H., Marchal, M., & Argelaguet, F. (2020). Does the Control Law Matter? Characterization and Evaluation of Control Laws for Virtual Steering Navigation. In International Conference on Artificial Reality and Telexistence & Eurographics Symposium on Virtual Environments (ICAT-EGVE)
- **Brument, H.**, Marchal, M., Olivier, A. H., & Argelaguet, F. (2020, November). Influence of Dynamic Field of View Restrictions on Rotation Gain Perception in Virtual Environments. In International Conference on Virtual Reality and Augmented Reality (EUROVR20). Springer, Cham., **Best scientific paper award**
- **Brument, H.**, Marchal, M., Olivier, A. H., & Argelaguet, F. (2021, November). Studying the Influence of Translational and Rotational Motion on the Perception of Rotation Gains in Virtual Environments. In Symposium on Spatial User Interaction (pp. 1-12).

Other

- **Brument, H.**, Fribourg, R., Gallagher, G., Howard, T., Lécuyer, F., Luong, T., Mercado, V., Peillard, E., de Tinguy, X. & Marchal, M. Pyramid Escape: Design of Novel Passive Haptics Interactions for an Immersive and Modular Scenario, *IEEE 3D User Interface Contest 2019*, **Best 3DUI Demo Award**
- **Brument, H.**, Marchal, M., Olivier, A. H., & Argelaguet, F. (September 2021). Poster presentation « Preliminary Results of the Impact of Translational and Rotational Motion on the Perception of Rotation Gains in VR », at the ACM Symposium on Applied Perception 2021 (SAP).

*« I'm a scientist; because I invent, transform, create, and destroy
for a living, and when I don't like something about the world, I
change it. »*

Rick and Morty, S3E3

Introduction

This thesis, entitled « Towards User-Adapted Navigation Techniques in Virtual Environments: Study of Factors Influencing Users Behavior in Virtual Reality » describes research contributing to navigation in Virtual Environments (VEs) literature. It aims at providing new insights about the influence of experimental conditions on users' navigation in Virtual Reality (VR) as well as new analyzes methods for assessing locomotion techniques to have a better understanding of human perception and action while navigating in VR.

The Desire of Navigating and Exploring Environments

Since my 20th birthday, I have had a desire to explore and discover new places. I became interested in nomadic peoples and their way of life which is mostly based on travel. Sedentary people's opinions regarding nomadic people seem as fascinated as repulsed. Free of their own movements and with little foresight, they are often considered as outlaw people, savages living in the wild, and who must be civilized. Yet, humans have always sought to explore the environments around them for diverse reasons (Figure 1). In prehistoric times, *Homo* genus has to explore its surroundings to find food, survive and reproduce; the Phoenicians, one of the most prolific seafarers and traders during the Antiquity, captains used travel logs, landmarks by day, and the moon and stars by night, to safely explore undiscovered seas; in the Middle Ages, philosophers, astronomers, and mathematicians came up with new interpretations for the workings of the world and universe; between the XVth and XVIIIth during Age of Discovery, economical challenges between the European countries led to several explorations across the world; nowadays issues regarding global warming or war make regions unlivable and force their inhabitants to migrate towards safer regions. The common variable between these examples is that, during exploration and navigation, humans always had to interact with their surrounding environment in order to reach new destinations. From walking in plains or mountains to being in orbit in a space

rocket, there exist many ways to perform locomotion and going from one destination to another. Regardless of the environment, the means to achieve navigation, and the task to achieve, or the destination to reach, humans have always found reasons to explore and interact with their surrounding environments to push the boundaries of their known world.



Figure 1 – Humans navigation in environments through history (from left to right): hunters in prehistoric era; phoenicians sailing during Antiquity; The astrolab invented in the Middle Ages to perform celestial navigation; European expeditions provided new resources and information about their surroundings environments; Mihály Munkácsy - Cigány család, a painting from the XIXth century representing a nomadic family in Hungary; ; Rockets enables space exploration that has received particular attention these last years

While locomotion in an environment is an essential daily task that is naturally performed without requiring high cognitive demand in neurotypical people, its neural processing is nonetheless complex. Successful navigation towards a goal involves safe body transportation while avoiding obstacles within the environment ([Winter 1991](#)). Then, humans must perceive a given environment and its current state in order to identify where they are located, where the objects are, what are the relations between the objects, and what actions are possible to perform ([Marshall and Fink 2001](#)). Gibson, the founder of the ecological theory of visual perception, stated that there is a strong coupling between humans and their environment. In particular, he mentioned that « We must perceive in order to move, but we must also move in order to perceive » ([Gibson 1979](#)). This means that humans interact with the environment through a perception-action loop that enables the perception of sensory information. For instance, one important motion cue perceived

during locomotion, called the optical flow, is the pattern of relative motion of objects between the walker and the environment. Such sensory information perceived from the environment allows humans to perform actions through motor commands, and then these actions provide new information to perceive and perform new movements. Thus, it is possible to perform tasks in different environments such as shopping in a supermarket, running in a park, or driving. Technological and scientific progress in computer graphics enabled simulation of 3-dimensional Virtual Environments (VEs). It is now possible to discover new environments that have never existed before, and above all to explore them.

Discovering New Environments through Virtual Reality

When I would mentioned that I was doing a Ph.D. in the field of Virtual Reality (VR), it often suggested interesting reactions. The existence of VR arouses people's curiosity, where VR seems to refer to a different reality that is not the actual reality, or even a reality that does not quite manage to be real. On the other hand, VR had received a lot of attention since its first characterization in 1965 by Ivan Sutherland. He described in his essay, *The Ultimate Display*, VR as « a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. (Sutherland 1965) » While VR is still a recent research topic and its underneath concepts are constantly evolving, the technology remains quite unknown to the general public that has already heard about it but has no idea about its functioning. In this manuscript, we refer to the definition given by (Arnaldi et al. 2003):

Virtual Reality is a technical and scientific area making use of computer science and behavioral interfaces in order to simulate the behavior of 3D entities in a virtual world that interact in real-time among themselves and with the user in pseudo-natural immersion through sensory-motor channels.

Then, VR technology allows to creation of new computer-generated environments in which users could perceive and interact with them (Jerald 2015). To provide a compelling and natural experience, interacting in VEs should be as similar as possible to interacting in Real Environments (REs). VR then must provide a real-time rendering of the VEs, a physical workspace in which users can use the VR setup and real interactions.

Human beings are always trying to push the limits of exploration but are faced with strong constraints that sometimes prevent them from discovering new territories. For example, under our feet, unknown areas are giving a vast playground for cavers. Concerning the seabed, only less than 10% of the relief beyond 200 meters depth is known. The exploration of space raises ecological and ethical questions concerning not to reproduce the same mistakes of the past. In contrast, VR and the simulation of VEs enable new possibilities for human exploration (Figure 2). For instance, reproduction of existing REs in VR is possible like in the Google Earth VR application. We can create new VEs like virtual forests or landscapes, but we can also defy the laws of physics and geometry by creating environments that follow different rules from those of the real world (e.g. noneuclidean VEs, infinite fractal VEs...). Thus, the desire of navigating in VEs remains one of the key elements of VR technology, but the way they explore VEs through VR differs from those in real life since additional hardware is required.



Figure 2 – From realistic to unrealistic VEs (from left to right): A view of the Yellowstone park in Google Earth VR app; A virtual forest from the Forest VR game; a Mandelbulb 3D VE.

In most VR setups, users are immersed in the VEs by using visual displays (e.g. screens, CAVE (Cruz-Neira et al. 1992), Head-Mounted Display (HMD), stereoscopic glasses) that enable visualization of the VE and 3D tracking technology enables movements. Over the last decade, HMDs prices started to become affordable to mass consumers, increasing the number of HMD-based VR applications in which users are immersed while no longer seeing the RE. This occlusion may influence users' perception, as the visual information gathered between REs and VEs differ, and users' actions, since the user interface provided by the VR system involves different actions to perform.

In particular, the way users navigate in VEs can be different than real walking in REs. In order for the users to have coherent feedback between the actions users perform and their perception in the VE, virtual cameras are used. The general principle consists in controlling a virtual camera in the VE that adapts to the user's movements and actions while respecting the rules defined by the VR system. Thus, during a navigation task in a VE, the user will have to control the position and orientation as well as the speed and acceleration of the virtual camera. For this,

several locomotion techniques have been designed to interpret the user's actions in order to update the characteristics of the virtual camera. It is possible to either use natural walking as in REs or a joystick to steer the virtual camera. Unrealistic locomotion techniques also exist such as being teleported from one place to another instantly or flying like a superhero. These interactions provided by the VR system can more or less stimulate the sensory systems, that is the common thread of this thesis: VR interactions devices, VR navigation techniques, and users' experience in VR may affect users' perception-action loop and in particular, the way users navigates VEs.

The Constraints of Navigating in Virtual Environments

Like in REs, users need to move in the VE to perform actions. This movement can be a simple movement of the head to observe objects as well as walking to visit a monument or to travel into the VE. Users moving in VEs are confronted with several challenges: they must be able to locate themselves in the VE, to look for the destinations where they have to go, and to know how to get there. Therefore, navigation involves the actions to move towards a new position and the route search based on a cognitive process to define a path in the environment. In this manuscript, we will only focus on movements that are physically feasible for a human being.

Locomotion is a common task performed in our daily lives and bipedal human walking remains the most common locomotion technique in REs (Steinicke et al. 2013). Likewise, locomotion is an important activity in VEs as it enables users to explore the virtual world. While virtual locomotion techniques (e.g. teleportation or steering) can be used, real walking in VR setups is considered to be the most ecological form of locomotion (Usoh et al. 1999). Implementing real walking in VEs is generally done by mapping the real position and orientation of users' head to their virtual ones. This isomorphic mapping enables to match of real movements with the virtual ones (e.g. walking one meter forward in the RE leads to walking one meter forward in the VE). This provides consistent sensory feedback between the real and virtual movements. However, walking requires a large physical workspace when exploring large VEs that typical VR setups do not have (a survey made on Reddit four years ago showed that 90% of VR users had a workspace smaller than 3×3 meters¹). This illustrates a major challenge of VR navigation that consists in creating new locomotion techniques that enable free and infinite locomotion in a VE larger than the physical workspace and based on real walking. For instance, hardware solutions such as omnidirection treadmills (Schwaiger et al. 2007a), or motion robot

1. https://www.reddit.com/r/Vive/comments/4fq44a/vr_roomscale_room_size_survey_answers_analysis/

tiles ([Iwata et al. 2005](#)) have been investigated to enable walking in VR. However, there are cumbersome, expensive, and hard to reuse in most common VR setups. Thus, in this manuscript, we rather focus on software solutions that are more used by VR consumers.

Among the alternative solutions that have been proposed for virtual locomotion in VR ([LaViola et al. 2017](#)), some encourage users' physical movement (e.g. redirected walking or walking-in-place), while others require minimal users' motion, such as virtual steering techniques or teleportation. Each technique has its benefits and drawbacks, and VR literature has been focusing a lot on assessing and comparing locomotion techniques between them. One major issue of virtual steering techniques is that they may alter the perception-action loop. For instance, users can wear an HMD and be seated on their sofa. They can use a hand-held joystick to move in the VE without moving in the RE. Then, the visual feedback in the HMD provides the perception of self-motion to the users. However, users are not moving in the REs, creating a discrepancy between the observed sensory feedback in the HMD and the absence of vestibular feedback that is provided during walking. In the case of VR navigation, a mismatch between the expected and the current movements could induce cybersickness ([Lo and So 2001](#)).

Thus, the design of locomotion techniques faces two main challenges. First, locomotion techniques should enable unlimited and unconstrained locomotion in VEs during navigation tasks. This requires either to have a large enough workspace to perform natural walking (that is in most of the cases not available), or providing techniques that do not require full movements of the users. Second, locomotion techniques in VR do not necessarily mimic natural walking and therefore may provide different perceptual feedback (or sensations).

Challenges and Research Axes

Even though numerous studies have focused on the design and assessments of locomotion techniques to provide interfaces enabling infinite and comfortable locomotion in VR, there are still some critical issues to improve their design. For instance, virtual steering techniques can still be uncomfortable as they create a mismatch between the virtual and physical movement perceived by the visual system ([Langbehn et al. 2018a](#)). Redirections techniques can be overt and therefore may break presence while navigating ([Williams et al. 2007](#)) and still require higher physical workspace than the average consumers' ones to achieve infinite walking.

One way to solve the challenges mentioned aforesaid is then to consider how users perceive through their human perceptual system, which is primordial for interacting in VR, and how the VR system might alter users' behavior during a navigation task. This requires understanding

the differences between locomotion in REs and VEs to exploit these differences in locomotion techniques. Since VR displays and locomotion interfaces alter humans' perception-action loop, it is, therefore, crucial to take into account human perception factors when designing locomotion techniques. Having a better understanding of users' perception and behavior while navigating in VR would provide insights about how to improve and provide a locomotion interface that can achieve unconstrained navigation in VEs while maximizing users' comfort. In addition, we should consider creating VR navigation experiences that reproduce at best the real situations. Since VR can be used as an experimental tool to study human behavior (Tarr and Warren 2002), it is important to get closer to ecological situations encountered in REs during VR experiences.

One objective to improve locomotion techniques could be to consider the levels at which the perception-action loop is altered. Human perception involves internal factors through multi-sensory integration, but also external factors since the task and context of the environment influence navigation behavior (e.g. walkers look at the region of the environments to maximize the degree of information to walk safely (Marigold and Patla 2007)). Furthermore, locomotion techniques involve several factors including user-related factors (age, gender, foot dominance...), the ecological context in which the navigation would be used (task to perform, the type of VE, etc.), but also parameters concerning the user interface itself (impact of HMD, navigation speed, manipulation of the field of view and optical flow, etc.). The link between users and VR interaction interfaces must be considered in both directions since users must learn how to use the system to interact with it, but at the same time, the system could also adapt to the user's actions in order to reduce its impact on the users' perception. Thus, considering knowledge from Biomechanics of human walking and Perception in addition to VR literature is an interesting approach if we want to reduce the impact of VR on users' perception-action loop.

Figure 3 describes the research's approach that we used during the thesis to investigate the impact of VR locomotion on users' perception-action loop. Users are interacting with their environment with a perception-action loop. Yet, in VR software applications, locomotion techniques are used to update users' virtual viewpoint in the VE. This provides visual feedback (green rectangular arrow) to the users that can be perceived in order to perform new actions (blue curved arrow). Users' actions include their real motion in the workspace (red curved arrow) that are additional motion cues perceived to users while navigating in a VE (green curved arrow), as well as the input device they are using to interact with the VE (blue rectangular arrow). In this manuscript, we investigated how some VR locomotion techniques factors (represented by rhombuses) could influence users' real motion and we measured this influence through metrics (represented by ellipses). We present contributions analyzing the impact of the locomotion

technique on the perception action-loop that are divided into two research axes and one transversal research axis.

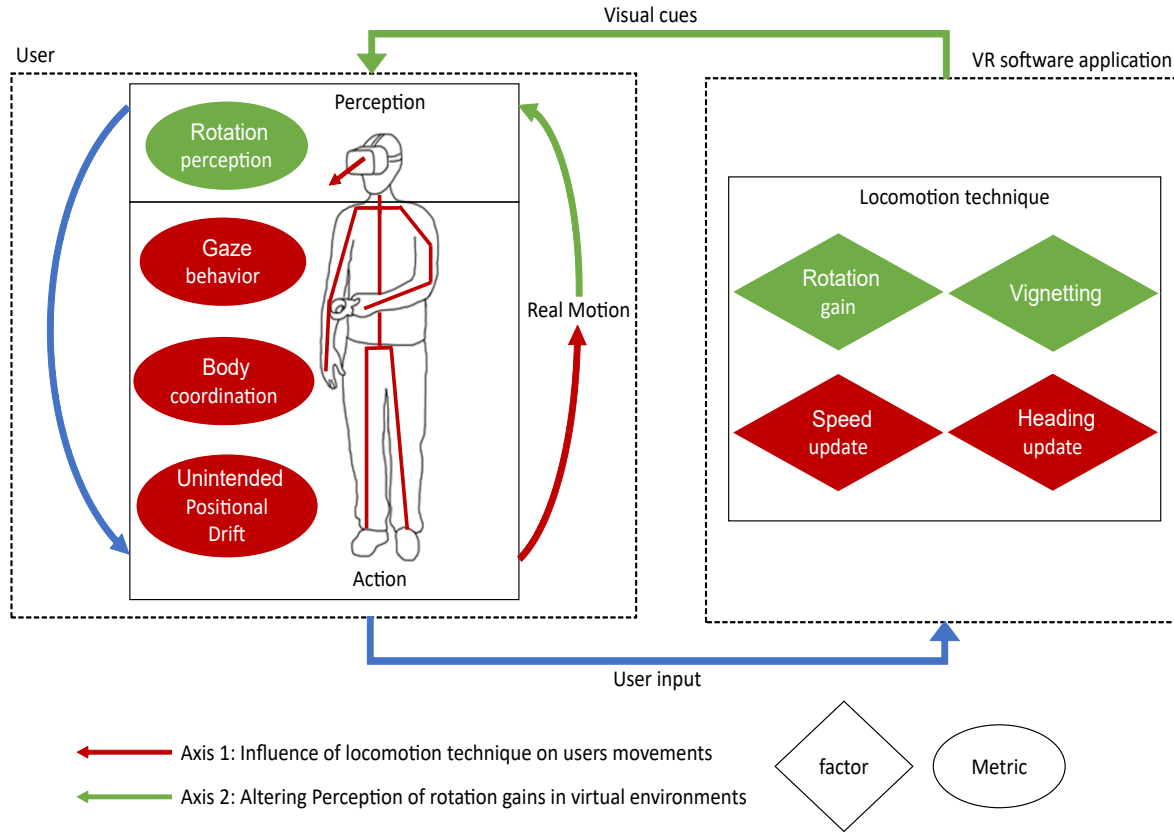


Figure 3 – Representation of some factors (represented by rhombuses) influencing users' perception-action loop. We measured the impact of these factors through metrics (represented by ellipses) measuring users' behavior while navigating in VR with locomotion techniques. The factors were separated into two research axes, one focusing on the influence of the locomotion technique on the users' movements (in red), the other focusing on how can we alter the perception of rotation gains (in green).

Axis 1: Influence of the locomotion technique and navigation task on users movements

Many locomotion techniques exist to explore VEs and their characteristics are known to influence users' navigation and experiences in VR (e.g. cybersickness, preferences, comfort...). The type of task to perform can also influence the way users navigate in VR. Yet, the impact of these techniques on users' motion in the workspace and virtual trajectories performed have been less studied in the literature. This axis focuses on how the locomotion technique, that enables movements in the VE, and the type of trajectories to perform in the VE, can modify the users' motion. Our objective was to find results regarding the impact of the locomotion technique on

user's movements in VEs. We performed first experiment to explore the differences between walking, steering and passive motion on users' gaze and body segment behavior during curvilinear trajectories. We showed that the locomotion technique can influence body coordination during VR navigation. Then, we investigated the impact of the control law (i.e., how users' virtual viewpoint is updated), and in particular the speed update, during a slalom task using a virtual steering technique. We showed that users' kinematics are altered by the control law and therefore the way that the speed is updated to navigate in VEs plays a role in users' experiences. Last, we analyzed the impact that steering techniques can have on unintended displacements of users in the physical workspace. We proposed a complete methodology to characterize, model, and simulated this particular phenomenon.

Axis 2: Influence of visual cues on perception of rotation

Perception in VR has been widely studied. In particular, to improve locomotion techniques, literature paid attention to the perception of physical rotation and how users can differentiate their physical rotation with amplified virtual rotations. It is fundamental to understand how users perceive these rotations through the different experimental conditions to improve locomotion techniques. This axis focuses on how manipulation of sensory feedback provided by the VR system to the user, and in particular the visual cues, could influence how users perceive self-rotation in VEs. In a first study, we explored how, manipulation of the users' Field of View (restricting the peripheral vision by adding blur or reducing contrast, referred as vignetting) could be used to alter the perception of rotation in VR. In a second study, while previous work has mainly considered tasks without translation, we explored how the translational and rotational speed in the VE could alter the perception of rotation gains. Our results showed that manipulation of visual cues and optical flow alter the perception of rotation gains, but they may also alter users' behavior such as their gaze activity and kinematics.

Transversal axis: New evaluations metrics and analyzes to assess locomotion techniques

This transversal axis considers new ways to assess locomotion techniques by considering new metrics. In particular, we demonstrated new results regarding gaze patterns and behavior during locomotion and proposed new statistical analyzes that could improve the understanding of users' navigation in VEs. The objective is to raise awareness to VR researchers about the usefulness to consider new evaluations metrics in VR locomotion techniques evaluations as well as taking into account the user at the center of the design of these techniques in order to assess each factors' impact on users perception-action loop.

Outline

The manuscript is divided as follows: Part I describes the state of the art regarding human navigation in both REs and VEs. We describe fundamental background about human perception and visual control of human locomotion in chapter 1, then we survey the various solutions to achieve locomotion in VR (with a specific focus on virtual locomotion techniques) in chapter 2, and their evaluations in chapter 3.

Part II reports experiments about the influence of locomotion techniques on users' movements. In particular, we evaluate the impact of locomotion techniques on body-segments coordination in chapter 4, the impact of the navigation speed on users kinematics in chapter 5 and the impact of virtual steering techniques on the unintended displacements of users in the physical workspace chapter 6.

Part III reports experiments about the influence of visual cues on the perception of rotations in VEs. We assess the influence of restricted Field of View (FoV) and manipulation of peripheral vision on the perception of rotations in VEs in chapter 7, and in chapter 8 we assess the influence of optical flow on the perception of rotations in VEs.

Part IV concludes the manuscript. First, we summarize the results and discuss them in chapter 9. Then, we provide guidelines and prospects about future work regarding the design and evaluations of locomotion techniques to improve users' VR experiences in chapter 10 before concluding this dissertation in chapter 11.

PART I

Related Work

« There are no facts, only interpretations. »

Friedrich Nietzsche

1

Perception and Action in Human Locomotion

The notion of perception constitutes the primary relationship that humans have with the external world. The perception is the preliminary to any knowledge, even the first possible form of knowledge (it is besides what indicates its Latin etymology *percipere*, meaning « to take together »). To perceive thus consists in receiving information coming from the senses and which give us information about the external world. Perception is a complex process that has been studied for several centuries, from philosophical approaches with the theory of mind from Kant (Kant 1781) to experimental approaches like Berkeley 1709 or Wundt funding the first experimental psychology lab in 1879¹. Perception is a thoughtful experience that is constrained by our representations (for example biological or social). Everything that cannot be established by vision can be mentally completed by a hypothesis: when the visual effect or other sensory inputs are not directly related to its cause, the brain makes assumptions, hypotheses about the consequences of a fact. In the case of human locomotion, it is a simulation of actions. Thus, the understanding of how visual information is modeled by humans and processed is essential to explain the relationship between perception and action.

Works from James Gibson are considered as the roots of ecological perception (Gibson 1950;

1. <https://www.simplypsychology.org/wundt.html>

Gibson and Carmichael 1966; Gibson 1979). In his first book, he covered research on depth perception by working with aviators during the second world war (Gibson 1950). He suggested that visual perception (depth and space) should be not considered as objects but surfaces of the environments. This coupling between the visual perception and the environment is emphasized in his last book (Gibson 1979). In his theory, he developed and argued that the perception is direct (i.e. information provided and perceived from the environment is meaningful) and for action (i.e. perception allows generation and control of action in an environment).

In this chapter, we describe in section 1.1 how humans perceive their environment through different physiological systems (with a strong focus on vision), how they process stimuli from the environment, and how they can interact with the environment from a perception-action loop. In addition to these fundamentals of the visual control of human locomotion, we added a foreword on the biomechanics of human walking in section 1.2, as walking remains the locomotion mode the most used by humans that is also considered as the most ecological approach to explores VEs. Last, we explain in section 1.3 how VR can alter the perceptual systems and therefore the perception of motion while navigating in VEs.

1.1 The Role of the Human Sensory System in Locomotion

The way that human perceives and acts in REs is different in VEs, as the perception-action loop is altered by the user interface provided by the VR system. According to the Human-Computer Interaction (HCI) theory, the human processor model states that human information processing can be split into three components: perception, cognition, and action (Card et al. 1986). This is inspired by how computer processes information (Figure 1.1). The user provides inputs to the computer, then the internal state of the system is updated with respect to the input and finally, the computer delivers feedback to the user. This feedback is perceived by the users who process the information and produces a new action that will be a new input for the computer. In VR, this loop is similar and repeated several times per second. For instance, the user perceives images displayed on its HMD and processes this information to decide where its future head direction would be. The head rotation is an input in the VR system and a new frame is rendered with respect to the new head direction. In this section, we describe the main sensory systems that enable users to interact with a VR interface.

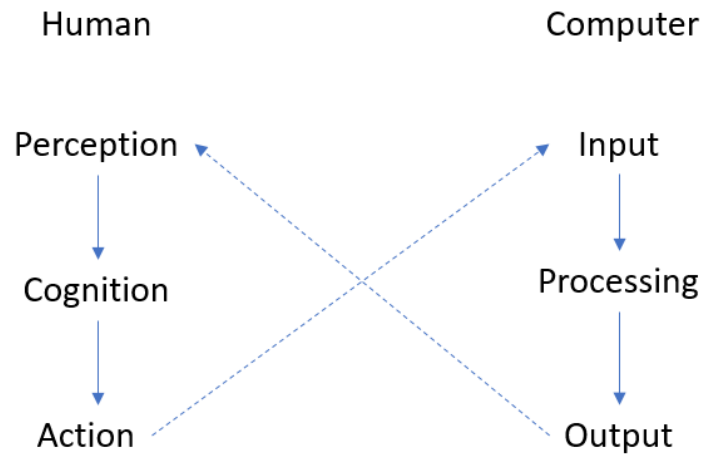


Figure 1.1 – Simplified version of human processor model (Card et al. 1986)

1.1.1 Visual Modality

Vision plays a major role during human locomotion (Warren Jr 1998). It allows the walkers to know their position in the environment, the position, and motion of the elements of the environment. The visual system is composed of the eyes, the peripheral organs that have paths connections through the visual cortex which processes visual information (Figure 1.2). The visual system enables the process of luminous signals from the environment mirrored on the retina to nerve signals via cells to build a representation of the environment. The maximal resolution of the environment is projected onto the fovea, a smaller area located at the center of the retina, through fixations (Zeki 1993).

Human vision is binocular in which both eyes are simultaneously used to create a stereoscopic vision. Two different images are perceived by the visual system for each eye. Oculomotor cues (convergence and accommodative focus) enable to provide a single stereoscopic image by « merging » both images. In human vision, the term « Field of View » (FoV) refers to the world that can be seen at any moment (Figure 1.3), and it is defined as « the number of degrees of visual angle during stable fixation of the eyes » (Strasburger and Pöppel 2002). Humans' effective visual field of view is 200° horizontally and 150° vertically (Wolpert et al. 1990). However, combining FoV of both eyes with head movements leads to a FoV up to 300°. Due to the particular sharp vision in the fovea, eyes movements are important in human locomotion in order to gather information to move safely (Marigold and Patla 2007).

There exist four basics eye movements to update points of interest and gather information in the environments: (1) **Saccades** are rapid and ballistic eye movements. They enable abruptly

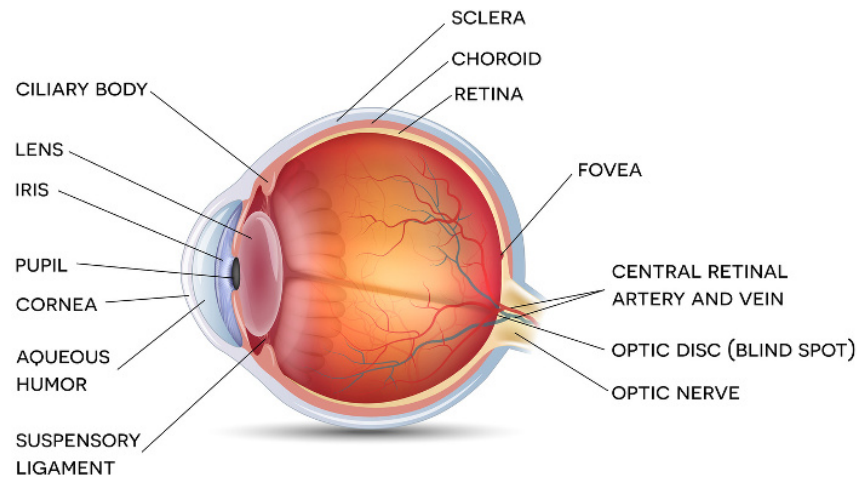


Figure 1.2 – Cross-section schema of the eye anatomy (<https://www.provisu.ch/en/dossiers-en/eye-and-vision.html>)

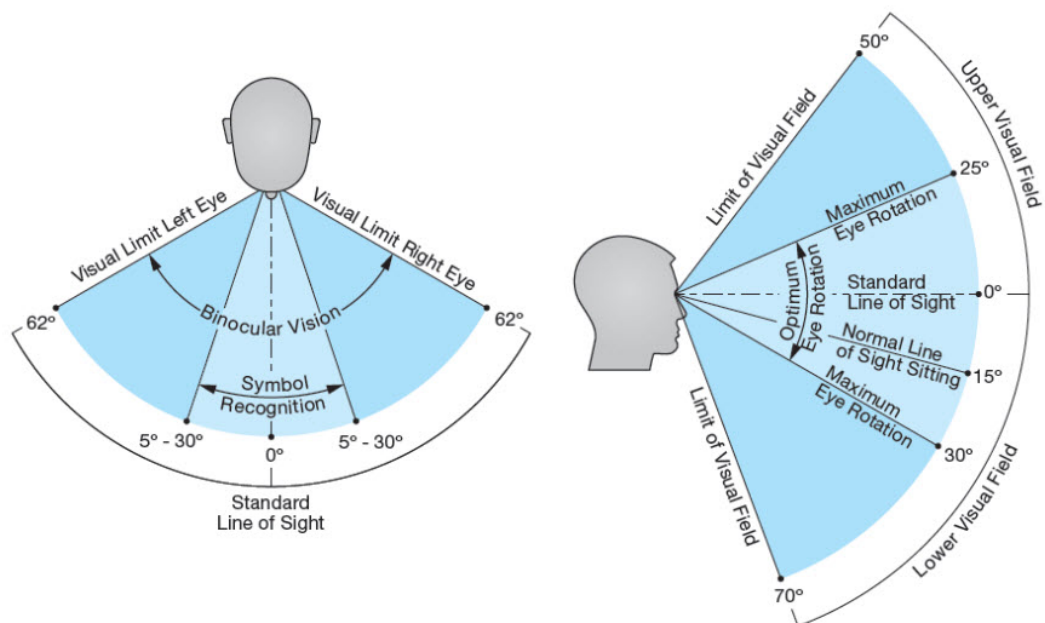


Figure 1.3 – Human Field of View: Horizontal angles on the left and Vertical angles on the right (<https://www.quora.com/What-is-the-maximum-human-field-of-vision>)

change the point of fixations. (2) **Pursuits** are slow tracking movements to maintain the point of interest in the fovea. (3) **Vergence** are movements that align the fovea of each eye with elements located at different distances from the observer. They imply either a convergence or divergence of each eye to observe an object respectively nearer or farther away. (4) **Vestibulo-Ocular Reflex**

(VOR) consists of movements that stabilize the eyes by compensating the head movements. Since head position varies during locomotion, these reflexes prevent bad projection of visual images on the surface of the retina. Head movements are thus compensated by the eyes with movements that have the same distances but opposite directions. These typical movements allow walkers to maximize the degree of information in the environments to navigate safely.

1.1.2 Other Sensory Modalities

The sense of hearing is provided by the auditory system, which is composed of the ears (the sensory organs) that are connected to auditory parts of the sensory system. The anatomy of the ear can be decomposed into three components: outer, middle, and inner. The outer ear forwards sound waves through the ear canal, that hit the tympanic membrane that vibrates small bones in the middle ear (malleus, incus, and stapes). That provokes movements of the fluid contained in the inner ear that stimulates receptors (hair cells). The sounds waves are then converted into nerves pulses in the cochlea. While auditory cues are not the scope of this manuscript, it is worth noticing that they can provide information about the distance of objects in environments ([Zahorik et al. 2005](#)).

In addition to the auditory system, the ear contains another one contributing to the sense of movement and balance: the vestibular system. In particular, the inner ear contains two components: two otoliths and three semicircular canals disposed orthogonally on the three main euclidean planes ([Berthoz 2000](#)). Otoliths are responsible for indicating linear accelerations (*macula sacculi* detects vertical acceleration whereas *macule utriculi* detects horizontal ones). Semicircular canals are responsible for indicating rotational accelerations (the *horizontal* one detects rotational movements on the horizontal plane, the *anterior* and *posterior* ones detects movements on the frontal and sagittal planes). Like the auditory system, the mechanical translations and rotations performed during a navigation task push fluid contained in the inner ear on the *cupula* which contains hair cells that transform the movements into electrical signals. While vision remains the dominant sensory system for navigating, the vestibular cues also contribute to human navigation ([Chance et al. 1998](#)).

Other sensory systems exist and can be stimulated. The somatosensory system is a complex system that is in charge of the sense of touch (tactile and kinesthetic/haptic). Tactile perception relies on mechanoreceptors under the skin that can feel pressure, pain, and temperature ([Johnson 2001](#)). Other receptors located on muscles and joints enable kinesthetic perception. Haptic perception can be either active (if a person explores a surface or an object) or passive (if a person is being touched or moved by an external force). In combination with proprioceptors, the central

nervous system can integrate the sense of self-motion, and the position of the body and limbs, that is called proprioception. During walking, the somatosensory system and proprioception sense play a role as they can detect contacts between feet, in which the sole is one of the most innervated parts of the human body (Berthoz 2000), and the surfaces humans are walking on while maintaining an overall representation of body position and movements (Berthoz even describe the sense of movement as our sixth sense). In addition, proprioception describes the perception of self-movements (kinesthetics) and the position of the body and limbs. While the scope of this manuscript does not focus on haptic feedback, it is worth noticing that it is an important research field in VR (Klatzky and Lederman 2003; Costes et al. 2020; Mercado et al. 2021; Hamza-Lup et al. 2019). Regarding navigation and haptics, it enabled in particular solutions for people with impaired vision to explore VEs (Kreimeier and Götzelmann 2020).

Last, the olfactory and gustatory systems, respectively responsible for the sense of smell and taste, are less not directly involved during human locomotion. They are not in the focus of the manuscript.

1.1.3 Multisensory Integration

During a locomotion task in a given environment, information from different sensory systems can be perceived. These cues can sometimes be related to the same characteristics. For example, while walking in an environment, several systems are involved and interact with each other such as the visual and the vestibular ones, but also the neck proprioception and efference copy of the motor command to perform (i.e. an internal copy of an efferent movement-producing signal generated by the motor system) (Holst and Mittelstaedt 1971). The visual system enables the disambiguation of the perceived feedback from the vestibular system. There exists a strong coupling between the organism interacting with its environment, in which sensory cues from the environment are perceived by the sensory systems, and processed by the central nervous system to regulate actions in the environment that will generate new sensory cues (Figure 1.4, Figure 1.5). Thus, multisensory information studies how multimodal perceptual cues from the environment can be integrated by the nervous system and transmitted to the organs to generate motor control (Stein et al. 2009).

Multisensory integration considers each sensory input that can contribute to perception. In the literature, two main models are used to describe the integration. First one relies on maximum-likelihood estimation (Equation 1.1). Based on statistical theory, its output is computed as the

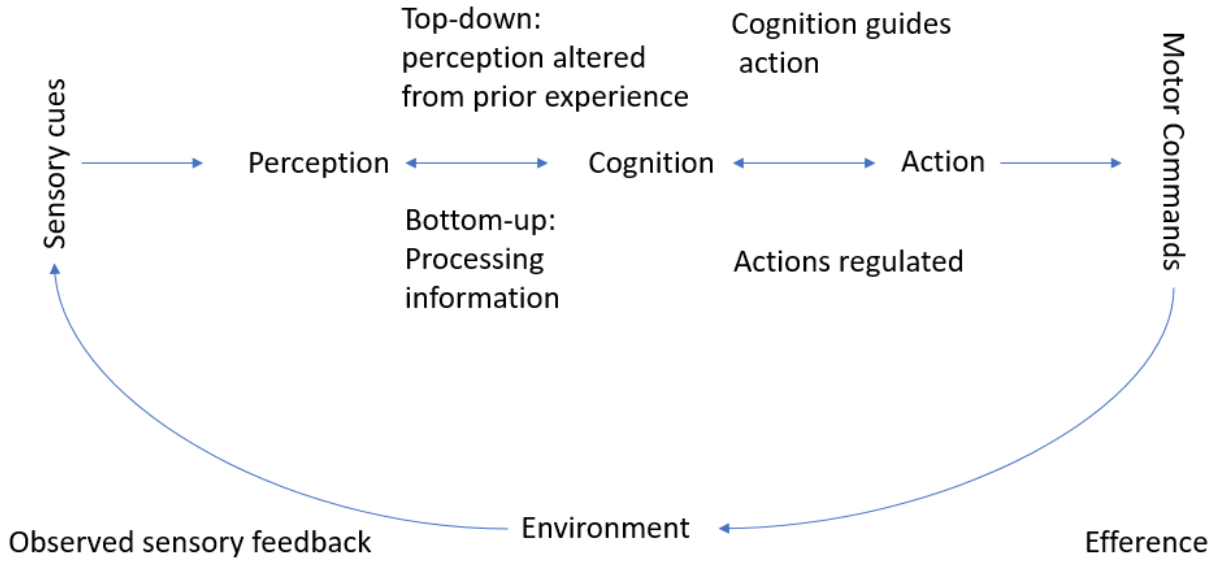


Figure 1.4 – Perception-Action Loop in REs (adapted from Steinicke’s keynote B(1)ending Realities)

most likely combination of the weighted sensory inputs:

$$I = \sum_{k=1}^N w_k \cdot i_k \quad (1.1)$$

with I the estimation of the integrated sensory information, i_k the sensory cues perceived by one sensory system, and w_k its normalized weight. Then, the quality of the sensory information determines its weight in the computation. For instance, the visual system will be predominant in a goal-directed task if the goal to reach is clearly visible (Posner et al. 1976). One shortcoming of this approach is that it only considers the sensory cues. The second model is based on Bayes inference and combines sensory information with prior knowledge regarding the environment to disambiguate sensory information (Angelaki et al. 2009).

While interacting with a VR system, the perception-action loop becomes altered since the sensory feedback from the VE is provided by a user interface (Figure 1.6). To deal with these modifications, the central nervous system uses efference copies that are processed in an internal forward model to predict the future effects of action by comparing the output of the forward model (predicted sensory feedback) with the perceived sensory feedback provided by the VR setup (Jeannerod and Arbib 2003). This mechanism finally helps humans to achieve sensory discrepancies and enable predictions of movements before they occur (Harris et al. 2002). The

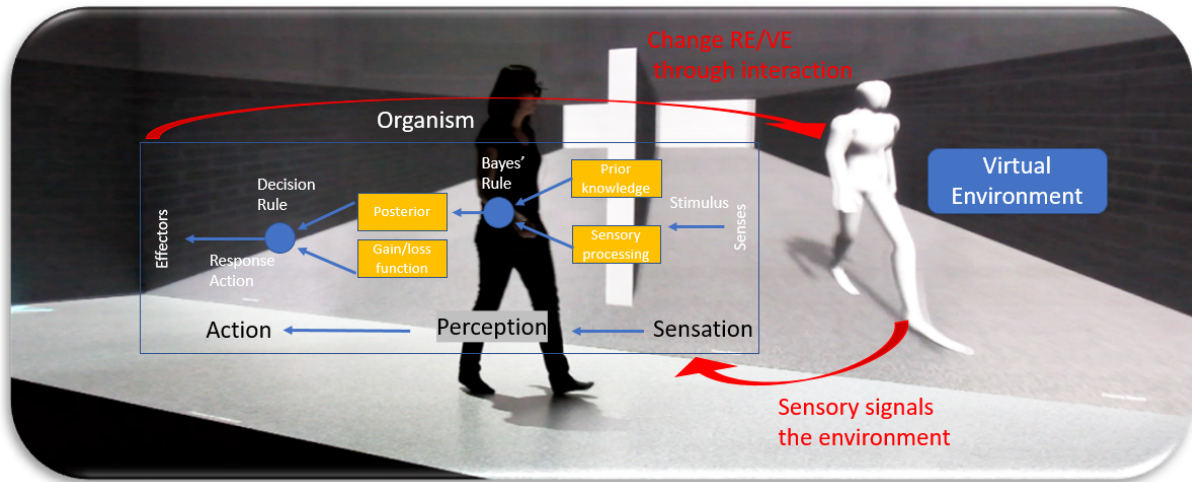


Figure 1.5 – Perception-Action loop and Multisensory integration adapted from (Ernst and Bühlhoff 2004).

differences between the actions performed by the user in real and the sensory feedback provided by the VR system can therefore be different. For instance, if a seated user navigates in a VE through a joystick, the user would see a virtual movement in the VE while being steady in the real one. This can cause some discomfort while navigating. This phenomenon, similar to motion sickness that occurs during passive motion like in public transports, is well known and is called *cybersickness*.

Cybersickness can cause discomfort and symptoms such as nausea, dizziness, headache and ocular fatigue (Rebenitsch and Owen 2016; LaViola 2000). The most plausible explanation about *cybersickness* remains the conflicts between sensory information and in particular the visuo-vestibular conflict (Rebenitsch and Owen 2016). Yet, other theories suggest that it could be caused by the constraints of the control of action (Riccio and Stoffregen 1991), or even the poison theory (Reason 1978). In VR, common approaches to measure *cybersickness* are the use of questionnaires (Kennedy et al. 1993), physiological signals (Kiryu et al. 2008), EEG signals with deep learning methods (Pane et al. 2018; Jeong et al. 2018) or postural analyses (Chardonnet et al. 2017). Thus, it is important to consider the multisensory integration in order to mitigate *cybersickness* during VR experiences (Weech et al. 2018).

1.1.4 Psychophysics

Psychophysics is one research tool to assess human sensory functions (Prins et al. 2016). It allows the investigation of the relationship between physical stimuli and their sensory representa-

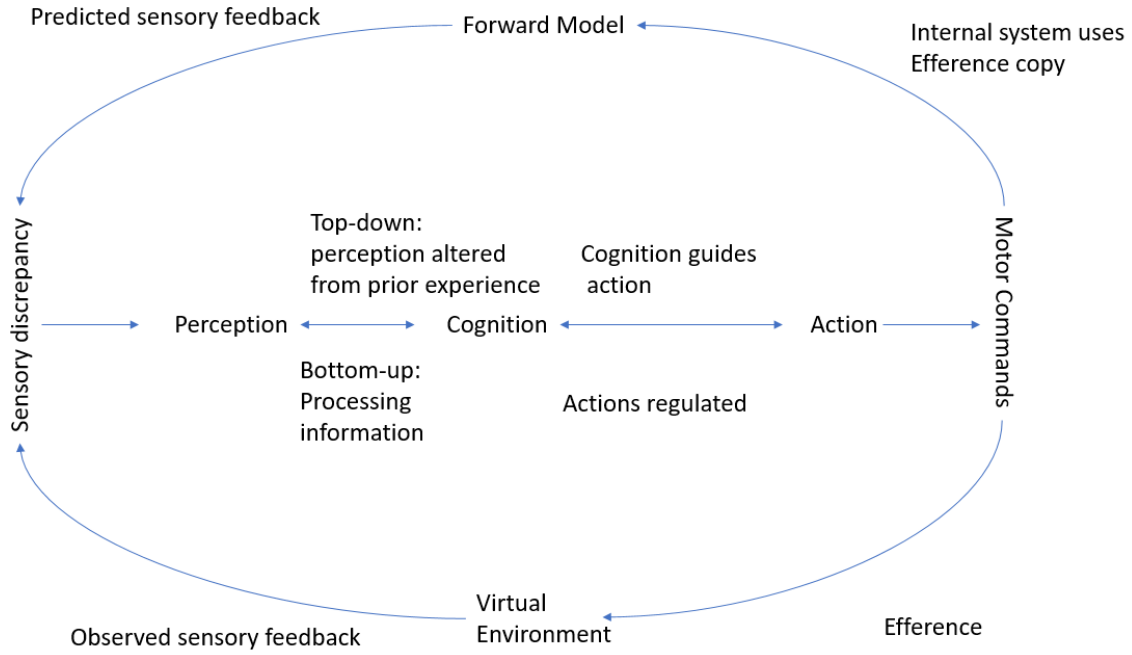


Figure 1.6 – Perception-Action Loop altered in VEs (adapted from Steinicke’s keynote B(l)ending Realities)

tions (i.e. their subjective perception by humans). The research question behind psychophysics experiments is to determine how a person can consciously detect physical stimuli (e.g. visual, auditory, or haptic stimulus).

Most empirical relationship found in psychophysics is Steven’s power law ([Stevens 1957](#)). It characterizes the exponential relationship, that can be applied over a wide range of stimuli and sensory systems, between the magnitude of a stimulus and its perceived magnitude (Equation 1.2).

$$p = cm_s^x \quad (1.2)$$

where p is the perceived magnitude, m_s is the magnitude of the stimulus, x the exponent defining the relation between the stimulus and its perception, c is a constant depending on the units. In case of perception of angular acceleration, it has been shown that the exponent value was around 1.4 during 5 seconds rotation stimulus ([Elsnert 1971](#)).

The Just Noticeable Difference (JND) defines the relation between the intensity of a stimulus and the perception of noticeable changes in this stimulus. The JND consists of the relative amount of the stimulus that needs to be changed to perceive a modification in at least 50% of

trials. The relation between the JND and the magnitude of the stimulus varies following Weber's law (Equation 1.3).

$$\frac{\Delta m_s}{m_s} = c \quad (1.3)$$

where Δm_s is the JND, m_s the magnitude of the stimulus. For instance, in the case of perception of linear speed, if a passenger in a car perceives the speed around 100 kilometers per hour, he may not notice a difference if the car speeds up to few kilometers whereas he must notice a change if the car speeds up around 50 kilometers per hour.

Detections thresholds (DTs) are defined as absolute intensity at which persons detect or not a given stimulus. This means that every stimulus above a DT should be perceived by humans whereas every stimulus below this DT should not be perceived. However, many variables can bias the perception of stimuli during a psychophysical study (e.g. prior knowledge of the experiment design, human factors, and variability). Then, in the case of psychophysics studies, researchers are generally interested in 25% and 75% DTs (values at which people can have respectively 25% and 75% of chances to detect a given stimulus), but also the 50% DT usually called the Point of Subjective Equality (PSE). PSE is the DT that is equally likely to be judged as higher or lower than a reference stimulus.

There exists different experimental protocols to assess DTs and PSE of physical stimuli such as staircase method, method of adjustment, or method of constant stimuli that are not the scope of the manuscript. We will only focus on one protocol called Alternative Forced-Choice (AFC) (Bogacz et al. 2006). AFC tasks consist in exposing users to different intensities of a given stimulus (e.g., in the case of virtual navigation, the amplification of the virtual rotation concerning the physical rotation). At each exposition, users have to answer a question, like « Was the stimulus more or less intense than a previous given reference stimulus? », and they must provide an answer (i.e., answers like « I do not know » are not possible). AFC tasks avoid participant response bias as participants are forced to guess even when they are unsure of the stimulus. On average, when participants do not know the answer, if participants answer randomly, they will be correct 50% of the time. These protocols are useful in VR evaluations as they enable to determine users' sensitivity for a given stimulus. For instance, in the case of human locomotion, it can help to understand users' motion perception such as translations (Zhang et al. 2018) or rotations (Steinicke et al. 2010).

1.2 Properties of Human Walking

Walking is the most used motion in daily life by humans. Learned during child's development, it becomes a completely natural action later on. This makes human walking an interesting paradigm for navigating in both real and virtual environments. Yet, walking remains a sophisticated action that we will briefly describe in the following subsections.

1.2.1 Walking Gait

Bipedal walking is an exclusive feature of human locomotion that does not exist in other primates. Walking can be considered as a cyclic action ([Gage 1990](#)) as each step follows a similar pattern over time, and can be decomposed into two actions: steps and strides. The step cycle includes a stance phase where the foot is on the ground and a swing phase where the leg is swinging in the air to prepare the foot strike ([Vaughan et al. 1992](#)). When the stance phase begins, both feet touch the ground. Then, the other leg will initiate swinging (i.e. one foot remain on the ground). Finally, the other foot that was in the swing phase will reach the ground and both feet are in contact with the ground again. In terms of proportion, the stance phase corresponds to 60% of the total cycle whereas the swing phase 40%. Since the walking cycle is symmetric between both legs, the average gait cycle can be represented as in Figure 1.7.

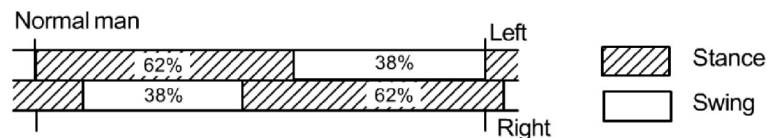


Figure 1.7 – Walking Cycle ([Vaughan et al. 1992](#))

According to ([Vaughan et al. 1992](#)), it is possible to more accurately decompose the walking cycle with respect to events (Figure 1.8):

- Stance phase: (1) Heel strike starts the gait cycle; Foot-flat consists in the foot reaching the ground ; (2) Midstance is the moment in which the swinging foot overtakes the stance foot; (3) Heel-off occurs as the heel loses contact with the ground; (4) Toe-off concludes the stance phase as of the foot leaves the ground.
- Swing phase: (1) Acceleration starts when the foot leaves the ground accelerates forward; (2) Midswing is the moment when the foot passes beneath the body; (3) Deceleration enables to slow down the leg and stabilize the posture to initiate the next heel strike.

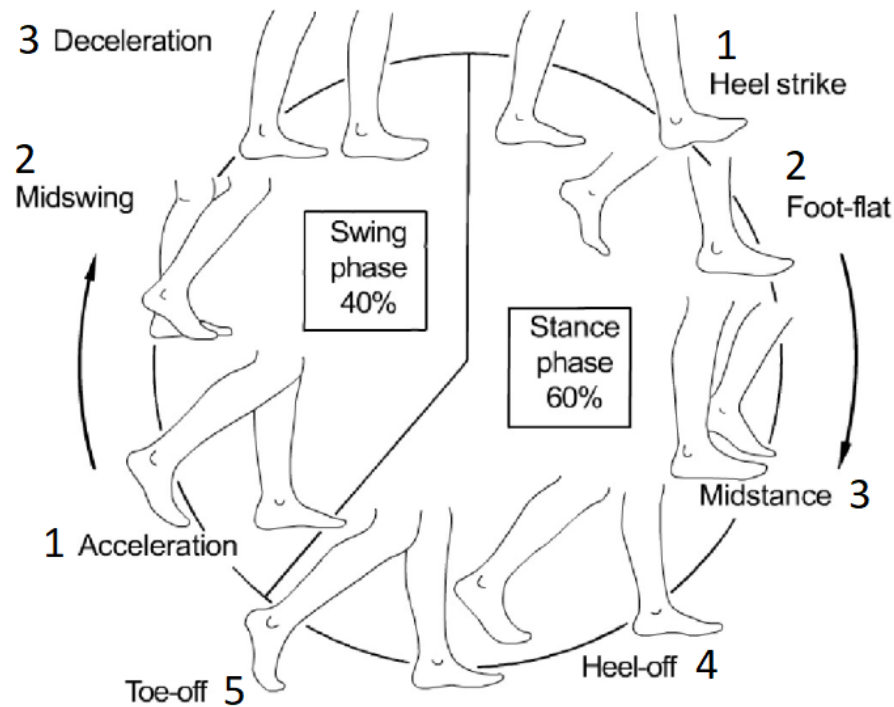


Figure 1.8 – Detailed Walking Cycle (Vaughan et al. 1992)

The head plays a major role in the walking gait. To maintain a dynamic stabilization of walking over time, the head has to be stabilized as well (Pozzo et al. 1990). Berthoz illustrated this fundamental property in his book « The brain's sense of movement ». He superposed photographs taken by Muybridge of a man in movement (Figure 1.9), he noticed that the line separating the external corner of the eye and the meatus of the ear remains parallel, indicating stability in rotation. This stabilization seems possible thanks to the vestibular system. Thus, the head works as a stable inertial platform to control gait and movements (Pozzo et al. 1990; Berthoz 2000) that allow also coordination of tasks implying human movements. The human gait can be altered after health issues such as stroke (Lamontagne and Fung 2009) or proprioceptive deficits (Reed-Jones and Vallis 2007) challenging postural control and locomotion. After explained we explained how human walking is accomplished, we will now follow up with the quantitative parameters that define the kinematics and dynamics of the human walking cycle.

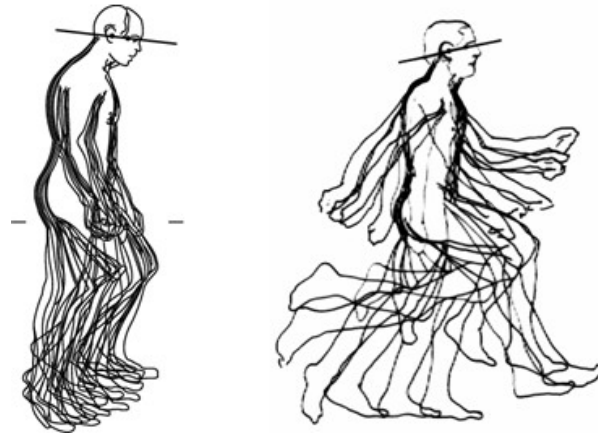


Figure 1.9 – Stability of the head during locomotion. By superimposing photographs taken by Muybridge of a man in movement, Alain Berthoz notices that the line separating the external corner of the eye and the meatus of the ear remains parallel. This indicates the stability of the head in rotation which would be possible thanks to the vestibular system (Berthoz 2000)

1.2.2 Locomotion Control Laws

In the case of linear walking (i.e. walking forward on a straight line), the walking speed (V) is a function of the step length (L) and the step frequency (F) (Equation 1.4).

$$V = L \times F \quad (1.4)$$

Then, to increase the walking speed, walkers have to increase both step length and frequency. Research work noticed that walkers tend to increase first the step length until a certain limit before increasing the frequency (Emmerik and Wagenaar 1996). However, there exists one invariant in the case of ground walking, called the walk ratio (defined as L/F), that remains constant over wide ranges of speed (Sekya et al. 1996). Since casual walking optimizes the energy costs that make walking a thrifty locomotion technique, it seems the walking pace, in general, is moderate and constant over a prescribed distance. In general, the average casual walking speed is around $1.4m/s$ but is slightly higher for people under 40 and lower for people older than 60 (Bohannon 1997).

The results from the previous paragraph were only observed during straight walking. In the case of non-linear walking (e.g. curved path involving rotations), the problem is more complex. For instance, the definitions of step width and length are discussed in the Biomechanics community. We refer to (Huxham et al. 2006) definition (Figure 1.10). Performing quick whole-body rotations while still maintaining balance and some momentum can be difficult. There exist

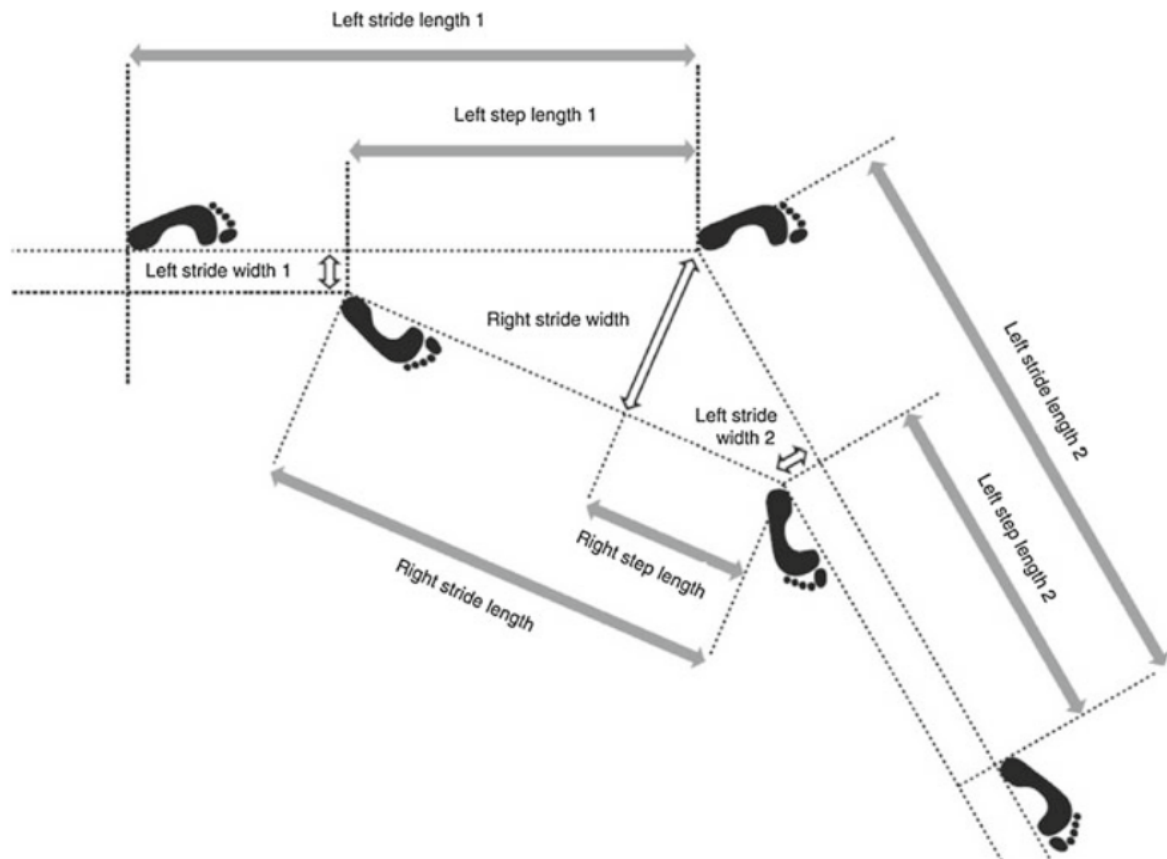


Figure 1.10 – Step length and width definition during curved walking (Huxham et al. 2006)

two main strategies to perform a turn that are based on feet placement (Hase and Stein 1999): (1) In the step-turn strategy, the change of direction is opposite to the contact foot (i.e. to turn left when the right foot is in front, subjects shift weight to the right leg, externally rotate the left hip, step onto the left leg, and continue turning until the right leg step in the new direction). This strategy tends to minimize the risk of falling by enlarging the base of support (area delimited by the borders of both feet). (2) In the spin-turn strategy, change of direction and contact foot are the same (i.e. to turn to the right when the right foot is placed in front, subjects generally altered direction by spinning the body around the right foot). This strategy reduces the base of support but allows faster rotational movements. In the case of curved trajectories during walking, some authors showed a preference for the step-turn strategy over the spin-turn one (Akram et al. 2010).

Regardless of the turn strategy used, research work regarding the generation of trajectories during goal-directed tasks generated some invariants. For instance, there exists a stereotypy of both trajectories and velocity profile generated (starting from a given position and orientation

and reaching another given position and orientation) in REs (Hicheur et al. 2007) and VEs (Cirio et al. 2013) (Figure 1.11). Additional research work showed how these stereotyped locomotor trajectories are generated (Arechavaleta et al. 2006; Arechavaleta et al. 2008b; Arechavaleta et al. 2008a). It seems that the optimization of trajectory tends to maximize the smoothness of the trajectory (Pham et al. 2007), and in particular minimizing the jerk (a derivative of the acceleration). Besides, there exists a relation between the speed and the curvature of the trajectory. First discovered for hand-writing trajectories (Viviani, Terzuolo, et al. 1982) and then for human locomotion (Vieilledent et al. 2001; Hicheur et al. 2005b), this relation specifies that during a continuous trajectory, the instantaneous speed varies according to the local radius of the curvature as a power law (Equation 1.5):

$$S(t) = K.R(t)^{\frac{1}{3}} \quad (1.5)$$

where $S(t)$ is the horizontal speed at time t , K is a constant, and $R(t)$ is the radius of the local curvature of the trajectory at time t . However, this relation does not describe every non-linear movement, where literature suggests that K may depend on the geometry of the trajectory and the one-third power may only apply to elliptic trajectories.

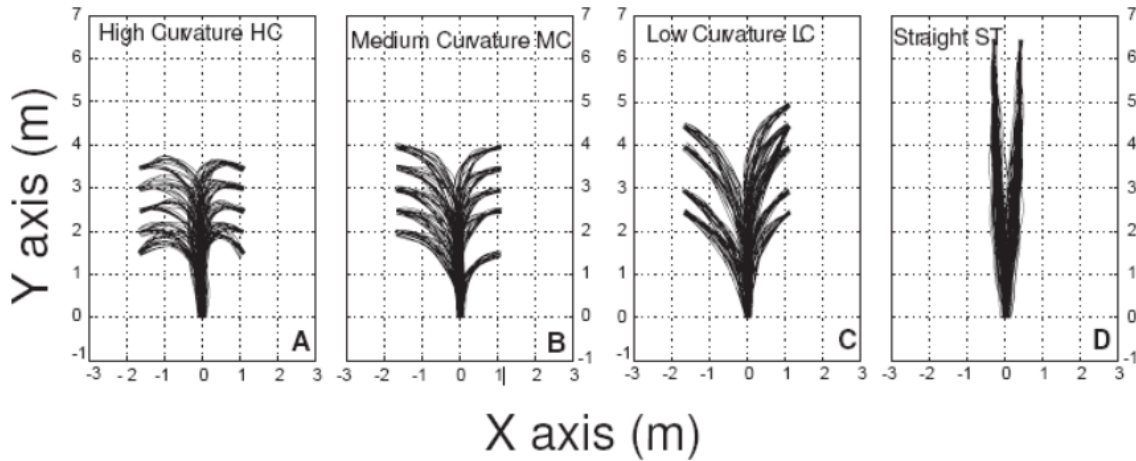


Figure 1.11 – Stereotypy of trajectories during goal-directed task regardless the curvature of the trajectory: A) high curvature, B) medium curvature, C) low curvature, D) straight line (Hicheur et al. 2007).

1.2.3 Body Segments Coordination

One interesting property during locomotion task with curved trajectories is that there exists a hierarchical « top-down » control during walking (Figure 1.12). The head anticipates the future direction, meaning that head orientation is not tangent to the locomotor path but always oriented towards the future direction before the other body segments such as the torso, the trunk, and the feet. Besides, the gaze has an important role in the control of locomotion. The control of movement during a change of direction can be associated with a strategy « I'm going where I'm looking » instead of « I'm looking where I'm going » (Prévost et al. 2003). In addition, to play an anticipatory function, the head and gaze would have an active role in guiding the body towards the future direction (Hollands et al. 2002) by providing a reference image for the control and reorientation of the body (Grasso et al. 1998; Hollands et al. 2001; Prévost et al. 2003).

In REs, several studies considered the eye and head coordination in relation to body segment synergies. The head anticipation has been observed with different experimental conditions: lemniscate (Hicheur et al. 2005a); trajectories at 90° (Grasso et al. 1998), but also trajectories at 30° and 60° (Hollands et al. 2002); walking forward or backward (Grasso et al. 1998); with or without vision (Courtine and Schieppati 2003; Authié et al. 2015); using different walking speeds (Prévost et al. 2003). No matter what the experimental conditions are, the head always anticipates the future direction. Researches showed that the head anticipates 200ms before the body (Grasso et al. 1998; Bernardin et al. 2012). Moreover, some studies showed that it also depends on the global trajectory where the higher the curvature of the path, the higher the anticipation is (Hicheur et al. 2007; Bernardin et al. 2012). Finally, this anticipation behavior was reinforced thanks to a study that immobilized the head to the trunk where results showed that the trunk reorients itself faster to align the head towards the future direction (Hollands et al. 2001).

In VEs, few works have investigated gaze and body segments behavior during navigation tasks. For instance, in a VE where the motion was simulated at different speeds, Grasso et al. found that during 90° turns the head turns at a constant distance instead of a constant time (Grasso et al. 2000). Reed-Jones et al. 2009 studied the effects of constraining eye movements during a 90° turn in a VE while walking in place. They found a significant difference in temporal and spatial coordination of body segments between free gaze and fixed gaze navigation. In free gaze condition, the top-down reorientation strategy is similar as in walking in RE (eyes then head, trunk and pelvis) whereas in fixed gaze condition the body segments moved in unison (« en-bloc »). These results point out that eye movements trigger the coordination of the whole-body reorientation in 90° turns. For further information, a recent survey gathered the studies investigating body segments coordination (López et al. 2019). In this section, we showed

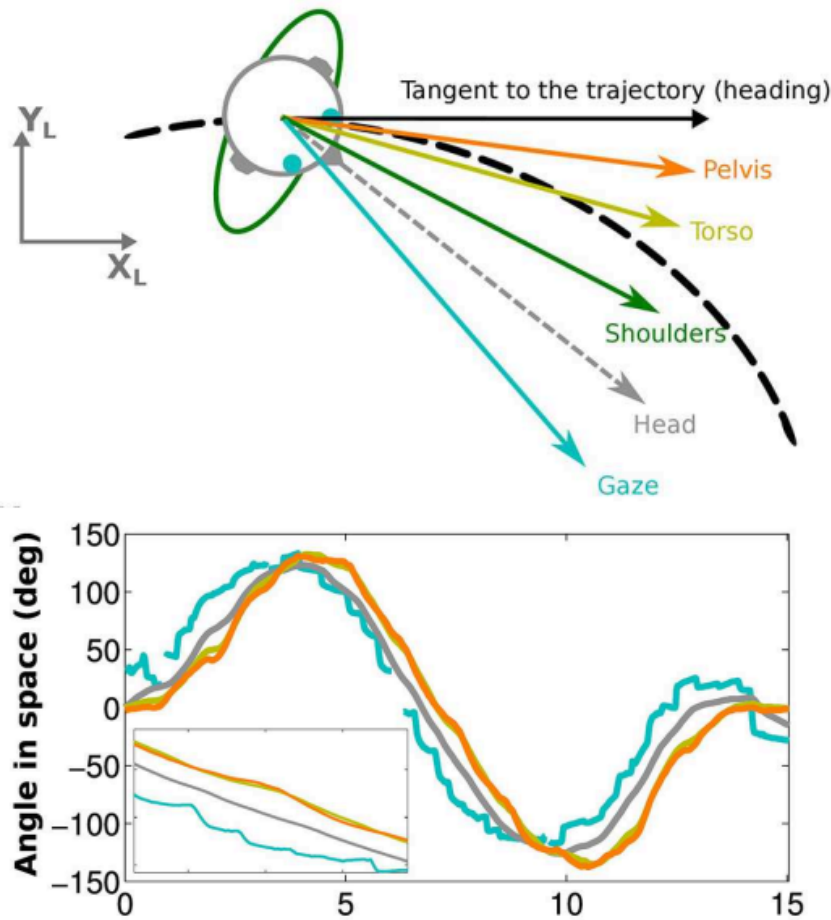


Figure 1.12 – Top down reorientation strategy while walking: gaze anticipates the future trajectory before the head, the torso and the pelvis. At the bottom, a typical example of the amplitude (in degrees) of body segments showing their orientation across time ([Authié et al. 2015](#)).

experimental results that confirm the idea that the perception of human movement is constrained by his motor repertoire (i.e., the laws of movement extracted from his motor skills). However, it is also necessary to consider how walkers perceive motion while navigating in environments.

1.3 Human Perception of Motion

In order to perform navigation tasks in environments, humans have to accurately estimate their heading (direction of navigation) and navigation speeds, but also the distances, speeds, and direction of potential objects in the surrounding environment. Extracting cues from the environment is then necessary to integrate the perception of self-motion in both REs and VEs. One

requirement of VR locomotion techniques is to enable navigation performance and comfort close to walking in REs. Unfortunately, research work demonstrated that navigation in VE generates mismatch perceptions compared to RE (Steinicke 2019). For instance, distance perception is an active research field in VR, and studies showed that users tend to overestimate short distances and underestimate large distances (Loomis et al. 1993), however, this cue is not in the scope of our manuscript and readers can refer to the following review for further information (El Jamiy and Marsh 2019; Renner et al. 2013). We will focus on the perception of direction (heading) and speed during navigation tasks in REs and VEs.

1.3.1 Perception of Direction

During navigation in REs, the patterns of light surrounding the observer are systematically changing over time. These changes, known as the optical flow (Gibson 1961), are due to the lights reaching eyes through surfaces and objects that have their textures in the environments. Optical flow provides a rich source of information about the structure of the environments and their apparent movement through them. When an observer acts and moves through an environment, every surface and texture exhibits its own relative motion. One common example to illustrate this point is from Gibson's early research work in which he explained the variation of optical flow when aviators fly over an airstrip or when people stare at the side view from a moving train (Figure 1.13). Therefore, the optical flow provides specific information of the apparent motion: (1) The motion in the environment is indicated by the flow of the ambient optic array whereas the absence of flow indicates a stagnancy within the environment. (2) Forward motion is indicated by the outflow (i.e. the flow that expands from in front and past the observer) whereas backward motion is indicated by the inflow (i.e. the flow that comes from behind the observer). (3) The Focus of Expansion (FoE) is the central point in the outflow and indicates the current direction of motion (heading). (4) A change of the FoE indicates a change of heading.

Gibson's theories (Gibson 1979) suggested that the heading is determined from the center of expansion of optic flow. This has been demonstrated for linear (Warren et al. 1988) and non linear paths (Warren et al. 1991; Burlingham and Heeger 2020). However, this strategy is discussed and Rushton proposed another strategy that aims at aligning the locomotor axis with the perceived egocentric direction of the target to reach (Rushton et al. 1998). Warren et al. further investigated whether the egocentric direction hypothesis or the optic flow hypothesis dominates (Warren Jr et al. 2001). Both strategies are used during locomotion steering (Warren Jr et al. 2001), with a different predominance depending on the amount of available visual information (Turano et al. 2005).

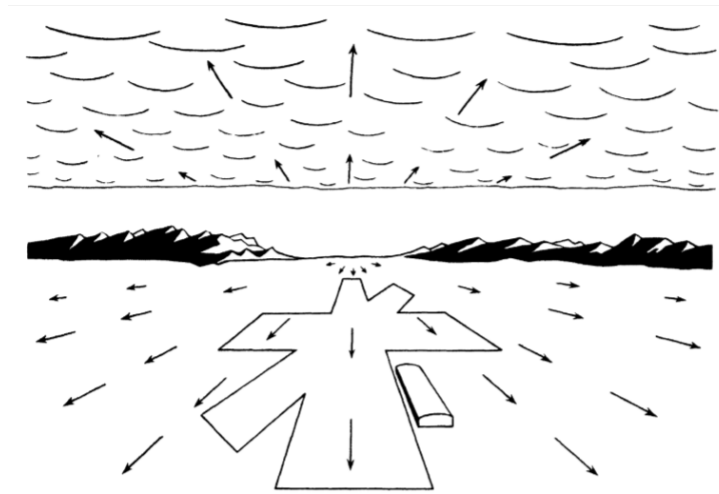


Figure 1.13 – Optical flow for an observer in translation. The focus of expansion, represented here at the center of the image, corresponds to the point from which the motion vectors radiate ([Gibson 1979](#))

In VEs, some studies demonstrated that users can determine precise heading direction based on dense motion parallax and references objects in the environment ([Li and Warren Jr 2000](#)). Furthermore, steering behavior can be altered while walking with an HMD, either by shifting the Field of Expansion ([Sarre et al. 2008](#)) or modifying the field of view patterns ([Chou 2005](#)). The particularity of navigation in VEs is that locomotion techniques that do not require walking can be used. Thus, perception of self-motion can be triggered differently ([Lappe et al. 1999](#)). Locomotion techniques enhance vection (i.e. a conscious experience of self-motion ([Palmisano et al. 2015](#))), which is induced by optokinetic stimulation and other sensory systems such as the vestibular one. Then, to generate self-motion illusions in VR setups, sensory stimulation is recommended. The reader is referred to ([Riecke 2010](#)) for a review.

1.3.2 Perception of Speed and Acceleration

Changes of position over time produce movement that defines the speed (i.e. the derivatives of position over time), which is fundamental during navigation as it enables to control the pace of the motion in order to navigate safely (e.g. avoiding obstacles). While visual cues provide information to perceive linear speed, the visual system is rather insensitive to accelerations ([Watamaniuk and Heinen 2003](#)). Overall, high changes of speed (around 30%) are required in order to detect accelerations ([Brouwer et al. 2002](#)) and it is also worth noticing that speed judgments can depend on the shape and direction of motion ([Manning et al. 2018](#)). In addition, peripheral vision is an

important cue for the perception of speed. A study showed that diagonal FoV lower than 60° can lead to underestimation of speed (Pretto et al. 2009). In VR, several studies showed that users tend to underestimate the navigation speed (Nilsson et al. 2015; Tran et al. 2018). Banton et al. 2005 suggested that the smaller FoV in HMDs could be one reason for this underestimation. Indeed, wearing an HMD reduces the amount of information in the peripheral area (Jones et al. 2013), which is known to provide accurate cues regarding motion perception (Hood and Leech 1974). In addition, Langbehn et al. 2016 showed that blurring the peripheral vision does not affect speed and distance perception during linear trajectories in VEs, but manipulation of the optic flow does (François et al. 2011; Bruder et al. 2012a).

We can differentiate two types of speeds, rotational (e.g. turning leftwards or rightwards) and translational (e.g. moving forward or backward) ones. Head and neck play a role in the perception of rotational speed. For instance, simulating neck through vibrations helps the perception of rotational, and the relation between the head position relative to the trunk affects Vestibulo-Ocular Reflex (VOR) (Panichi et al. 2011). In addition, vection and rotational speed perception can be increased by using a physical platform in VR systems (Marchal et al. 2011; Rietzler et al. 2018b) or haptic feedback to allow users to less under-estimate the angle turns during navigation (Lécuyer et al. 2004). While the importance of rotational cues for efficient spatial perception in VEs has been demonstrated (Chance et al. 1998; Ruddle and Lessels 2006; Ruddle and Lessels 2009), the importance and impact of translation perception are still not clear (Ruddle 2013). Research work showed that the absence of embodied translational cues yielded a lower navigation performance than with translational body-based cues (Nguyen-Vo et al. 2019).

We reviewed characteristics of human walking in environments, from the perception of information provided by the environment to the actions performed to explore. Understanding how users perceive and perform movements in REs is essential if we want to design comfortable VR systems. Studies done in REs are the baseline information we have and considering it enable also to compare potential differences between observation from studies in REs and VEs and therefore having a better understanding of users behavior while navigating in VR. We will now detail solutions that have been designed to enable navigation in large VEs.

« Does virtual reality provide us with new ways to augment, enhance, and experience reality, or does it undermine and threaten that reality? Virtual reality is equally prone to portrayals as either the bearer of bright utopian possibilities or dark dystopian nightmares, and both of these views have some basis to recommend them. »

Derek Stanovsky

2

Locomotion Techniques in Virtual Environments

Navigation is a fundamental interaction in VR since many applications require the ability to navigate through an environment (e.g visiting a virtual building, moving in a video game). The expression « the user is navigating in a VE » can be ambiguous. For instance, we do not know the type of navigation used (e.g., walking, flying, sailing...), we do not know whether the navigation is goal-directed or not and we do not know if we focus only on the movements or the ability to find a direction in the environment. « Navigation » (or « maneuvering ») can be decomposed into three major components:

- **Locomotion:** the ability to produce motion of the center of mass. For example, it can be walking, running, swimming, crawling, etc. In VR, locomotion indicates the user's control of movement through the VE ([Chance et al. 1998](#)) and it is similar to travel or viewpoint motion control ([LaViola et al. 2017](#)).
- **Path integration:** the ability of humans to mentally update their « position and orientation using information about self-velocity and self-acceleration over time » ([Chance et al. 1998](#)).

-
- **Wayfinding:** cognitive component defined by the ability to update self-position and orientation relative to the known places in the environments and defining a path through it ([Darken and Sibert 1996](#)).

Locomotion is the aptitude to achieve displacements in a given environment and corresponds to the motor aspect. In the case of human walking, three components are involved: the skeleton provides the resistant elements, articulated between them, likely to transmit and multiply the forces which are applied to them; the muscular system which, through contractions, mobilizes the bones of the skeleton and the nervous system which stimulates and controls the contraction of the muscles. Path integration and wayfinding are related to spatial and topological knowledge, where users estimate and update their location and heading thanks to continuous positions changes. Path integration provides short-term and low-level awareness of the navigation task provides short-term and low-level awareness of the navigation task by combining gathered information such as translations and rotations in order to integrate velocity and acceleration cues. It allows determining translational and rotational movements from the starting position ([Loomis et al. 1999](#)). Wayfinding is rather a high-level cognitive component where users have to consider the surrounding environment to go from one position to another. In general, it is rare to assess all together these components in the same studies, as each component can be influenced by several different variables. For instance, in this manuscript, our objective is to understand the factors that can influence users' perception-action loop during goal-directed tasks in VR. Thus, we did not focus on path integration and wayfinding, but rather on the impact of the locomotion technique provided by the VR system.

Numerous types of techniques have been proposed to provide navigation in VEs. In the following sections, we describe the most relevant techniques in the literature. Our classification is inspired from several surveys and organized into Physical and Virtual walking-based locomotion techniques ([Hollerbach 2002](#); [LaViola et al. 2017](#); [Nilsson et al. 2018b](#); [Nilsson et al. 2018a](#); [Zayer et al. 2018](#); [Boletsis 2017](#)). This means that we will only focus on techniques that could reproduce human walking. Even though they are not in the scope of this manuscript, we will briefly mention selection techniques or manipulation techniques since they produce some discontinuities during navigation and therefore differ from human walking. While we mostly focused on the input and control mechanisms, we will also present how sensory feedback can be provided to improve users' presence and comfort during navigation. Finally, we will present the navigation taxonomies that have been done proposed by the authors.

2.1 Physical VR Locomotion Techniques

Physical VR locomotion techniques imply users' body translation or rotation in order to control the viewpoint of the VE. Natural walking remains the ideal locomotion technique for room-scaled applications since it is the method we use to travel in our daily life. The isometric mapping between real and virtual motion allows a natural and realistic way of traveling in the VE, as well as vestibular and proprioceptive feedback, to match the visual information of the VE, reinforcing the perception of self-motion. Besides, acoustic and tactile cues generated during the gait cycle reinforce the user's immersion. Therefore, natural walking gives the best task performance ([Ruddle and Lessels 2009](#)), more presence ([Usuh et al. 1999](#)) and reduces cybersickness effects ([Jaeger and Mourant 2001](#)).

However, current VR systems, either projection-based or HMD-based, only enable walking several meters. However, the VE can be larger than the available workspace, meaning that VR systems are physically restricted by the workspace's size. In order to overcome this constraint while preserving gait, researchers have proposed techniques based on locomotion that we will describe hereunder. We sorted the techniques depending on how the human gait cycle is respected (full, partial, or negation).

2.1.1 Full Gait Techniques

Full gait techniques involve stance and swing phases. They include real walking and redirection techniques that try to compensate for the limited physical workspace while maintaining real walking to navigate in the VE. [Nilsson et al. 2018a](#) split redirection techniques into two different categories: (1) the ones that manipulate the mapping between the user's real and virtual translation and rotation and thereby steer the user away from the edges of the tracking space and physical obstacles, and (2) the ones that manipulate the VE itself by changing its internal structure (e.g. changing the locations of objects, doors, corridors to produce overlapped virtual spaces and allow to have bigger VEs than working areas). [Suma et al. 2012a](#) precise that we can also distinguish redirection techniques with respect to their continuity and subtlety. Continuity means that modifications of the mapping between the user's real and virtual translation and rotation or the manipulation of the VE are applied either instantaneously (discrete) or over time (continuous). Subtlety means that can be used without the user's awareness (subtle) and techniques that can be noticed by the user (overt). The main advantage of subtle techniques is that they are imperceptible to the user and therefore do not break presence during navigation but overt techniques can be necessary for safety purposes.

2.1.1.1 Subtle Manipulation of Viewpoints

A first solution to achieve infinite walking in the VE in a limited workspace was proposed by (Razzaque et al. 2001) and called redirected walking (Figure 2.1). They exploited the imperfection of the visual system (and its dominance over the vestibular system) to make a user walk in a straight line in the VE while making curved trajectories in the RE. They added imperceptible yaw rotational gain (i.e. changing the mapping between the physical and virtual rotation performed) to the user's viewpoint in the HMD to reorient back and forth the user in the RE. This research work was at the origin of extensive research on redirection techniques and rotation gains.

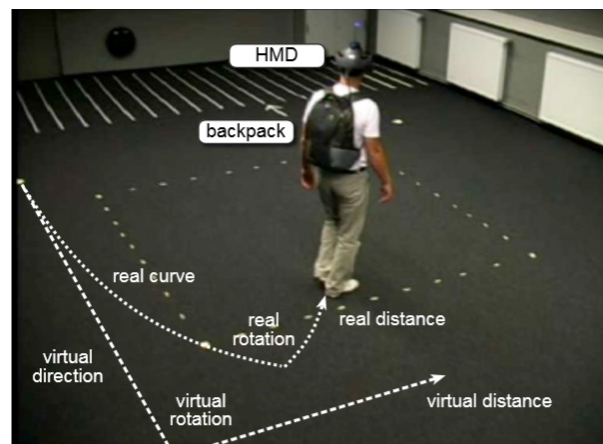


Figure 2.1 – One example of redirected walking: User wearing a HMD and performing a 90 degrees turn in the VE while doing a smaller curved trajectory in the RE (Steinicke et al. 2010).

There exists several ways to manipulate users' rotations and translations. These manipulations, called gains (Figure 2.2), have been used to reorient users in the working area and we describe hereunder the main gains used (Nilsson et al. 2018b):

- **Rotation gains** - They enable to change the amount of rotation performed in the VE based on the users' physical rotation. They are the key components of most subtle redirection controllers (Razzaque et al. 2001; Hodgson and Bachmann 2013), but they can also be used to enable an easier exploration of VEs for users having limited head movements (Norouzi et al. 2019).
- **Translation gains** - They are used to increase the user's translation. For instance, the Seven-League-Boot is an overt solution that allows the user to enable translation gains by pressing a hand-held wand (Interrante et al. 2007). In addition, (Zhang and Kuhl 2013a) combined translation and rotation gains to design a redirection technique that uses heuristics based on the *a priori* knowledge of the RE.

- **Curvature gains** - Based on redirected walking, (Nitzsche et al. 2004) developed a technique called Motion Compression. It rotates the VE and keeps the user away from the limits of the workspace. The difference with redirected walking is that there are no rotation injections, meaning that only the VE rotates (rotation and translation of the user are isomorphic).
- **Bending gains** - Another type of gain recently introduced by (Langbehn et al. 2017) consists in bending gain. Similar to curvature gain, it redirects the users to the left or to the right while they are performing a curved virtual trajectory. It means that the curved virtual path is bent to the real path with a higher curvature to perform navigation in a smaller workspace than the VE. (Rietzler et al. 2018a) showed that this type of gain would require a 6x6 meters workspace to perform infinite forward walking in the VE.

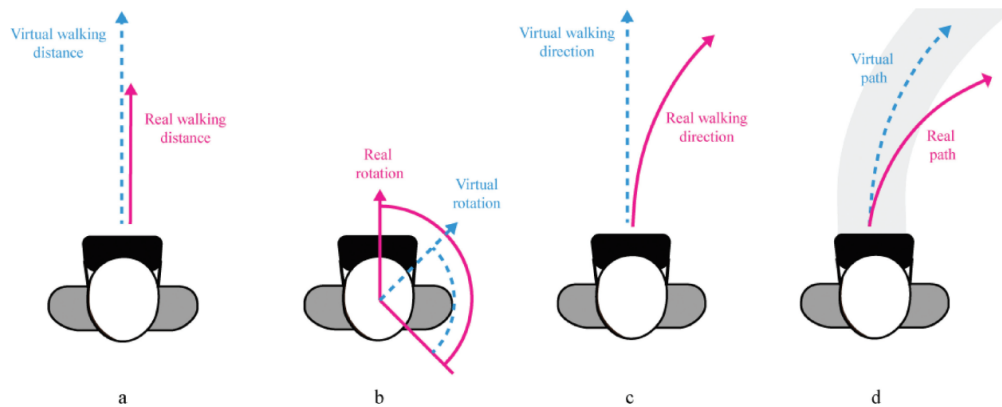


Figure 2.2 – Illustration of the type of gains used to manipulate the mapping between user's real and virtual movement: (a) translation (b) rotation (c) curvature (d) bending. Pink and blue lines indicate respectively the virtual and real motions (Nilsson et al. 2018b).

It is also worth noticing that the gains we presented always map either respectively physical rotations with virtual rotations and physical translations with real translations, but other types of gains could be considered. For instance, (Steinicke et al. 2009) introduced displacement gains that map physical rotations to virtual translations. The idea is to create a « virtual drift » based on the users' rotational movements.

Other approaches can be considered to apply gains. For instance, methods taking advantage of users' blinks (Langbehn et al. 2018b) or saccades (Sun et al. 2018a) can be possible to change the position and the orientation of the camera to redirect them into the RE so that they can move and avoid obstacles in the VE. It is also possible to use passive haptic feedback during redirected walking. For example, (Matsumoto et al. 2016) designed the unlimited corridor. The

users walk in a straight path in the VE while walking around in the RE. Synchronization between touching the physical wall and the virtual hand touching the virtual wall provides haptic feedback (providing additional sensory feedback and enhancing immersion) and allows unlimited forward walking in the VE. Finally, electrical stimulation ([Auda et al. 2019](#); [Langbehn et al. 2019a](#)) can be used for redirected users in the workspace.

We can notice that most of the techniques described above are subtle and the gains are applied continuously in order to prevent perception conflicts. However, it is possible to design overt redirection techniques requiring user intervention.

2.1.1.2 Overt Redirections and User Interventions

The main advantage to rely on overt techniques is that we can warn the users when they reach the boundaries of the workspace, which increases safety than subtle techniques where the redirection might fail. The objective of these techniques is to « reset » users position (i.e., to replace the user at the center of the workspace) while trying to not break users immersion.

For example, ([Williams et al. 2007](#)) designed three overt techniques to fulfill this requirement: (1) **freeze-backup** technique where the VE is « frozen » (i.e., the virtual position is not updated) and the experimenter helps the user to reach the center of the VE to resume the VE; (2) the **freeze-turn** technique where the VE is frozen and the user has to turn towards the center of the VE which unfreezes the VE; (3) the **2:1 turn** where the user has to perform physically a half turn (180°) while the VE is rotated to 360° . These three techniques allow the users to infinitely walk in the VE while being recentered at the center of the workspace when they reach boundaries while minimizing the number of resets. The Magic Barrier (Figure 2.3) is an improvement of Williams et al. work that is more user-friendly ([Cirio et al. 2009](#)). It displays a virtual barrier to mark the real boundaries of the tracked space. Besides, reorientation techniques were also designed for CAVE environments in order to prevent the user from seeing the missing wall ([Cirio et al. 2012](#); [LaViola et al. 2001](#)).

Furthermore, it is also possible to force the user to perform rotations by using visual ([Chen and Fuchs 2017](#); [Peck et al. 2010](#)) or auditory ([Rewkowski et al. 2019](#); [Yu et al. 2017](#)) distractors in the VE. When the users are distracted, it is possible to apply the rotation gain in order to redirect them.

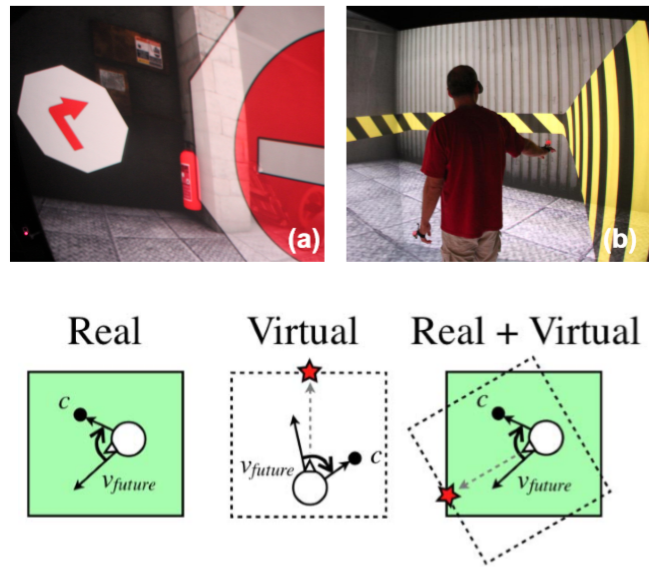


Figure 2.3 – Example of overt redirection techniques. On top, constrained wands and signs force the user to reorient in order to continue the navigation (Cirio et al. 2012). On bottom - Distractors (red star) used to force the user to look at another direction in order to modify the VE orientation (Peck et al. 2010).

2.1.1.3 Manipulation of the Virtual Environment

A different approach is to manipulate the objects from VE while taking into account the available workspace. To achieve this, several solutions have been considered in the literature. For instance, (Suma et al. 2011) introduced change blindness that redirects users thanks to the dynamic evolution of the VE. While the user is focusing on a specific task, the VE is changed (e.g. rotation of a doorway or realignment of a corridor) without being noticed by the user. As shown in Figure 2.4, the manipulation of the VE allows the users to navigate in a larger VE (18x18 meters) than the workspace (4x4 meters). As in subtle redirection techniques, gaze information can be used to change the layout of the VE where users are not staring at (Marwecki et al. 2019).

Impossible spaces (Figure 2.4) is a technique compressing VEs into smaller workspace thanks to self-overlapping (Suma et al. 2012b). It means that the same position in the RE can correspond to several positions in the VE. To enable the transition between the different overlapped areas in the VE, they use corridors to move from an area to another. They showed that it is possible to overlap up to 56% two small virtual rooms without users noticing it. It, therefore, allows users to walk in the VE through several overlapping rooms. Based on change blindness and impossible spaces, (Vasylevska et al. 2013) developed the flexible spaces that consist of an algorithm allowing 100% overlapping if we do not need to replicate the spatial layout of the

workspace.

The advantage of full gait techniques is that they enable walking, which provides vestibular and proprioceptive feedback while exploring the VE. However, the main limitation of this group of techniques is that they are limited by the size of the available workspace. In particular, the main challenge for redirection techniques based on gains is to solve the trade-off between the intensity of the gains and the ability of users to perceive them. Techniques based on manipulations of the VE are dependant on the VE's layout and are therefore generally limited to interior environments. In the next subsection, we will cover solutions that use partial gait or gestures to overcome the workspace limitations.

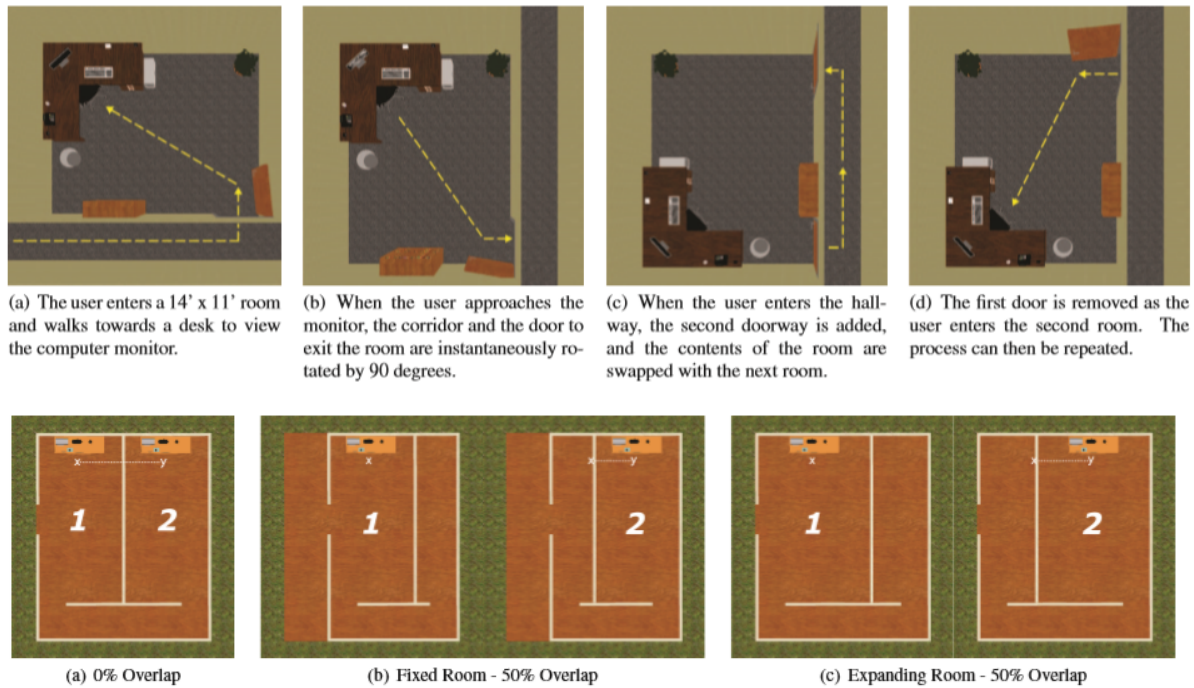


Figure 2.4 – Top - Sequence of changes exploiting change blindness, allowing the user to navigate in a VE large than the real workspace without noticing it (image from [Suma et al. 2011](#)). Bottom - Impossible Spaces: the virtual rooms overlaps on the real workspace (image from [Suma et al. 2012b](#)).

2.1.2 Partial Gait and Gesture Techniques

Unlike full gait techniques, partial gait techniques are based on the stance phase (as described in subsection 1.2.1), where users step in place without any translation. We also consider techniques requiring users to do gestures that are used as a proxy for actual steps ([Nilsson et al.](#)

2018b) as they try to mimic gait or involve partial users movements. In this subsection, we distinguish gestures made with the upper or the lower parts of the body.

2.1.2.1 Lower Body Gestures

Since the objective of physical VR locomotion techniques is to produce a similar experience to real walking, partial gait techniques usually rely on the lower body. The most common approach is called Walking-In-Place (WIP). It uses a stepping-in-place gesture to control locomotion speed and direction. The first implementation, called the virtual treadmill, was proposed by (Slater et al. 1995a). They trained a neural network that can detect head oscillations and determine continuously whether a walking action was detected in order to translate users' viewpoint in the VE according to where they were looking at. Its main advantage is that it does not require additional hardware than head tracking. However, the virtual treadmill showed some limitations: the neural network needs to be trained for each user and it only provides forward traveling.

Regarding the implementation of WIP techniques, Zayer et al. 2018 proposed the following criteria to characterize them:

- **Pattern** - The most common gesture used for WIP is marching, but other patterns can be used like wiping or tapping in place (Figure 2.5). Nilsson et al. 2013a found that tapping-in-place was considered more natural and less demanding than the others patterns. A similar approach was proposed in the LazyNav technique (Guy et al. 2015; Punpongsanon et al. 2017): users step by putting one foot forward then backward or they can bend their knees to translate in the VE. In most WIP implementations, rotation is enabled thanks to upper body gestures.
- **Speed** - WIP techniques generally need to handle three requirements: (1) the ability to set a similar speed profile to real walking ; (2) dealing with the latency to detect the start and stop of locomotion ; (3) providing a smooth and continuous locomotion speed during the navigation. To overcome these issues, (Feasel et al. 2008) proposed the Low-Latency, Continuous-Motion WIP (LLCM-WIP). By tracking heel position and using signal-processing methods, they provided a WIP technique that reduce the latency and smooth the user translation between steps. Based on the LLCM-WIP, improvements were made by (Wendt et al. 2010; Bruno et al. 2013) that modeled WIP gait cycle with a state machine to adapt speed control. Mun et al. implemented a learning-based regressor that estimates spatiotemporal gait parameters using the step frequency information during WIP and body anthropometric data (Mun et al. 2018).
- **Direction** - While users are performing WIP, they need to define their direction of

locomotion (heading). The most common solution is to use the head forward direction like in (Slater et al. 1995a) or head tilting (Terziman et al. 2010), but other body segments can be used such as the torso (Wendt et al. 2010), the feet (Bruno et al. 2013) or the hip (Bruno et al. 2017).

- **Sensing** - There are several ways to track user movements. For instance, inertial information from smartphones gyroscopes can be used to enable WIP for VR with mobile phone (Kim et al. 2012; Tregillus and Folmer 2016). An optical camera like a web-cam (Terziman et al. 2010) or a depth camera like the Kinect (Williams et al. 2013) can be used as well. Pressure devices such as the Wii balance board (Williams et al. 2011), a cushion put on a seat in which the user is sat on (Ohshima et al. 2016) or pedals (Klamka et al. 2015) can also be alternatives.
- **Movements** - While all WIP technique provide forward direction, some of them also allow users to go backward (Guy et al. 2015; Punpongsanon et al. 2017), strafe and crawl (Terziman et al. 2010) or jump (Tregillus and Folmer 2016; Terziman et al. 2010).

WIP techniques are user-friendly, mostly hands-free which allow users to interact with the VE, can be used in a small workspace (or even medium workspace by alternating walking and WIP (Bhandari et al. 2017)), and are inexpensive since they may not need additional hardware. Besides, they provide some proprioceptive feedback related to real walking and may increase presence (Usoh et al. 1999). However, specific movements such as strafing or going backward are not possible with WIP.

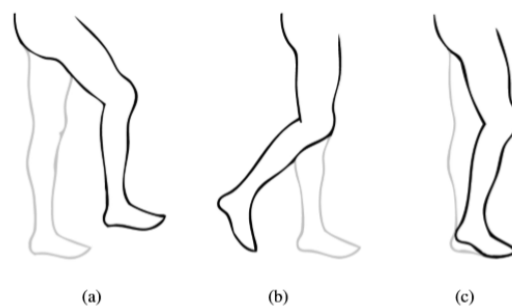


Figure 2.5 – The three gestures used for WIP pattern (with two new introduced by (Nilsson et al. 2013a)). (a) Marching: The user alternately lifts each foot off the ground by raising the thighs in front of the body. (b) Wiping: The user in turn bends each knee while keeping the upper leg relatively steady which results in backward movement of the feet. (c) Tapping: The user alternately lifts each heel of the ground while keeping the toes in contact with the ground.

2.1.2.2 Upper Body Gestures

Even though lower body gestures seem to be more convenient to give real walking sensations than upper body gestures, some researchers proposed techniques based on gestures that do not require leg movements. For instance, (McCullough et al. 2015) used a Myo armband to track users' arms. They can swing their arms back and forth to update their viewpoint in the VE.

Kim et al. substituted the use of legs by fingers to offer a WIP technique (Kim et al. 2008) (Figure 2.6). Users' viewpoint is updated by sliding fingers in place and the speed is controlled with respect to the length of sliding gestures. A recent patent presented a new solution to navigate through pinch and hold gestures and provides several navigation options such as zooming-in/zooming-out, translation, and rotations (Stafford 2018). Users wear gloves with sensors on their fingers for detecting positions of the finger segments. Pinch (contact between thumb and finger) gestures (e.g pulling-in) enable the navigation interaction. (Huang et al. 2019) combined a leap motion attached to an HMD to provide finger gesture navigation based on hand posture to define the direction of navigation (move backward, resting, move forward). Other gestures techniques have been considered, with a leap motion attached to the HMD (Cardoso 2016; Zhang et al. 2017) (Figure 2.6), body-driven (Sugarman et al. 2012), or with hand-held controllers to mimic walking gait (Sarupuri et al. 2017).

Nevertheless, upper body gestures can have some shortcomings. A user study showed that arm swinging provides lower spatial awareness than WIP and real walking (Wilson et al. 2016). Besides, since these techniques require the upper body part, users cannot use their hands in the meantime to interact with the VE.

2.1.3 Gait Negation Techniques

Gait negation techniques rely on compensating users' movements by negating them. Most of the gait negation techniques use a device that creates a sense of walking in a VE and provides the experience of physical walking while the walker's body is kept at the same position in the real world (Iwata 2013). We can distinguish two types of gait negation techniques: foot-based devices which compensate motion of each foot and recentering floors that negate the forward movement of the user.

2.1.3.1 Foot-based Devices

Foot-based devices control the feet' trajectory. There exist solutions that consist in wearing a pair of special shoes (foot-wearables) or a pair of foot platforms supporting the users' feet.

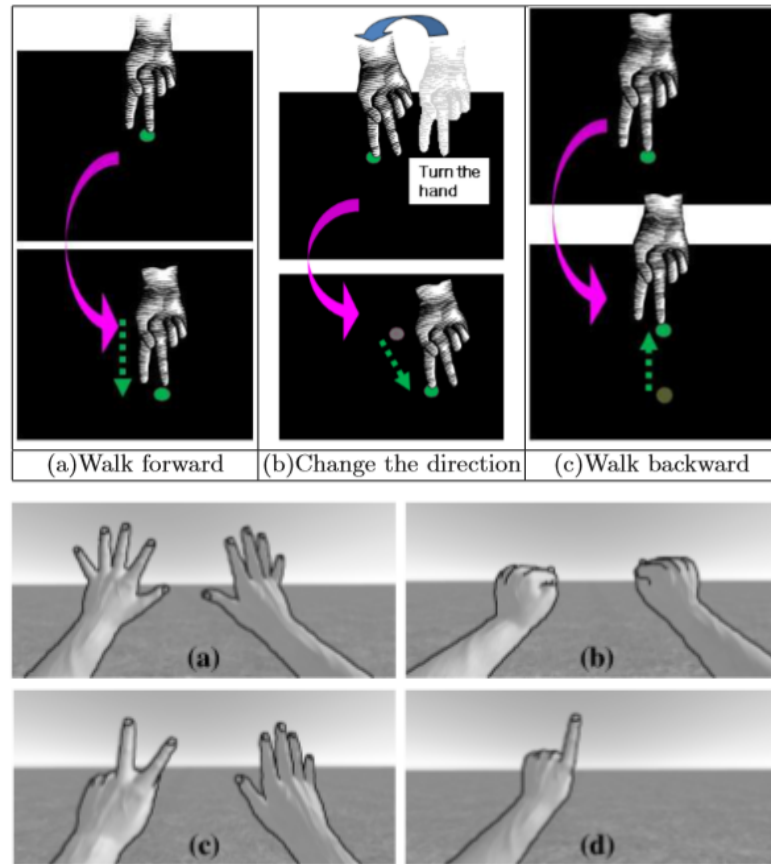


Figure 2.6 – Finger WIP: Three different sliding patterns to enable navigation in VEs (Kim et al. 2008). Hand poses proposed for the LMTravel techniques: (a) start (b) stop (c) movement speed defined by the number of fingers (d) speed control (Cardoso 2016).

Regarding foot-wearables, Iwata et al. designed several prototypes like the Virtual Perambulator (Figure 2.7) where the users wear a pair of roller skates and their waist is fixed to a hoop in order to limit their movement (Iwata and Fujii 1996). Thanks to the special shoes they can slide on the ground while the user remains stationary. The Powered Shoes uses motorized roller skates to recenter users' feet and compensate their movements (Iwata et al. 2006). The String Walker (Iwata et al. 2007) ties the users' feet with strings actuated by motor-pulley mechanisms (Figure 2.7). One problem of the foot-wearables category is they cannot present uneven surfaces. Since locomotion interfaces are frequently applied for simulation of urban spaces or training simulators including stairs, a walker should feel the sense of going up or down the stairs. Foot platforms can provide this sensation.

Unlike foot-wearables, foot platforms are based on physical platforms attached to the user's

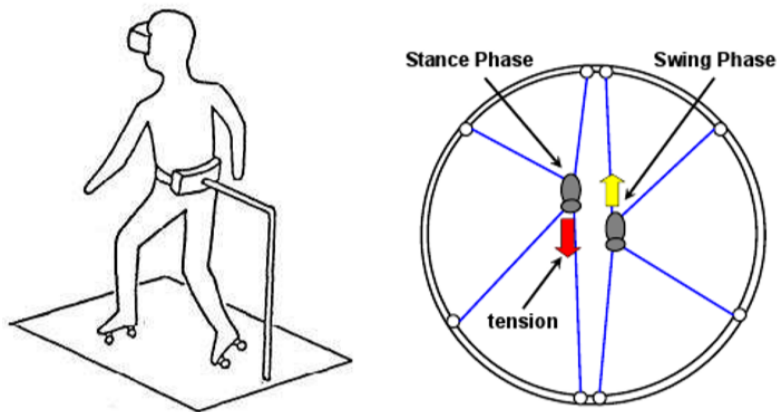


Figure 2.7 – Example of foot-wearables devices. Left: the Virtual Perambulator (Iwata and Fujii 1996). Right: the String Walker (Iwata et al. 2007).

feet. Roston and Peurach first proposed a platform that can move in the 3D space and follow users feet movements without applying any resistance (Roston and Peurach 1997), meaning that the two pads applied to each foot follow the motion of the user’s foot while physically walking is used to move them back to their initial position. Figure 2.8 shows three typical examples of foot platforms: The Gait Master (Iwata et al. 2001), the Sarcos Biport (Stanney and Hale 2014) and the Rutgers Mega-Ankle (Boian et al. 2004). Even though they allow flat or uneven grounds simulation, mechanical constraints from these foot platforms only allow moderate walking. Note that cheaper and less cumbersome alternatives can be considered such as mini exercise bike (Freiwald et al. 2020) for household usage.

2.1.3.2 Recentering Devices

Recentering devices rely on a different approach that consists in keeping the users in a limited space by moving the ground under their feet during the walk. There exist several types of devices that differ from their mechanical characteristics: linear treadmills, active and passive omnidirectional treadmills, and low friction surfaces.

The simplest recentering system is a linear treadmill, a platform allowing to reproduce walking gait while standing in place (Figure 2.9). The Sarcos treadport is a treadmill that uses a tether attached to the user in order to provide tracking, adapt users’ speed, and simulate physical constraints (e.g slopes or inertial forces) by pushing or pulling forces to the user’s torso (Hollerbach et al. 2000). Besides, the IVERT (Feasel et al. 2011) treadmill was designed for locomotion rehabilitation. It provides real-time feedback regarding gait speed and asymmetry during navigation.

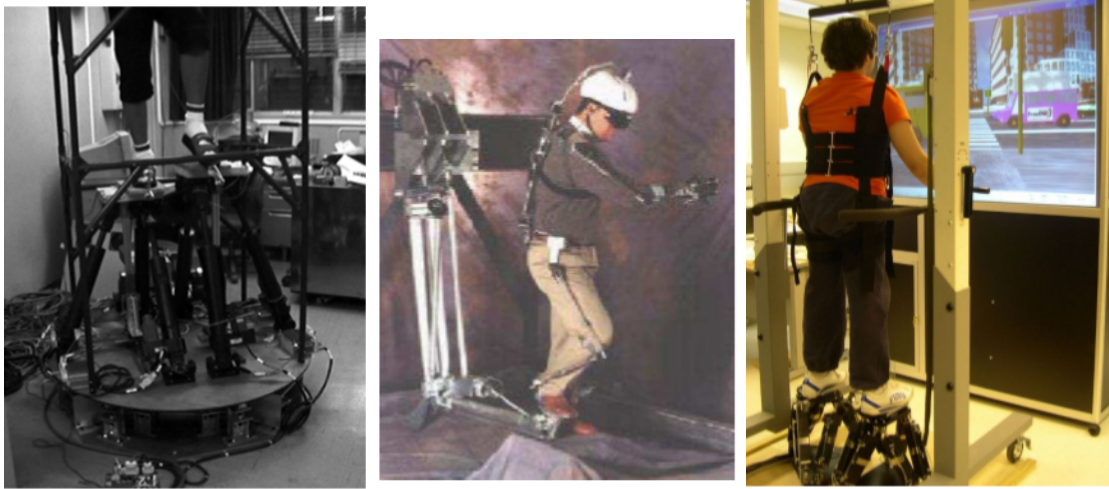


Figure 2.8 – Example of foot-platforms devices. Left: The Gait Master (Iwata et al. 2001). Middle: the Sarcos Biport (Stanney and Hale 2014). Right: Rutgers Mega-Ankle robots as foot platform (Boian et al. 2004).

However, these treadmills only allow forward walking without turning capabilities.



Figure 2.9 – Example of linear treadmills : the Sarcos treadport (Hollerbach et al. 2000).

One solution for omnidirectional walking on a treadmill is to use small rollers to move the walker in perpendicular directions (Figure 2.10). Darken and Carmein proposed an omnidirectional treadmill (ODT) made up of two perpendicular treadmills, one inside the other (Darken et al. 1997). Users' movements are compensated in any direction by combining the two perpendicular rotation motions of the treadmill, allowing omnidirectional walking. Nevertheless, the user study showed some limitations of the device such as inaccurate tracking. The Torus treadmill uses 12 small treadmills connected to each other making a belt that provides a 1 by 1 square meter walking area (Iwata 1999). The Cyberwalk platform (Schwaiger et al. 2007a) is a

more recent ODT that has a bigger walkable area (4.7x2.6 meters) than previous ODTs cited. Its main distinction from other ODTs is its ability to handle abrupt changes regarding navigation speed: it keeps the user stable and close to the center of the treadmill. Another approach is based on small balls instead of belts. For instance, the Cybercarpet ([Schwaiger et al. 2007b](#)) is inspired from the Ball Array Treadmill ([Nagamori 2005](#)) and consists of an array of balls actuated by a belt (that generates linear motion) mounted on a turntable (that allows one rotational degree of freedom). Unlike active ODTs, passive ones rely on the user's motion to activate their surfaces and recenter users. The Virtusphere ([Medina et al. 2008](#)) is a passive ODT in which users are inside a spherical « hamster ball » that rolls in place during users locomotion (Figure 2.11).

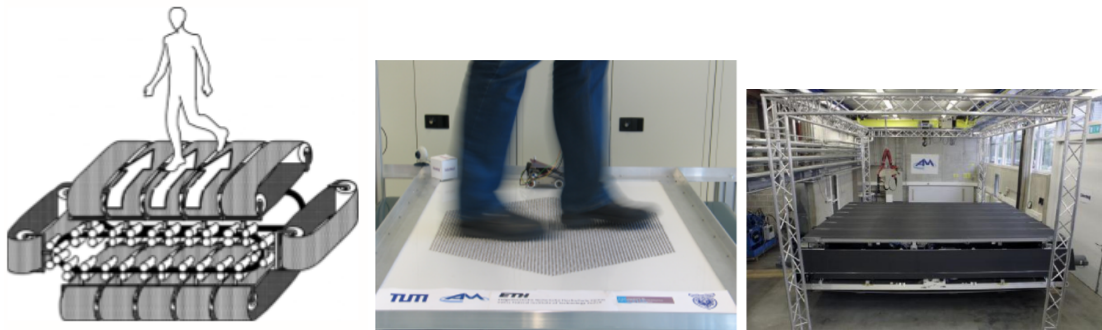


Figure 2.10 – Example of ODTs. Left - the torus treadmill ([Iwata 1999](#)). Middle - the Cybercarpet ([Schwaiger et al. 2007b](#)). Right - The CyberWalk ([Schwaiger et al. 2007a](#)).

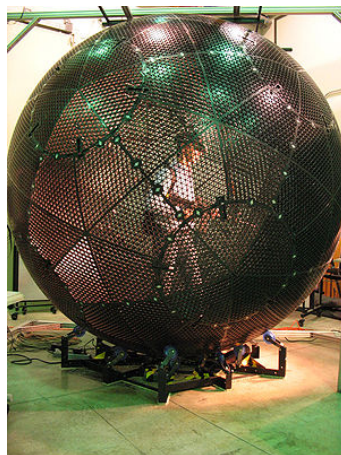


Figure 2.11 – Passive ODTs. The virtusphere ([Medina et al. 2008](#)).

Low-friction surfaces (Figure 2.12) are based on devices at which users slide their feet in the opposite direction of travel. For example, the Wizzdish ([Swapp et al. 2010](#)) is a concave surface that negates walking forces by bringing back the user to the center of the platform thanks to low

friction shoes. The Cyberith Virtualizer is a similar implementation the difference is that the user is also fixed in a belt system (allowing 360 degrees rotation) attached to an outer ring which can vertically move ([Cakmak and Hager 2014](#)).



Figure 2.12 – Low-friction surfaces devices. Left and Center: the Wizdish ([Swapp et al. 2010](#)). Right: the Cyberith Virtualizer ([Cakmak and Hager 2014](#)).

There exists a lot of locomotion interfaces designed for walking in VEs. They are based on dedicated platforms which differ from the mechanical solutions to keep the user in a particular space by negating their motion. They provide an efficient and ecological solution for walking in VEs thanks to the kinesthetic and proprioceptive feedback to the users. However, since they depend on specific platforms, their implementation in VR setups can be more difficult. They are mostly expensive, cumbersome, and may produce a different sensation of locomotion. For example, biomechanics generated from low friction surfaces are rather similar to skating than walking and they may need a higher learning time than other gait negation interfaces. Besides, velocity and accelerations are limited and running scenarios cannot be considered. Finally, performance can be affected and they can require more training.

2.2 Virtual Locomotion Techniques

To encounter limitations of workspace, virtual locomotion techniques have been developed and allow to explore VEs without physical displacement using other modalities than walking. When designing virtual locomotion techniques three major components can be identified ([LaViola et al. 2017](#)): (1) the direction/target selection (i.e., how users or the system can update the future heading or future position), (2) the input conditions (i.e., how users or the system can enable or disable motion through users or systems inputs) and (3) the speed/acceleration selection (i.e., how users or the system increase or decrease the navigation speed). In this thesis, we are interested in techniques providing a continuous motion as well as a continuous control of direction. That's why regarding virtual locomotion techniques, we will focus on spatial steering techniques (i.e., using a user's body segment to define the future direction) that are described in subsection 2.2.1.

The main reason to focus on these techniques is that they allow using an input device (e.g., a joystick) to have continuous control of the trajectory performed. It is worth noticing that there also exist physical steering techniques that use physical props (Rietzler et al. 2018c) to provide steering (e.g. vehicle, bikes, or cockpits for flight simulations) but are not used for walking-based navigation. Besides, we will also briefly mention other types of virtual techniques (selection and manipulation based) for completeness in subsection 2.2.2.

2.2.1 Spatial Steering Techniques

In virtual steering techniques, the **virtual direction** is typically defined by a body segment (e.g. gaze, hand, or torso) or a derivative (e.g. the projection of the head position). Then, the **navigation speed** is determined by a control law that relies on users' inputs (discrete, e.g. a button press or continuous, e.g. a joystick). Even though there exist some techniques in which the direction of motion is defined by other interaction devices as inputs (e.g. a joystick) (Langbehn et al. 2018a), we will only focus on spatial steering techniques that control motion direction with users body segments. We describe in subsubsection 2.2.1.1 how heading, and in subsubsection 2.2.1.2, how the speed can be updated.

2.2.1.1 Heading Selection

In **Gaze and head steering**, the virtual direction is defined by where the user is looking at. These techniques mainly use only head orientation to define the future direction (Mine 1995). The head orientation is tracked thanks to the HMD or a tracking device. This orientation corresponds to a direction vector that is normalized and used to translate the user along this vector in the VE. (Tregillus et al. 2017) used head tilt for mobile VR navigation where the users move forward or backward by respectively tilting their head up or down. Few implementations use an eye-tracking system to determine the future direction based on eye movements (e.g. for flying navigation (Qian and Teather 2018) or video-games navigation (Smith and Graham 2006)). Stellmach and Dachselt 2012 designed an eye-based user interface (Figure 2.13) that allows to strafe (move forward, backward, up, down, left and right) in the VE. Gaze-steering techniques have two main limitations: the coupling between gaze direction and travel direction prevents (1) users from looking in another direction while navigating in another one, and (2) gaze anticipation during the trajectory performed. Even these limitations could be considered as minor, research work in REs showed that we can look in a different direction during locomotion. In particular, when the environment is unknown, head changing directions increase comparing

to the trajectory (Patla 2004). In addition, prevent users from anticipating could alter users' behavior in VR since gaze anticipation is an invariant of human locomotion in REs. Then, other body segments can be considered.

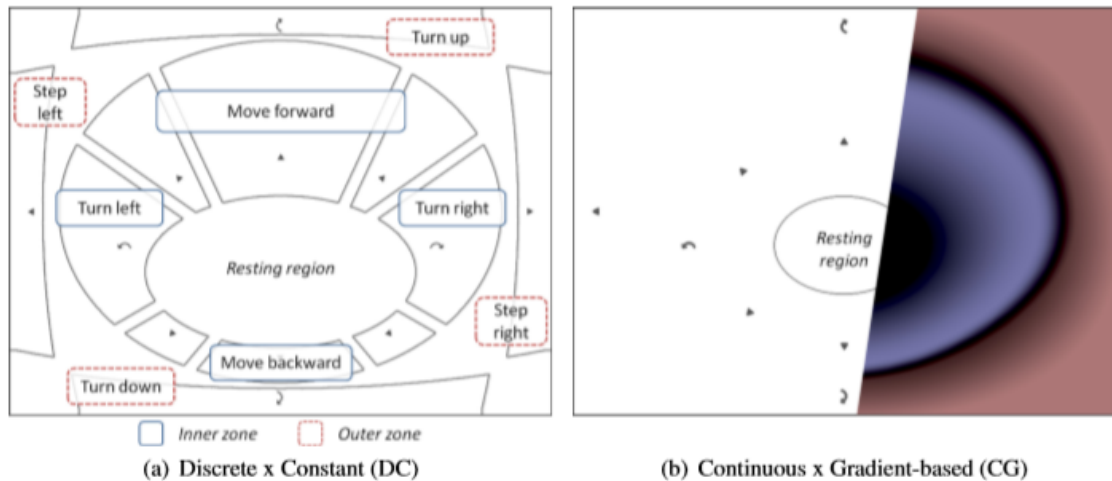


Figure 2.13 – A gaze user interface based on the eye orientation for navigating in VEs (Stellmach and Dachsel 2012).

Hand-steering techniques typically rely on tracked hand-held devices to define the future direction. For instance, it is possible to use a hand-held joystick (e.g an HTC Vive controller) and uses its orientation to define the future direction. With the same technique as gaze-steering, it produces a direction vector that is normalized and used to move the user in the VE. Besides, Cirio et al. 2009 implemented a technique to overcome limits of workspace with a virtual barrier tape that users have to « push » in order to control their direction and speed. Bowman et al. 2001a designed the PinchGloves™. Users wear gloves equipped with sensors that allow flying navigation with one hand specifying the forward direction and the other the upward or downward direction.

In **Torso-steering** techniques, the user's torso is used to specify the direction of travel (Bowman et al. 1998). Its implementation is similar to gaze and hand steering. However, since it requires additional tracking compared to gaze or hand steering, this technique has been less explored. The advantage is that it decouples both gaze direction and hand selection although its usage is limited to a horizontal plane as it will be inconvenient for the users to bend their torso up and down (Zielasko et al. 2020).

Lean-based steering techniques differ in terms of the body segments involved and the user's posture (Figure 2.15). For instance, the PenguFly is a bimanual travel technique. It uses projection

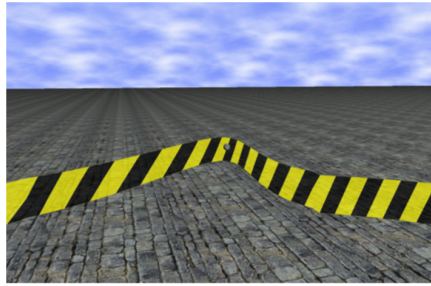


Figure 2.14 – The Magic Barrier Tape metaphor: the user "pushes" the barrier to define the future direction (Cirio et al. 2009).

onto the ground of head position and left/right hands to define the forward direction vector and the velocity (Kapri et al. 2011). Main implementations are based on physical interfaces like the ChairIO (Beckhaus et al. 2007), the NaviChair (Nguyen-Vo et al. 2019), the PerchFlex (Zhang et al. 2019) or the VRChairRacer (Willich et al. 2019) that are chair-based interfaces that can swivel. The user defines the translational movements by leaning in the desired direction. Similarly, the Joyman is a leaning interface where users stand on a platform and lean to define the future direction in the VE (Marchal et al. 2011). Others implementations use Wii Balance Board where the users lean forward or backward to respectively move forward or backward, strafe is enabled by leaning on either side (Haan et al. 2008). A similar implementation is the Human Transporter (Valkov et al. 2010), except that strafing is not offered and turning is activated by leaning on one of the Wii Balance Board sides. Wang and Lindeman 2011 improved it by adding an accelerometer on the arm to control the velocity. Even though lean-based steering techniques can be an interesting solution for navigating in large, they produce rather sensation of skating or surfing than real walking, and they may require additional physical props.

Although gaze-steering is easy to use and does not require additional hardware as the user's head is typically tracked, they can restrict users' head movements. Hand-steering decouples the view and the navigation direction but can increase the complexity of the task. Leaning-based techniques require additional hardware but leverage user proprioception (e.g. leaning) providing intuitive interfaces. Finally, torso steering requires tracking the torso and they have not been extensively evaluated.

In the next subsection, we review how control laws are implemented in spatial steering techniques.

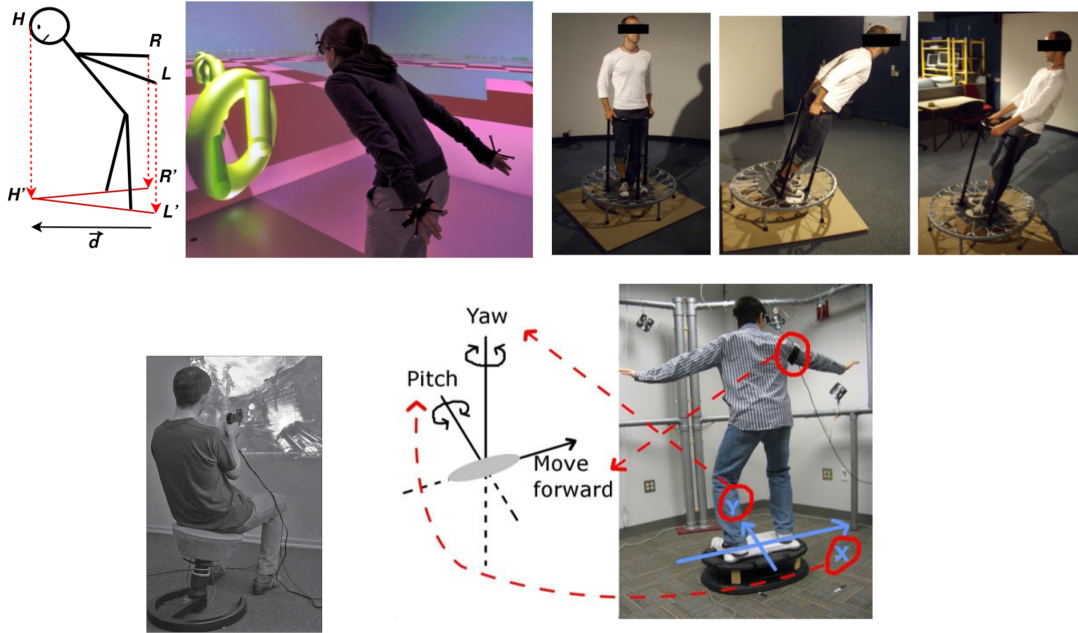


Figure 2.15 – Lean-based steering techniques: The Pengufly ([Kapri et al. 2011](#)) ; The Joyman ([Marchal et al. 2011](#)) ; The ChairIO ([Beckhaus et al. 2007](#)) and the Silver surfer ([Wang and Lindeman 2011](#)).

2.2.1.2 Control Law

The control law models how the user translation and rotation viewpoint are updated in the VE considering the state of the system. Rotational speed update laws are less used, except for redirected walking techniques ([Schmitz et al. 2018](#)), since it has been proven that altering users' rotational speed with a joystick can provoke cybersickness ([Langbehn et al. 2018a](#)). In the context of virtual steering, other works have explored the impact of rotational gains for virtual steering techniques ([Sargunam et al. 2017](#)). However, we will not discuss these implementations and only focus on the linear speed update.

The control law is a key component of the locomotion technique as it should provide the user the ability to achieve a comfortable navigation speed. Poorly designed control laws can lead to usability issues such as too low speeds resulting in boredom or too high speeds decreasing the control and even potentially generating cybersickness ([So et al. 2001](#); [Kwok et al. 2018](#)). The control law takes as input the state of the system, which encompasses the current navigation state and the user's input, but it can also consider other parameters such as the scale of the environment ([McCrae et al. 2009](#)), the viewpoint quality ([Freitag et al. 2016](#)) or the user's perceived motion ([Argelaguet 2014](#)). The control law, in addition, to provide smooth control of

the navigation speed, must handle two particular states, namely the beginning and the end of the motion (Bowman et al. 1998). To enable speed changes, control laws determine the navigation speed given the user's inputs (discrete, e.g. a button press or continuous, e.g. a joystick) and a transfer function that defines the mapping between each input data and transforms it into an output value (Frohlich et al. 2006). According to their degree of control, control laws can be categorized into three different groups: discrete, continuous, and adaptive.

Discrete control laws enable the user to select one navigation speed from a predefined set of speeds. The simplest law will consider just one speed, i.e. the user presses a button to navigate and releases it to stop. Other implementations might consider two speeds (e.g. walking and running) or a wider range (e.g. one button to increase the speed and another to decrease it). The designer of the application has to determine the actual walking speed values, although, in a human-scale environment, the optimal navigation speed would range between 1m/s and 1.4m/s because it matches human comfort speed (Bohannon 1997).

Continuous control laws increase the control of the user over the final navigation speed by allowing the user to choose the speed over a continuous scale. A basic implementation is to linearly map the input range of a joystick axis to the range between the minimal and the maximal navigation speed. Continuous control laws are typically used on lean-based techniques, for example specifying the speed according to the position of the head relative to the body (Fairchild et al. 1993; Song and Norman 1993). Depending on the application, quadratic or logarithmic mappings could also be considered. Similarly, as discrete techniques, the designer of the application is responsible for defining the range of suitable navigation speeds.

Finally, **adaptive** control laws take into account additional system states to adjust the navigation speed. Several adaptive techniques have explored the relative position of the user with respect to the virtual environment. Freitag et al. (Freitag et al. 2016) proposed the use of viewpoint quality measures to adjust the navigation speed in which the speed is adjusted considering the amount of information visible from the user's viewpoint. Another example is the work from Argelaguet et al. (Argelaguet 2014) in which the spatial relationship between the user and the virtual environment on one side and the perceived navigation speed on the other side is used to adjust the speed. In contrast, other techniques have explored the trajectory of the user to modulate the navigation speed. The Joyman (Marchal et al. 2011) modulates the tangential speed according to the actual rotational speed, to better resemble the dynamics of real walking. (Wang et al. 2021b) designed a control law inspired by the Biomechanics of walking in which they try to optimize the navigation speed by minimizing the total jerk during users translations. Finally, it is also possible to use physiological measures such as electrodermal activity to adjust the

navigation speed ([Plouzeau et al. 2018](#)). Adaptive navigation speeds can be discrete or continuous depending on the input mechanism considered and enable a fine adjustment of the locomotion technique to better support the user.

In overall, discrete control laws are easy to use but might generate navigation speeds that are not always well adapted to all navigation tasks. Continuous control laws, although they increase user control, are more complex to operate. Finally, adaptive laws although try to provide the optimal navigation state can generate a lack of perceived control and could potentially increase user frustration. Figure 2.16 summarizes some transfer functions used in VR experiments.

2.2.2 Other techniques

Even though we focus rather on techniques involving gait phases as described in section 2.1 or body segments in subsection 2.2.1, research work has been done to design techniques that allow faster navigation even it does not reproduce real walking sensations.

2.2.2.1 Selection-based

In selection-based techniques, there exist two main approaches (target selection and route-planning). In target selection, users select a target destination in the VE and their viewpoint is moved to the selected destination. The most common approach is teleportation (Figure 2.17) where the user's viewpoint can be updated instantly, with a fixed speed to provide optical cues ([Bhandari et al. 2018](#)), or with reorientation mechanisms so that the user would remain at the center of the workspace ([Freitag et al. 2014](#); [Liu et al. 2018](#)), or even with jumping metaphor ([Bolte et al. 2011](#)). While most of the teleportation techniques use a hand-held controller to select the future direction, other inputs can be considered such as the feet ([Willich et al. 2020](#)). World-In-Miniature (WIM) is another technique that consists in providing a representation of the VE to the users so that they could select the future direction. For instance, a representation of the VE can be displayed on the ground and users can step on the future location to update their position ([LaViola et al. 2001](#)). WIM provides better performances for distances upper than 50m than steering or teleportation ([Berger and Wolf 2018](#)).

In route-planning, either the navigation paths are computed by the VR application ([Galyean 1995](#); [Salomon et al. 2003](#)) with motion planning techniques or the user can choose some nodes in the VE to travel through ([Habgood et al. 2018](#)). Moreover, the path can be defined thanks to a map where the user indicates the direction with respect to the checkpoints they defined. In most implementations, the users do not have control over the velocity.

Transfer Function Types	Body Parts	Mapping Mechanisms
Linear Function (L): $v_v = k \times \theta \quad (1)$	Torso, Hand	Angle to speed mapping: the leaning angle of torso (θ) is mapped to the speed of user's viewpoint in VR (v_v) with a scale factor k .
Linear Function: $v_v = k \times d_r \quad (2)$	Foot	Displacement to speed mapping: the displacement (d_r) of step lift and lower is linearly mapped to the speed of user's viewpoint (v_v) with a factor k in VR.
Power Function (P): $v_v = k \times d_r^3 \quad (3)$	Hand	Displacement to speed mapping: the displacement of hand movement (d_r) is mapped to the speed of user's viewpoint in VR (v_v) with a scale factor k .
Power Function: $d_v = k \times \theta^2 \quad (4)$	Arm	Angle to displacement mapping: the angle of arm swing (θ) is mapped to the displacement of user's viewpoint in VR (d_v) with a scale factor k .
Piecewise Function with Constant and Linear Functions (CL): $v_r = \frac{\min(\frac{d_r}{t} , 0.5)}{0.5}$ $v_v = \begin{cases} 0 & \text{if } v_r < 0.05 \\ k \times v_r & \text{if otherwise} \end{cases} \quad (5)$	Head	Displacement to speed mapping: 0.05 and 0.5 are two threshold values. d_r means the head movement displacement. t represents time. v_r represents the normalized value ([0, 1]) of head movement speed. v_r is mapped to the speed of user's viewpoint in VR (v_v) with a scale factor k .
Piecewise Function with Linear and Power Functions: $d_v = \begin{cases} d_r & \text{if } d_r < a \\ d_r + k \times (d_r - a)^2 & \text{if otherwise} \end{cases} \quad (6)$	Hand, Torso	Displacement to displacement mapping: the displacement of body movement (d_r) is mapped to the displacement of the virtual hand in VR (d_v). k is a scale factor. a is two thirds of the length of user's arm.
Piecewise Function with Constant and Power Functions (CP): $v_v = \begin{cases} 0 & \text{if } \theta \in [0, a] \\ k \times (\frac{\theta - a}{1 - a})^b & \text{if } \theta \in [a, 1] \end{cases} \quad (7)$	Shoulder, Hip, Knee, Foot	Angle to speed mapping. a is a constant between 0 and 1, and b equals 2 or 3. θ is the normalized value ([0, 1]) of the angle of the movement of tracked body parts, which is mapped to the speed of user's viewpoint in VR (v_v) with k factor.

Figure 2.16 – Examples of control laws used in VR literature (adapted from [Gao et al. 2021](#))

2.2.2.2 Manipulation-based

Manipulation-based techniques work by manipulating the users' position, orientation, or their viewpoint or even the VE itself ([LaViola et al. 2017](#)). For instance, in the « grab the air »



Figure 2.17 – New solution of teleportation based on continuously moving the user to the destination (A to C) instead of discontinuously translates the user’s viewpoint over a distance (A to B) (Bhandari et al. 2018).

technique (Mapes and Moshell 1995), users perform a grabbing gesture on the VE and move their hand to move the entire VE while their viewpoint remain stationary. In this way, it is not the user’s viewpoint which changes but the VE relatively to the user’s viewpoint. A technique for traveling in a desktop VE called the camera-in-hand is based on a tracker held in users’ hand (Ware and Osborne 1990) that enables them to modify their viewpoint by moving their hand. Even though this technique is easy to implement, a recent study showed that the mismatch between the exocentric view that the users have and the egocentric point of view of the VE does not convey for navigation in VEs as it decreases presence and task performance (Medeiros et al. 2018). WIM manipulation can be used as well: users’ viewpoint is represented by an avatar that consists of a representation of the VE and the users can manipulate the avatar to move their position in the VE (Wingrave et al. 2006).

2.2.2.3 Multiscale-based

Some VR applications can require multiscale exploration of the VE. The scaling can be manipulated by the user by pressing controllers or using the hand (LaViola et al. 2001) or fully automated. Besides, scaling can be either discrete or continuous for smooth transitions among the different level of scales. Implementations focus on travel speed adaptation (Argelaguet and Maignant 2016; Abtahi et al. 2019) or enlarging the virtual avatar and altering distance perception of objects (Krekhov et al. 2018; Cmentowski et al. 2019).

Overall, selection, manipulation, and multiscale-based technique are good for traveling high distances in VEs quickly. The instantaneous position update provided by teleportation is faster than walking, but the further users want to teleport, the less precise the selection will be. Manipulation can provide more information about the layout of the VE as it is based on displaying a representation of the VE users are exploring, but it may require more training to perform navigation tasks in room-scaled VE than walking (Medeiros et al. 2018). Multiscale-based techniques are less used in VR systems can be a good compromise to enable fast exploration while having walking or steering.

2.3 Improving Locomotion in VR through Sensory Feedback

Walking is a task involving several sensory channels (that we described in section 1.1) to provide enough perceptual information about the surrounding environment as well as the walking gait. It can be then interesting to provide similar sensory feedback while navigating in VEs than in REs. However, most of the techniques presented so far focused on input and control mechanisms and do not always provide multisensory feedbacks. We will present how research work tried to provide users with appropriate feedback in order to reproduce the sensation of real walking in VEs. We will first focus on exteroceptive (i.e., sensations based on external stimuli) sensations such as the visual cues in subsection 2.3.1, then the auditory ones in subsection 2.3.2 and the haptic ones in subsection 2.3.3. We will also briefly mention interoceptive sensations (i.e., internal visceral sensation) such as the vestibular ones in subsection 2.3.4.

2.3.1 Visual

When all the human sensory systems can inform about the surroundings of the environment, their own position in it, and their movement through it, the visual system serves as a rich source of information during walking. While for all previous methods mentioned in section 2.1 and section 2.2, visual information is provided to the users, this information can be enriched.

[Tanikawa et al. 2012](#) proposed a new HMD based that provides vection thanks to smartphones attached around the peripheral vision of the user. The smartphone produces a visual flow to give more information about the walking speed in the VE. [Lecuyer et al. 2006](#) introduced a camera motion model that adds oscillations to the virtual camera to reproduce the user's head motion during walking. The user viewpoint, therefore, oscillates in order to follow the user's head movements. A user study showed that camera motion improves the sensation of walking and immersion than a basic linear implementation. Additional work reported that camera motion could provide a more accurate distance perception for short navigation distances in passive navigation ([Terziman et al. 2009](#)) and walking in CAVE ([Bossard et al. 2016](#)).

Another approach is to manipulate the user's FoV by either restricting it or applying visual effects (Figure 2.18). In VR applications, the FoV refers rather to what is visible while wearing additional apparatus. Most of HMDs have limited FoVs ranging from 40° to 110° diagonal, which are considerably smaller than human FoV. The most common technique to alter users' FoV is called vignetting and consists in reducing the virtual camera's brightness or saturation toward the periphery compared to the virtual camera's center. Hence, it gradually reduces the users' FoV by applying mostly a black color, some blur effects in the peripheral vision ([Langbehn et al.](#)

2016; Budhiraja et al. 2017) or altering the contrast (Bruder et al. 2012a). Several vignetting models have been designed, either using a constant restriction (Kopper et al. 2011), based on controller-based inputs (Fernandes and Feiner 2016; Sargunam and Ragan 2018), head movements (Norouzi et al. 2018) or ocular activity (Adhanom et al. 2020). User studies have been conducted to determine whether vignetting could be a promising solution for decreasing cybersickness while preserving presence. However, the conclusions remain different across authors. Fernandes and Feiner assessed vignetting during navigation with a hand-held controller and they showed that vignetting can reduce cybersickness and improve users' comfort (Fernandes and Feiner 2016). Budhiraja et al. proposed a vignetting where mouse acceleration increased or decreased the Gaussian blur applied to the virtual camera (Budhiraja et al. 2017). Their vignetting allowed participants to experience less cybersickness during a first-person shooter game in VR than the baseline group. Norouzi et al. studied the effect of vignetting during an exploration task in a virtual forest where head rotations gains were applied (Norouzi et al. 2018). They found that most of the participants experienced more cybersickness with vignetting than without. These results could be explained by the difference in how users explored a VE using head movements (resulting in higher exploration) or a hand-held controller (resulting in slower exploration). Furthermore, vignetting seems not to have a negative effect on path integration (Al Zayer et al. 2019), or spatial awareness (Sargunam and Ragan 2018). Yet, some studies revealed that vignetting techniques are less preferred for navigation tasks (Sargunam and Ragan 2018; Norouzi et al. 2018) where participants tend to prefer conditions without FoV restrictions and could lead to lower presence (Lin et al. 2002).

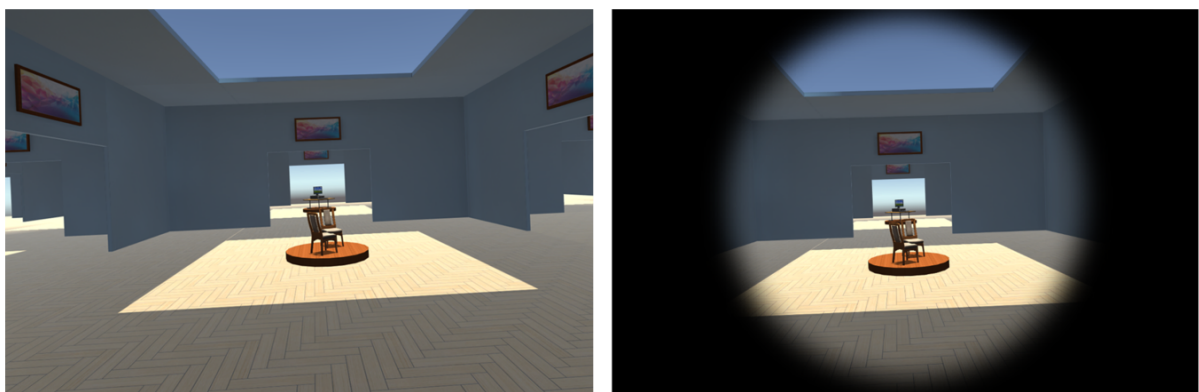


Figure 2.18 – One example of vignetting: on the left, the view of the VE without the vignetting and on the right, the vignetting reduces the FoV (Sargunam and Ragan 2018).

2.3.2 Auditory

Even though visual information can be sufficient for performing spatial tasks like speed, distance, and heading estimations, it can be inefficient for other tasks like circular vection estimation (Klatzky et al. 1998). Other external senses such as audition can provide information about the surrounding environment. For instance, (Riecke et al. 2009) showed that auditory stimuli can increase circular vection and presence in VEs. Besides, echolocation can give to users an improved sense of spatial knowledge in VEs (Andrade et al. 2018). However, auditory is generally not as rich as information from the visual system but may be considered when designing walking-based locomotion techniques. For further information, some reviews discuss how sound feedback can influence motion perception (Waller and Hodgson 2013; Våljamäe 2009) or how sensation of walking can be enhanced through external cues and the interaction between footsteps and the ground (Marchal et al. 2013).

2.3.3 Haptic

Cutaneous senses are external information that is also used during walking where the feet mechanoreceptors provide the walkers' information about the physical contact with the ground or objects in the environment. Haptic feedback represents the sense of touch that includes the perception of forces, movements, and cutaneous sensations provided by the VR system (Johnson 2001; Klatzky and Lederman 2003). In navigation tasks, the objective of haptic feedback is therefore to increase users' perception of motion and properties of the VE (e.g. ground properties). Marchal et al. 2013 argue that even low-fidelity haptic feedback may improve the sensation of walking in VEs and recent work done by (Kruijff et al. 2016) showed that haptic feedback could enhance users self-motion perception during steering or leaning-based navigation.

As described in the previous section, some wearable shoes have been designed to provide vibrations to the feet during the navigation (Papetti et al. 2010). Another example is the Shoe Sole Sense that provides heat and vibration feedbacks on the feet to inform the user about ground temperature (Matthies et al. 2013). Besides, some platforms such as treadmills (Noma et al. 2000) or instrumented floors (Law et al. 2008; Visell et al. 2007; Visell and Cooperstock 2010) can provide active haptic feedback thanks to actuated floor tiles. It is also possible to stimulate lower body muscles with vibrating sensations to improve presence and reduce cybersickness during steering task (Plouzeau et al. 2015). Finally, Terziman et al. 2012 created a multimodal feedback system for VR desktop applications called "King-Kong effects". A foot platform detects users' footsteps then haptic and visual signals are exaggerated to modify the virtual camera with pulses.

Results showed that the sensation of walking is increased for seated users with the multimodal rendering.

2.3.4 Vestibular

Since the vestibular system provides cues about position and movement (angular and linear acceleration of the head) during walking, considering its stimulation can be interesting to improve walking sensations in VEs. For example, Galvanic Vestibular Stimulation (GVS) can be used. GVS is the process of sending specific electric messages to nerves located in the ear. One implementation in VR was proposed by (Maeda et al. 2005), consists of two electrodes placed on the mastoids behind the ears that create an electrical impulse. A study showed that GVS can improve the perception of self-motion and defined the stimulus threshold to perceive the image motion (Nagaya et al. 2005). GVS can also contribute to reduce *cybersickness* (Sra et al. 2019). For instance, Langbehn et al. 2019a showed that transcranial direct-current stimulation can decrease oculomotor cybersickness symptoms after using redirecting walking.



Figure 2.19 – Example of Galvanic Vestibular Stimulation done by (Nagaya et al. 2005).

Kon et al. 2017 developed the HangerON technique based on the hanger effect (a phenomenon caused by the compression of two points on body segments like the head, the wrist, waist, or ankle). They designed a wearable belt with pneumatic driven balloons that compresses users' waists. The remote control allows an external person to alter the user's walking direction (as in the optical marionette (Ishii et al. 2016)). Last, Peng et al. 2020 added small vibrators motors that stimulate behind the ears. Even though the devices remain cheap and small, they only contribute to the vestibular sense of the users and sometimes require another person to remote control the system.

2.4 Taxonomy of Locomotion Techniques

Several taxonomies for VR locomotion techniques have been created to describe the relationships between them. While several taxonomies and classifications have been done to understand better the shared characteristics of similar techniques, most of the literature has focused rather on surveys about VR locomotion techniques than taxonomies, which makes it more difficult how locomotion techniques can be distinguished, compared, and assessed. For example, clustering techniques can help researchers to reused their experiment design to compare and assess the locomotion techniques. It makes the results comparable and allows experimenters to save time and effort in their study designs. Besides, these clusters allow the comparison of advantages and shortcomings of techniques between the different groups. [Prinz et al. 2021](#) explain in their analyses of publications on locomotion techniques taxonomies that there exist at least 29 unique taxonomies. This section gives an overview of the main taxonomies of locomotion techniques that have been done so far.

2.4.1 General Taxonomies

Most of the taxonomies rely on how users' movements are achieved in both REs and VEs. The first approach proposed by ([Mine 1995](#)) was to decompose a locomotion technique depending on the direction of the trajectory and the navigation speed, two fundamental components. He separated the direction into Head Steering, Gaze Steering, physical control, virtual control, object-driven, and goal-driven. Speed was subdivided into constant speed, constant acceleration, hand-controlled, physically controlled, and virtually controlled. A similar decomposition by ([Bowman et al. 1997](#)) added an input criteria to define when the navigation starts and ends (Figure 2.20). It states that a locomotion technique can be defined by three main components: direction-target selection, velocity/acceleration selection, and conditions of input. Inspired from the previous taxonomy, they proposed a new taxonomy that considers the control of users viewpoint (translation and orientation) ([Bowman et al. 1999](#)) (Figure 2.20). [Arns 2002](#) proposed a new taxonomy based on the rotation and translation achieved with the different locomotion techniques, but he also added other factors such as the VR display used and the interaction interfaces. [Wendt 2010](#) classified the locomotion techniques depending on whether the users remain stationary or mobile (physical translation). A taxonomy proposed by [Boletsis 2017](#) classifies the techniques depending on 3 dimensions: interaction type (physical or virtual), motion (continuous or noncontinuous), and the workspace (open or limited). A common taxonomy described in the *3D User Interfaces book* sorts the techniques depending on the mode of traveling (e.g. physical, steering,

selection-based, and manipulation-based) (LaViola et al. 2017). Cherni et al. 2020 identified through their literature review three main categories to categorize VR locomotion techniques: user body-centered methods (e.g. walked-based, steering-based, or leaning-based), external peripheral centered methods (e.g. gait negation techniques or manipulation and selections), and mixed methods using both of the two previous categories.

Other taxonomies focused on different features to cluster the locomotion techniques. Slater and Usoh 1994 distinguished the techniques according to their plausibility with either mundane or magical techniques. A mundane interaction tends to reproduce realistic everyday interactions (e.g. driving an automobile) whereas magical interactions include actions that are not possible in REs (e.g. teleportation and flying). Nilsson et al. 2016a proposed a taxonomy mixing two taxonomies (LaViola et al. 2017; Slater and Usoh 1994) in which they decomposed locomotion techniques into three orthogonal dimensions: (1) the user mobility (i.e. whether a user performs movements stationary or not), (2) whether the technique involves a vehicle or body-centric movement (source of motion), (3) whether the technique is mundane or magical (plausibility). Cardoso and Perrotta 2019 categorized the locomotion techniques based on the way to prevent users from reaching the boundaries of the physical workspace. They sorted the techniques as unmediated (absence of any system intervention in the locomotion process), warnings to indicate physical boundaries of workspace, reorientation and resetting (to reposition user when they reach the boundaries), scaling (uses of gains to modify the mapping between real and virtual movements), redirection (to steer the user away from the boundaries of the workspace), and Dynamic VE (manipulation of the VE). (Albert and Sung 2018) used three user-centered dimensions to sort the locomotion techniques (motion sickness, presence, and fatigue) that allow having a 3D visualization of the performance of different locomotion techniques. A recent project, called the Locomotion Vault, has been created (Di Luca et al. 2021). They made an online database and visualizations of over a hundred locomotion techniques¹. It describes the features of each technique and their similarities with each other. Using a data-driven approach, they showed that direction of motion is at the core of the design of the locomotion technique, and also that the similarities they found based on the metadata attributes correlated with expert similarity assessments.

2.4.2 Specific Taxonomies

Some taxonomies focused only on one particular set of locomotion techniques. For example, redirected walking techniques were separated depending on the type of gain (Figure 2.2) used to

1. <https://locomotionvault.github.io/>

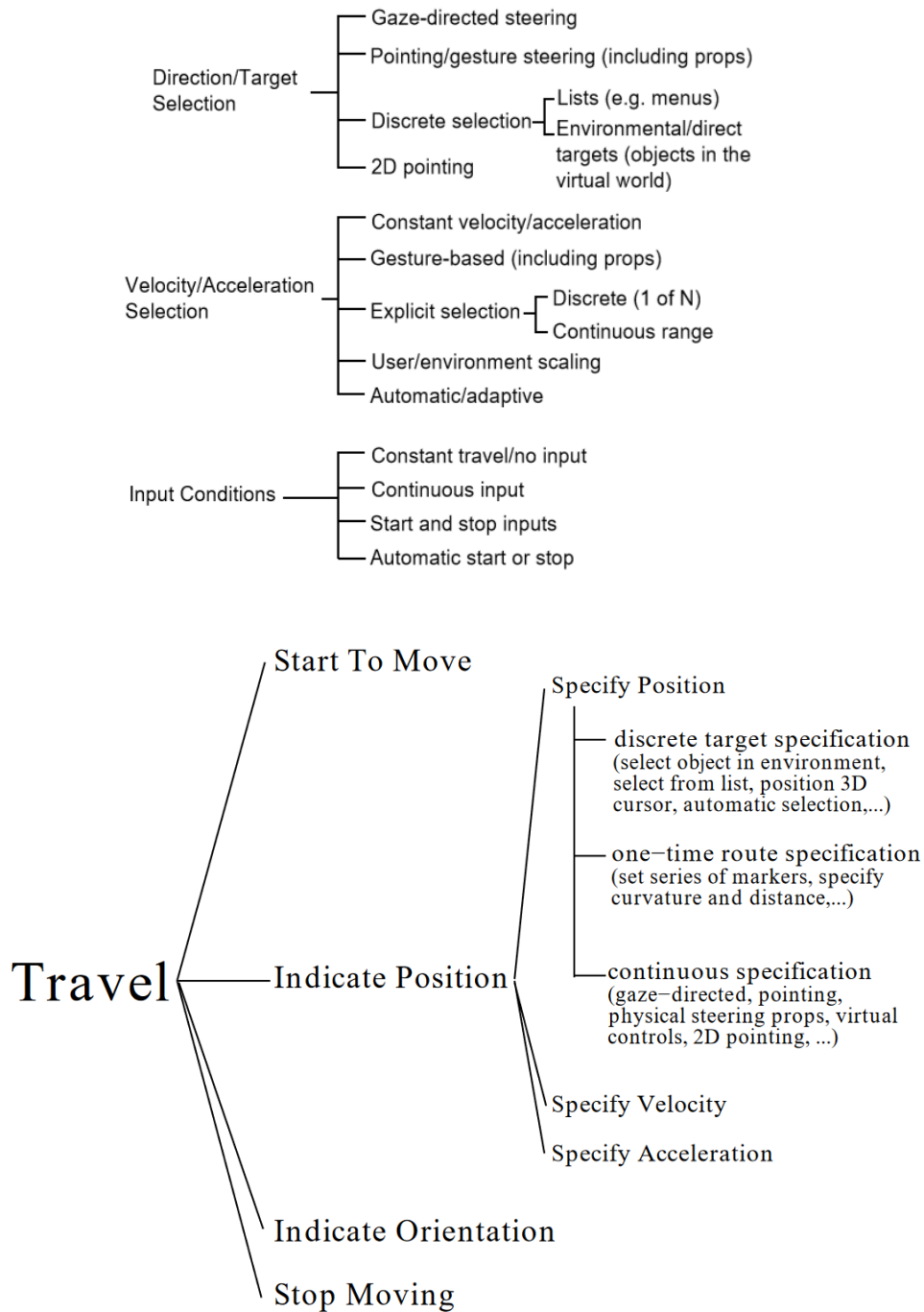


Figure 2.20 – Two taxonomies proposed by Bowman et al., on the left the locomotion technique is decomposed into three main components (Bowman et al. 1997) and on the right, the taxonomy specifies the control of users viewpoint (Bowman et al. 1999)

modify users' virtual viewpoint (Steinicke et al. 2008; Nilsson et al. 2018a). Suma et al. 2012a generalized the taxonomy for every redirected techniques described in subsubsection 2.1.1.1 and subsubsection 2.1.1.2 with three dimensions: type of redirection (reorientation or repositioning), the subtlety (overt or subtle) and the continuity (continuous or discrete). Another taxonomy decomposed walking-based techniques into six components including the control law of the locomotion techniques (Nabiyouni and Bowman 2016) (Figure 2.21). Anthes et al. 2004 classified and presented models of different control laws that can be used to update the translational and rotational speed in VR virtual locomotion techniques.

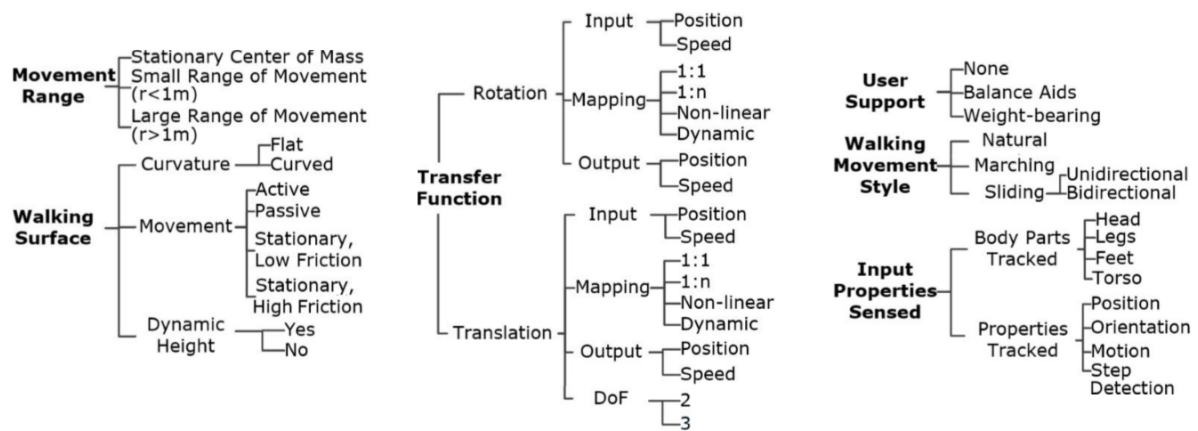


Figure 2.21 – Taxonomy proposed by (Nabiyouni and Bowman 2016) walking-based techniques that is composed of six components.

In this chapter, we reviewed the numerous locomotion techniques that have been designed, as well as solutions to improve navigation comfort. We showed that each technique can be grouped into taxonomies. They play an important role in assessing and comparing locomotion techniques. A lack of understanding about the differences between the locomotion techniques could prevent the spread of new locomotion techniques designs. Taxonomies reveal similarities between locomotion techniques, then it influences their choices and designs. In the next section, we will cover the relationship between the locomotion techniques and their taxonomies with the assessments of locomotion techniques in VR.

«Feminism is a collective adventure, for women, for men, and others. A revolution, well underway. A vision of the world, a choice. It is not about opposing the small advantages of women to the small achievements of men, but rather about screwing up everything.»

Virginie Desportes, King Kong Theory

3

Evaluation of Locomotion Techniques in Virtual Environments

Which locomotion technique is better for a given navigation task in VR? What are the main factors influencing users' navigation in VR? For instance, what is the minimum FoV required to navigate in VEs or what techniques are easier and more fun to use for users in VR, or do the individual factors matter in VR? VR researchers and practitioners wish to have the answers to those questions, but at the moment, it is hard to get a consensus because of the numerous factors influencing human perception and human interaction with VR systems. It requires analyzing and compare so many variables including users' performance, comfort, spatial knowledge, and so on. Having an exhaustive list of results demonstrating what are the best modalities for navigating in VEs remains therefore very challenging.

As we mentioned before, the VR interactions may alter the perception-action loop on several scales since the way we interact in VR could differ from real life. This implies that many mistakes can be done while designing new interactions techniques, from the sensory feedback provided by the VR system to the interaction hardware or software solutions to perform actions in VR. It has been now around 3 decades that we are aware that investigating human navigation and

motion control is essential to create effective locomotion techniques (Herndon et al. 1994). Consequently, various locomotion techniques have been designed for this purpose (Zayer et al. 2018; LaViola et al. 2017). The objective of this thesis is to understand which factors can influence users experience during locomotion in VR, in particular the perception-action loop. To achieve this, it is then necessary to have an overview of how evaluations are conducted and which evaluations have been already conducted in order to explore new factors and compare the effects of locomotion techniques on users' experience. In this section, we describe how the evaluation of locomotion techniques in VR is designed, what are the main factors assessed and the metrics used to measure, and what are the main results discovered from those studies (i.e. which humans factors are involved and affected with different locomotion techniques).

3.1 Design of VR Evaluations

The evaluations of VR interfaces can be complicated because they involve additional factors than traditional human-computer interfaces such as the physical environment (e.g. size of the workspace, users sitting or standing), multi-modal input generating more activity logs, or users related issues (e.g. VR can cause sickness or fatigue, the user experience with VR can impact the usability and comfort in VR). Besides, the design space of VR locomotion techniques evaluations is very vast, which means that it is unrealistic to have exhaustive evaluations assessing every factor. Also, one issue is to have an over-generalization of results that compare one or several techniques in an evaluation.

One of the most used VR evaluation methodologies was proposed by Bowman et al. in several publications (Bowman et al. 1997; Bowman et al. 1998; Bowman and Hodges 1999; Bowman et al. 1999). In these papers, they described the main methodology and required components to design and create an experimental platform to study locomotion techniques in VEs (Figure 3.1). The first step, the initial evaluation (1) establishes the base of the evaluations, in which the experimenters test and observe the interactions they want to investigate. This can be done by preliminary evaluation of a group of users on given technique and tasks. Then, taxonomies (2) of tasks and techniques (section 2.4) allows the experimenter to create a guided design by choosing techniques from similar or different taxons to compare them on different levels. In the meantime, the experiments should consider the metrics (3,4) they want to use described in section 3.2 as variables in their study. The final stage is the testbed experiments (5) that consist of a factorial experimental design assessing metrics for a given task. It produces data (6) that can be analyzed to provide guidelines (7) regarding the results of the testbed. These results help to have a better

understanding of techniques and allow the design of user-centered techniques (8). We will not get into detail regarding this whole framework methodology, but rather focus on the testbed evaluations that are a key component used in most recent VR evaluations. For further details, please refer to the following references ([Bowman et al. 2002](#); [Bowman et al. 1999](#)).

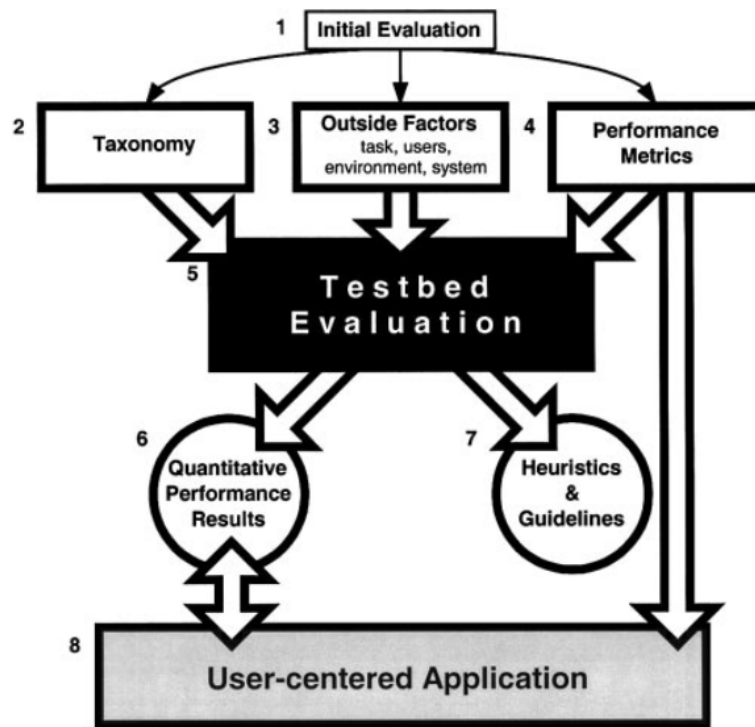


Figure 3.1 – Design, evaluation and application approach designed by ([Bowman and Hodges 1999](#)).

Testbed experiments is an evaluation methodology commonly used in HCI evaluation that takes into account outside influences describe just before. It uses formal frameworks and formal experiments with multiple independent and dependent variables to obtain a wide range of performance data for VE interaction techniques ([Bowman et al. 2001b](#)). They allow to test some aspects of the locomotion techniques (our dependent variables based on the metrics recorded) for a given task. Thus, it is possible to embed new locomotion techniques while keeping the standardized VEs and tasks designed for one experiment. From the performance data recorded thanks to the various metrics described before, it is possible to assess their effect on the different locomotion techniques used in the experiment through statistical analyses. While testbeds are considered the gold standard for evaluating locomotion techniques in VR, the literature regarding the theoretical design of testbeds evaluations is sparse. ([Cannavò et al. 2020](#)) introduced a novel

testbed evaluation that can automatically rank locomotion techniques based on objective and subjective data. The experiment is divided into several scenarios (corresponding to navigation tasks) and uses different metrics with respect to the given task to give a score for each task per locomotion techniques.

To evaluate the locomotion techniques, it is necessary to consider which metrics to use and the outside factors independent from the locomotion techniques that will be included in the testbed evaluation.

3.2 Factors to Assess VR Locomotion Techniques

During locomotion in VEs, users' comfort and performance can be altered by several factors that we can split into two categories. The first one is the factors related to the locomotion technique itself (dependent, i.e., the influence of the locomotion technique on user's motion) and the second one is the factors related to other characteristics of the VR system (independent, such as the type of task and VE). In this section, we describe the main factors used (i.e. the variables studied and how they are measured) in evaluations of locomotion techniques.

3.2.1 Dependent Factors

Dependent factors for evaluating and comparing locomotion techniques can be divided into two categories: objective and subjective. Objective factors will define values that are gathered or computed during the navigation task (e.g. to assess the efficiency, comfort, movements, or effectiveness of a given task). Subjective factors will mainly consist of users' feedback regarding their comfort during the navigation task or feedback regarding the locomotion techniques used. The main factors used in VR studies are related to the following categories:

- **Performance** - Time is a good indicator and is generally used to measure how much time the users need to perform a given task. Success or failure of the task can be also measured. In the case of complex VEs, collisions with the VE could be also considered as a performance metric. Other approaches, inspired from Fitt's Law, evaluated locomotion techniques using the Steering Law ([Monteiro et al. 2018](#)). It assesses users' ability to perform a path by computing the quantitative relationship between human temporal performance and the movement path's spatial characteristics. Questionnaires can be also used: for instance, the NASA-TLX assesses locomotion techniques based on their mental demand, performance, effort, and frustration ([Hart 1986](#)).

- **Spatial awareness** - Spatial awareness corresponds to the users' ability to understand the way the spatial layout of the VE. To assess users spatial perception, some measures such as knowledge of the user's viewpoint in the VE (Bowman et al. 1999), remembering locations of objects (Suma et al. 2007), using questionnaires such as part five of the Guilford-Zimmerman Aptitude Survey (Guilford and Zimmerman 1948), the relative turning angle error when we ask users to point the starting point of a navigation task (Williams et al. 2011) or even distance estimation (Iwata and Yoshida 1999; Keil et al. 2021) can be used.
- **Cognition** - Most measures about cognition during navigation in VEs consist of asking users to sketch maps of the VE after performing the navigation task (Peck et al. 2010), ask for object position and recall (Suma et al. 2010; Chance et al. 1998), memory efficiency (Marsh et al. 2013) and the ability to perform the dual task at the same time (Bruder et al. 2015). Cognition questionnaire can be also used such as the NASA-TLX or questionnaires inspired from Bloom's taxonomy (Zanbaka et al. 2004).
- **Virtual trajectories and user motion** - Trajectories performed by users while navigating can be also considered. For instance, deviation from the optimal path can be computed to check the difficulty to navigate in VR (Jeong et al. 2005). Cirio et al. 2013 considered also local characteristics (presence of stops, collisions...) as well as continuous variables (the overall shape, speed profile, path curvature...) to evaluate kinematics of trajectories during navigation with several techniques. Biomechanics features can be also used like step count and step length, toe-in/out, and swing and stance phases (Janež et al. 2017). (Nilsson et al. 2013c) investigated how users have involuntary position shifts in the workspace using WIP.
- **Cybersickness** - Motion sickness symptoms can indicate that a technique is not usable for a given task. In most studies, the Simulator Sickness Questionnaire (SSQ) is used at the end of the navigation task to assess potential motion sickness on several scales (nausea, oculomotor, and disorientation) (Kennedy et al. 1993). A shorten questionnaire, the fast-SSQ questionnaire can be used during the navigation task (Rebenitsch and Owen 2014). It is also possible to use objective measures such as physiological (Kiryu et al. 2008), postural (Chardonnet et al. 2017) or electroencephalogram (Jeong et al. 2018; Pane et al. 2018) to assess cybersickness. These physiological measures are most of the time analyzed through mathematical such as fuzzy inferences system (Wang et al. 2021a) or deep-learning models (Kim et al. 2019; Islam 2020; Lee et al. 2019) that allow real-time detection of cybersickness. A recent study showed that gaze activity can provide

interesting insights about users' cybersickness ([Lopes et al. 2020](#)).

- **Presence** - A number of papers have explored the impact of the locomotion technique on presence. It is a good indicator of the quality of the virtual experience and it is typically assessed using questionnaires (e.g., Steed-Usch-Slater questionnaire ([Slater et al. 1995b](#)), the Witmer and Singer questionnaire ([Witmer and Singer 1998](#)) and the Igroup Presence Questionnaire questionnaire ([Schubert et al. 2001](#))). While presence has been particularly investigated in VR, including for navigation with avatar ([Griffin and Folmer 2019](#); [Dewez et al. 2020](#)), they are not in the scope of the manuscript.
- **User preferences** - Some subjective questionnaires can be used to ask the user which techniques they preferred, how comfortable they felt. They are mainly based on the Likert scale. Note that it is also possible to ask for detailed feedback from users after the experiment.

3.2.2 Independent Factors

Even though the locomotion technique is one factor that can influence users navigation in VEs, other factors can influence users experience as well ([Bowman and Hodges 1999](#)):

- **Task characteristics** - The type of task (e.g., path to perform, presence or not of obstacles...) can alter users' performance and behavior in VR navigation. For instance, traveling can be affected by the type of trajectories to do and the degrees of freedom of motion required that can affect the distance traveled ([Weißker et al. 2018](#)).
- **Environment characteristics** - It is possible to design an infinite number of VEs, meaning that the amount of information provided by a VE could differ from one experiment to another. The same task in different environments could give different results. For instance, the richness of the visual information or number of obstacles in the VE can impact navigation ([Ruddle and Lessels 2006](#)).
- **User characteristics** - Human factors need to be carefully considered in VR since users are at the heart of the VR system. Taking into account users' differences then is required for VR experiences. Several criteria can be considered such as age, gender, visual acuity, experience in VR and video games, and eventual ocular or locomotor disorders.
- **System characteristics** - They include hardware and software parameters that can impact the global user experience in VR. For instance, display characteristics (mono versus stereo rendering) or the size of FoV ([Riecke et al. 2005a](#)), the lighting model of the scene used ([Vasylevska et al. 2019](#)) or the latency of the VR system ([Ware and Balakrishnan 1994](#)) can have an impact on user interactions.

Few research work has been done to determine different factors and metrics from the previously mentioned. [Sherstyuk et al. 2010](#) tried to evaluate user's activity in VR in real-time by analyzing users' intention of movement and fatigue of users. McMahan et al. hypothesized that high and low-fidelity locomotion techniques often perform better than medium-fidelity ones ([McMahan et al. 2016](#)). In other words, they argued that the relationship between interaction fidelity and performance might look like a U-shaped curve, with higher performance at the two extremes and lower performance in the middle ([McMahan et al. 2012](#)). Investigating new factors or metrics and focus on the travel system instead of the traveler could be interesting to understand better human behavior during navigation. For instance, [Pfeuffer et al. 2019](#) presented analyses and models based on random forests and support vector machines to identify user's intra-variability in VR interactions based on body-segments movements and coordination. In the case of walking tasks, those head movements are a better feature to describe individual user walking than hand movements.

We reviewed the main factors used in evaluations of locomotion techniques in VR, but it is worth noticing that researchers can define their own or new metrics to assess locomotion techniques. In the next section, we aim to give guidelines about the recurrent results VR researchers found in their studies.

3.3 Foreword about Key Results in VR Locomotion Evaluations

We will now describe the main and recurrent results from the various studies already done to evaluate different locomotion techniques with different tasks. We will only focus on natural walking, redirected walking, virtual techniques because they are the scope of the contributions described in the next parts.

3.3.1 Comparison between Walking and Virtual Techniques

In the VR community, walking is considered as the most ecological approach for navigating in VEs since the users' motion in the RE and the VE are the same, thus, providing an intuitive interface for users. However, research work has been done to show the benefits of walking versus the use of virtual locomotion techniques.

First evaluations showed that walking increases the presence compared to WIP or steering ([Usuh et al. 1999](#)) thanks to the proprioceptive and vestibular feedbacks provided by walk-

ing (Slater et al. 1995b). Besides, walking induces fewer cybersickness symptoms than virtual steering techniques during straight navigation tasks in VEs (Jaeger and Mourant 2001). However, the type of task can influence these results. Suma et al. 2009 showed that during short exposure (five minutes) in a virtual complex 3D maze, walking increased SSQ scores than head steering. Walking at room-scale seems also to provide better spatial awareness. Zambaka et al. 2004 showed that users, after exploring a VE, had better map sketching and cognition questionnaire results than with head steering with HMD or using a desktop computer. However, they did not notice an effect on cybersickness. Another work indicated that locomotion with a less natural interface increases spatial working memory demands and that locomotion with a lower FOV increases general attentional demands (Marsh et al. 2013).

In terms of performance to achieve different tasks in a VE, Ruddle et al. conducted several experiments regarding the benefits of walking compared to other techniques. First, walking with full body-based information provided better search results than the other techniques (Ruddle and Lessels 2006). They confirmed these results in another experiment where walking yielded to less imperfect search than the head steering or joystick control with monitor (Ruddle and Lessels 2009). Last, in another experiment, they asked users to traverse a 24m-long route by following a virtual arrow in a VE with corridors several times. They used either walking or head steering and showed that task completion was faster and the number of collisions was lower with walking (Ruddle et al. 2013).

Walking also improves the precision of turning during the exploration of VEs. For instance, in their experiment, Williams et al. 2011 asked users to reach targets in a museum environment then turn themselves to face the required object that was removed between trials. They compare walking, a leaning interface based on the Wii Balance Board, and joystick steering. Even though they did not find an effect on the time to complete the task, walking generated less turning error than the leaning and joystick interfaces. In another similar study, walking generated less turning error than WIP interfaces, but also provided lower distance estimation than WIP (Wilson et al. 2016).

Regarding virtual trajectories and user's motion, a study showed that the navigation through real walking yielded better results when it comes to performance index based on the steering law, but also cybersickness, and user satisfaction than using a gamepad (Monteiro et al. 2018). Whitton et al. 2005 compared spatiotemporal features of locomotion techniques in a study where users had to navigate in a virtual maze and walk towards targets displayed on the walls. They had to go as close as possible to the wall without touching it. They compared walking, WIP and steering and showed that walking and WIP had closer spatio-temporal features (peak velocity

and peak deceleration) from walking in REs.

All of these results show the benefits from having a walking interface¹. However, walking requires a large workspace to enable locomotion in the whole VE, which is not available in most VR setups. Then, walking remains still the most privileged option for navigating in room-scale VEs, but the use of redirected techniques can be required as the VE increases or the RE decreases.

3.3.2 Side Effects of Redirected Walking

The goal of redirected walking is to apply gains that should be subtle to alter users' motion during a navigation task. Then, the main challenge is to understand how users perceive gains under different conditions. Razzaque's work showed that it is easier to apply rotation gains if users are already rotating and that small changes are more likely to be not detected ([Razzaque et al. 2001](#)).

Rotations gains have been widely studied in VR ([Steinicke et al. 2010](#); [Jerald et al. 2008](#)), using mostly 2AFC protocols. Different experimental conditions have been explored such as varying the amount of rotation to perform ([Bruder et al. 2009](#)) (ranging from 10° to 180°); adding visual effects ([Bruder et al. 2012a](#); [Paludan et al. 2016](#)) (e.g. contrast inversion or sinus gratings); varying the gain implementation ([Congdon and Steed 2019](#); [Zhang and Kuhl 2013b](#)) (delaying the gain rotation based on the amount of rotation performed); using auditory cues ([Serafin et al. 2013](#); [Nilsson et al. 2016b](#)) (specialized sound to redirected users) or distractors ([Peck et al. 2009](#); [Williams and Peck 2019](#)) (to lose focus on the gains); using different FoVs ([Williams and Peck 2019](#); [Bolte et al. 2010](#)) (e.g 40° vs 110°); comparing perception of gain between a CAVE and a HMD ([Ragan et al. 2016](#)) or different locomotion interfaces ([Bruder et al. 2012b](#)) (walking and wheelchair steering). These studies resulted in different PSE and thresholds values but in general, 25% and 75% thresholds ranged respectively between 0.59-0.93 (25% DT) and 1.10-1.27 (75% DT), where the gains tested were between 0.5 and 1.5. Readers can refer to the following references for further information about the detection threshold of head rotation gains ([Langbehn and Steinicke 2018](#); [Nilsson et al. 2018a](#)).

Redirection techniques are based on a distortion between the perception-action mapping and therefore can produce some discomfort as the rotation of the virtual camera differ from the physical rotation performed by users. Even though ([Razzaque et al. 2001](#)) noticed no particularly

1. We want to note the readers that some results presented in the subsection could also be influenced by the VR system used, and that some of the presented results were obtained with older VR equipment with potentially higher latency values. Then, the results presented regarding cybersickness could be reconsidered with newer VR equipment but we suggest that the one regarding spatial awareness might be the same.

cybersickness effects during their pilot study, further research work showed an increase of cybersickness during injection of rotation gains during redirected walking (Schmitz et al. 2018; Hildebrandt et al. 2018).

Even though redirected walking can be considered as a subconscious process, this technique can require more cognitive resources (Bruder et al. 2015). They found that navigation performance decreased and mental workload increased as the rotation gain increased while doing a spatial memory task.

Another effect detected during redirected walking is how it can affect users' movements and biomechanics. For instance, applying curvature gains can alter the inside and outside toe in/out (Matsumoto et al. 2018) or applying translation gains can alter the step length and frequency where authors suggest that these features might be correlated to users discomfort (Tirado Cortes et al. 2019). In addition, Janeh et al. 2017 showed that participants walked differently in VEs with translation gains than in REs. They found in particular that most of the spatio-temporal features of walking gait were affected during straight-line walking in VR with translation gains.

Redirected walking is an interesting technique to achieve walking in a constrained workspace, yet the state-of-the-art implementation still requires a higher workspace (around 6×6 meters) than most VR consumers do not have (Azmandian et al. 2015). Long exposure to this technique may also lead to cybersickness and their generalizability are difficult since literature about spatial awareness and cognitive resources of redirected walking. Then, the use of virtual techniques can be sometimes preferred as they are easier to be implemented in VR systems.

3.3.3 Apropos of the Use Steering Techniques

The first evaluation of steering techniques was introduced by Bowman et al. at the same time they introduced the design of evaluations of locomotion techniques in VR (Bowman et al. 1997; Bowman et al. 1998; Bowman et al. 2001b). Based on a taxonomy, Bowman et al. 1997 studied two components of a locomotion technique (the input that provides the direction and the velocity specification). One experiment consisted in comparing head and hand steering in a goal-directed task (users had to reach a sphere at different target distances in the VE). Results showed that there was no significant effect on the task completion between both steering techniques, but they noticed in another experiment that hand steering was better performed in distance estimation than head steering. They also noticed that teleportation led to increased disorientation than steering. They reproduced similar experiments in which they varied the VE and showed that it has a significant impact on users' navigation (Bowman et al. 1998). Last, they showed that in a search task in a VE, steering techniques outperformed manipulation-based techniques (Bowman et al.

2001b).

Steering and teleportation are often compared. In one experiment, participants had to go from one point to another (information was given through a map) and collect tokens in a VE (Christou and Aristidou 2017). They reported that task completion was faster with teleportation than steering, and in addition lower SSQ scores. Similar results were found in another study in a point origin task (Weißker et al. 2018). In terms of presence, they both seem to provide similar immersion but teleportation seems more usable than steering in goal-directed tasks (Buttussi and Chittaro 2019). Langbehn et al. 2018a also demonstrated in their experiment that teleportation is generally preferred by users than steering, which also provided higher cybersickness.

Regarding the control law evaluation, less research work has been done. One investigated the differences between the body segment providing heading (torso, head, and virtual direction) but also the input device to define the start and end of motion (gamepad versus leaning) in a goal-directed task (Zielasko et al. 2020). They showed that task completion was lower with a gamepad than leaning, and that torso steering reduced the number of collisions with the VE. A recent study investigated both heading selection (head, hand, torso, and knee) and navigation speed update (power, piecewise with constant and linear functions, piecewise with constant and power functions) (Gao et al. 2021). Participants had to reach a target (located at different distances across trials) by performing a straight motion. They proposed a quantitative evaluation of the four transfer functions and body segments used to navigate and demonstrated that linear functions allow to perform the fastest but the least precisely, while power-law provided better precision but longer task completion. In addition, using head steering resulted in the lowest trials failures and torso the highest.

Concerning the virtual trajectories achieved with steering techniques, Cirio et al. 2013 showed that in the case of goal-directed locomotion with different interfaces (joystick, joyman, keyboard) the control of the trajectory was similar, even though continuous interfaces were more conform with the kinematics of real walking trajectories than binary interfaces. Terziman et al. 2011 compared WIP and steering during a slalom task. They showed that distance to shortest trajectory was lower with steering than WIP and also that steering generated more smooth trajectories than WIP, suggesting that steering provides more easily continuous motion during curvilinear trajectories than WIP.

3.3.4 Individual Factors and Users Preferences

Human variability is something difficult to control when designing evaluations of locomotion techniques in VR, as many individual factors may influence the results. These factors are often

ignored while recruiting participants and analyzing the results. Still, additional insights could be extracted from these factors.

Recently, [Peck et al. 2020](#) discussed the issue concerning the participants' diversity in VR studies. The generality of the results may be hampered by the female and male ratio in the experiments, since the results may be biased in terms of gender. Authors showed differences between males and females while navigating in VR, as well as at the cerebral level where MRI data showed that brain areas activations differ according to the gender ([Grön et al. 2000](#)), but also in terms of spatial performance ([Suma et al. 2010](#)) or in terms of cybersickness where women are more sensitive to simulator sickness than men ([Stanney et al. 2003](#)). In [Suma et al. 2010](#), users had to follow a target in different virtual mazes (either simple or complex ones) while answering to auditory stimuli in the meantime. Results showed that male participants performed worse (i.e. higher delay response to the auditory stimuli) than females in the complex maze.

Regarding age and gender, age can alter the navigation performance in VR ([Driscoll et al. 2005](#)). They asked participants to perform a virtualized Morris Water Task and their results showed that the youngest group outperformed the oldest group. In addition, they mentioned that spatial learning was higher for males and might be explained by the higher level of circulating testosterone. Sometimes, gender differences are not found. For example, [Kitson et al. 2016](#) were unable to find gender differences of spatial performance in a point-to-origin task and [Al Zayer et al. 2019](#) did not find gender differences in a triangle completion task. Last, other factors could be considered such as the dominant foot and hand, where we could eventually investigate differences between left or right-handed, or the height, weight, ocular or locomotor disorders, but little is known about the potential effect of such factors in VR navigation.

Users' experience with 3D environments can also influence the results of VR evaluations. For instance, a study compared navigation performance between persons with high and low experience in videogames ([Soler-Dominguez et al. 2019](#)). They had to collect as fast as possible coins in VEs while using joystick steering or WIP. Results showed that users with higher video game experience outperformed those without.

User subjective feedback is also important while assessing locomotion techniques. Regarding the movement of the virtual camera, a preliminary study showed that realistic camera model translation and rotation are preferred while navigating with desktop application ([De Barros et al. 2009](#)), but a second experiment refuted this hypothesis ([Barros et al. 2009](#)). Participant's interviews at the end of the experiment can also help to have insights about which techniques users may prefer ([Bozgeyikli et al. 2019](#); [Boletsis and Cedergren 2019](#)). For example, joystick, WIP, and teleportation were compared regarding their usability and preferences ([Bozgeyikli](#)

[et al. 2016b](#)). The results show that teleportation and joystick were subjectively preferred over WIP during a goal-directed task. Considering navigation in VR for neuroatypical users is also important. [Bozgeyikli et al. 2016a](#) studied preferences of individuals with an autism spectrum disorder. They showed that they preferred joystick or teleportation techniques over WIP or gesture-based interfaces.

Conclusion

In VR, the users are at the heart of the system. They are immersed in a VE and they interact through a perception-action loop allowing them to use the VR system and to perceive the sensory feedback provided by it. In this thesis, we focus on a major interaction in VR that is navigation. Exploring VEs is the main requirement in VR. While there are several ways to go from one initial position to a given destination, we showed that the disadvantage of some VR locomotion methods is that they can generate more or less a sensory conflict that can cause discomfort and cybersickness, but also affect users performance. We have seen that the control of locomotion is characterized by perceptual and locomotor invariants in the context of walking. However, we do not yet know if these invariants are found in the case of a walker navigating in VEs. This is why using knowledge of the human locomotor system to apply it to VR could be relevant. We also saw that the evaluation of VR locomotion technique is a trendy topic in VR research, but the literature lacks references regarding the influence of locomotion technique on users' movements, but also regarding how users perceive these movements navigation in VEs. In particular, as shown in Figure 3, we investigated some factors involved in human locomotion such as visual cues (FoV, vignetting), movements (locomotion speed and rotations) and assessed if they would alter users behavior during navigation tasks. So far, discomfort while navigating in VEs is a major obstacle to the expansion of VR. Thus, a challenge related to VR navigation would be therefore to understand the users' behavior when being immersed in VR. By accumulating knowledge on how users act and behave in VR, new interaction techniques could be designed to better support the laws governing human motor control. The two following parts of the manuscript present the contributions of this Ph.D. that aimed at understanding human behavior during navigation in VEs. We separated the experiments into two different categories: (1) those that evaluated the impact of the locomotion technique on users' movements and (2) those who investigated the perception of rotation gains in VEs.

PART II

Influence of Locomotion Techniques on Users Movements

Introduction

This part details the first research axis of the manuscript in which we investigated how can navigation techniques influence unconsciously the way users perform movements in VEs (Figure 3.2). It provides new information and results in particular for steering techniques that have been less considered regarding evaluations of users kinematics. The objective is to better understand why and how steering can differ from walking in order to improve these techniques so that they could provide closer motor actions than walking.

We present three contributions. The first one entitled « Virtual vs. Physical Navigation in VR: Study of Gaze and Body Segments Temporal Reorientation Behaviour » is a conference paper presented at the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) that paid attention to how users body is coordinate during a curvilinear trajectory during walking in VR or using steering techniques.

The second contribution « Does the Control Law Matter? Characterization and Evaluation of Control Laws for Virtual Steering Navigation », focused on how the way the virtual navigation speed is updated can alter the way users physically rotates during a slalom task. This conference paper was presented at the 2020 International Conference on Artificial Reality and Telexistence & Eurographics Symposium on Virtual Environments (ICAT-EGVE).

The last contribution, « Understanding, Modeling and Simulating Unintended Positional Drift during Repetitive Steering Navigation Tasks in Virtual Reality » was presented as a TVCG journal paper at the 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR). This paper explored to understand how users tend to unintentionally move in the physical workspace while using steering techniques in order to create and simulate models that aim to give insights into this quite unknown phenomenon.

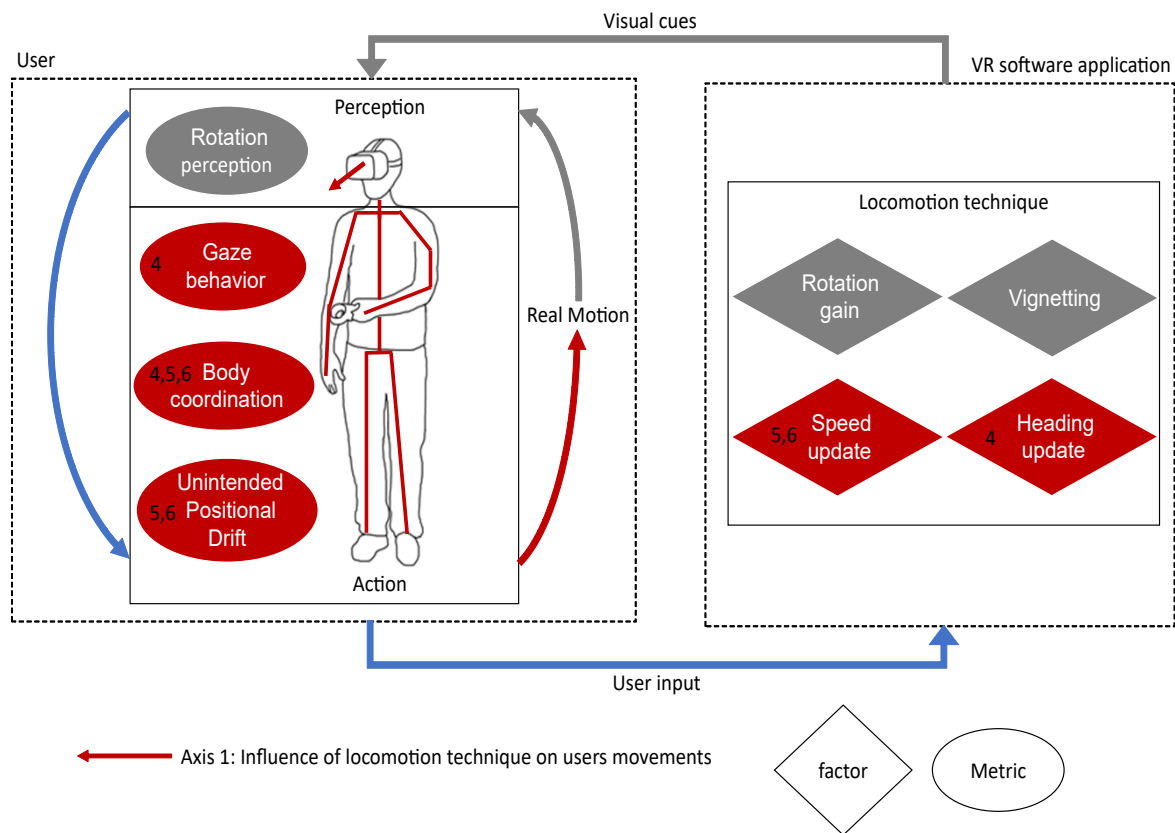


Figure 3.2 – Factors (red rhombuses) and metrics (red ellipses) studies in this part. The number referred to the chapter where the factors and metrics were investigated.

*« Until you make the unconscious conscious, it will direct your
life and you will call it fate. »*

Carl Gustav Jung

4

Virtual vs. Physical Navigation in VR: Study of Gaze and Body Segments Temporal Reorientation Behaviour

4.1 Motivations

Various number of studies have focused on the impact of virtual navigation techniques in terms of performance, spatial awareness, or even cybersickness. However, little is known about the impact of such techniques on user behavior. In this chapter, we try to shed some light on how navigation techniques influence visuo-locomotor coordination, and in particular the anticipation strategies between body segments like gaze, head, and shoulders.

Human locomotion is a complex task involving motor and cognitive controls. Studies in the field of Neuroscience have shown the importance of the head to control locomotion, acting as an inertial platform and a frame of reference to help the coordination of body segments ([Pozzo et al. 1990](#)). In particular, while performing a curved path in a Real Environment (RE), a top-down reorientation strategy is consistently observed ([Courtine and Schieppati 2003](#); [Bernardin et al.](#)

2012; Hollands et al. 2002): the gaze anticipates the future direction of the movement, followed by the head and then the shoulders. However, this anticipation, which is common to all humans, can be affected by health issues challenging postural control and locomotion (Lamontagne and Fung 2009; Reed-Jones and Vallis 2007). These locomotion invariants have been mainly considered in REs, but there have been only a few studies regarding the top-down hierarchy and gaze anticipation mechanisms during a navigation task (Grasso et al. 2000; Reed-Jones et al. 2009). These works mainly assessed gaze and body segments behavior for 90° turns with passive or walking-in-place techniques.

In this chapter, we evaluated how users perform a navigation task in VR according to different navigation techniques. We proposed for the first time to analyze gaze behavior and body segments orientation strategy during curved trajectories using several navigation techniques including walking, steering, and passive techniques (Figure 4.1). Our results enrich the understanding of human behavior in VEs and are discussed concerning the design of new, human-centered navigation techniques which could improve users' experience.

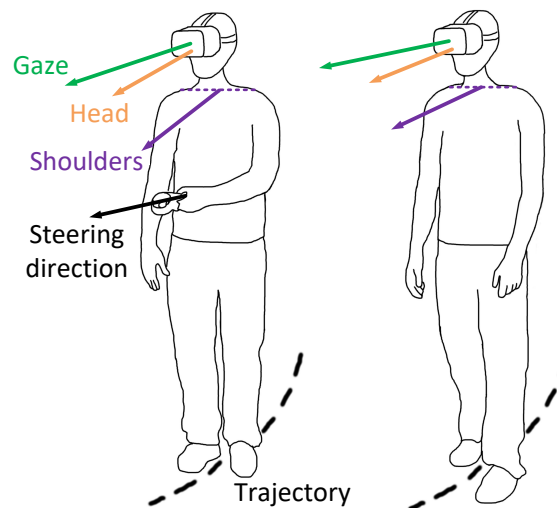


Figure 4.1 – In our experiment, participants wore a head-mounted display and performed a lemniscate trajectory in a virtual environment. We investigated body segments (gaze, head and shoulders) anticipation synergies during navigation with five techniques including hand steering (left) and walking (right).

4.2 User Study

The goal of this study was to investigate the temporal synergies between body segments (gaze, head, and shoulders) during a navigation task along a curved trajectory. While a wide number of navigation techniques could have been analyzed, this study assessed five navigation techniques that are widely employed in VR systems and also provide a different degree of user control. In particular, we focused on real walking, three virtual steering techniques, and one passive navigation technique. Our main hypothesis was that navigation techniques with higher fidelity to real walking would lead to synergies between body segments closer to the ones observed during real locomotion tasks. This experience was strongly inspired by paradigms already used to assess gaze anticipation during curved trajectories in RE ([Bernardin et al. 2012](#); [Authié et al. 2015](#)).

4.2.1 Participants and Apparatus

20 participants (15 males and 5 females) aged between 19 and 29 years old (23.5 ± 2.33 , mean \pm SD) without any ocular or locomotion disorders volunteered to this study. They all have already experienced VR once (33% regularly, 66% few times) and videos games (70% regularly, 30% few times). They were naive to the purpose of the experiment and signed an informed consent form. The study was approved by the Inria Ethics Committee (reference: 2018-008/02) and conformed with the standard of the declaration of Helsinki.

Users were immersed in the VE using the FOVE HMD that includes an eye-tracker. The display Field of View (FoV) was 90° (horizontal). We used three HTC Vive trackers and two HTC Vive base stations to track users' head and shoulders positions. Users wore an MSI VR One 7RE backpack, including a GTX 1070 GDDR5 and 16Gb RAM (Figure 4.2). We paid particular attention to the HMD cables to prevent users from being bothered by them, as it could potentially influence users' behavior.

The VE (Figure 4.2) was a 8x8x4 meters rectangular parallelepiped. We added a noise texture to the walls so that rotations generate motion flow but without any salient features. We designed a bigger VE than the workspace (which was 4x4 meters) in order to preserve users' personal space. Indeed, there exists a « collision envelop » which defines the comfortable distance between a user and an obstacle. This distance would depend on the internal perception for safe navigation. This was confirmed in our pilot studies where we noticed that coming close to a wall in the VE disturbed the users during the navigation task.

In order to study body reorientation strategies during navigation, we defined the trajectory to perform as a Geronio lemniscate defined by the parametric Equation 4.1. This standardized

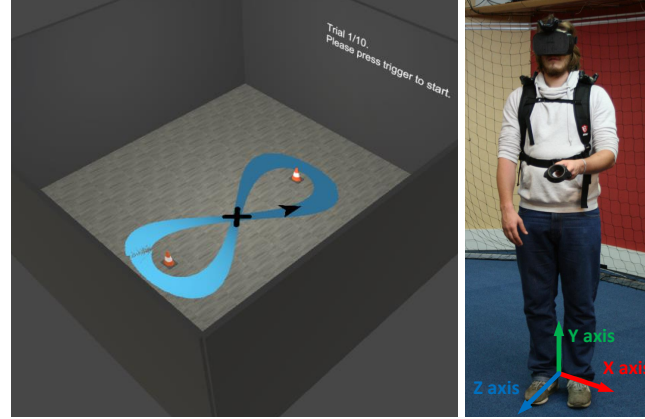


Figure 4.2 – Left - The VE used for the experiment. The roof was removed for illustration purposes. Right - Participant equipped with the FOVE HMD, a backpack, the HTC Vive trackers, and the HTC Vive controller. The trackers were used to track the user’s head and shoulders.

trajectory has been already used in studies about human locomotion in REs ([Bernardin et al. 2012](#); [Authié et al. 2015](#)).

$$\begin{cases} x(t) = \cos(t) \\ z(t) = \sin(t) * \cos(t) \end{cases} \quad (4.1)$$

The center of the VE was represented by a black cross, which also corresponded to the center of symmetry of the trajectory displayed in blue on the ground. Two cones were arranged in the VE to delimit the trajectory (placed two meters on either side of the center). Besides, an arrow indicated in which direction the user had to perform the trajectory (either from the left or from the right as shown in Figure 4.2). Some feedback text was displayed in front of users’ initial position wall to provide the information during the experiment. All visual information was hidden when users performed the trajectory, only the walls and the floor were displayed during the task.

4.2.2 Control law based on the biomechanics of walking

In the experiment, participants had to perform lemniscate trajectories. During the pilot experiment, we observed that the most common control laws for virtual steering were not appropriate for the given task. Due to the coupling between speed and curvature during human locomotion, constant speed methods resulted in unrealistic speed profiles, and user-controlled methods were difficult to master. Although the control law described in ([Marchal et al. 2011](#))

could have been used, it was designed for a joystick-based input. Thus, we designed a new control law based on the biomechanics of human walking that uses the relationship between speed and curvature (Vieilledent et al. 2001; Hicheur et al. 2005b). During a continuous trajectory, the instantaneous speed varies according to the local radius of the curvature (see Equation 4.2) as a power law:

$$R(t) = \frac{(\dot{x}^2 + \dot{z}^2)^{\frac{3}{2}}}{\dot{x}\ddot{z} - \ddot{x}\dot{z}} \quad (4.2)$$

where \dot{x} , \dot{z} , \ddot{x} and \ddot{z} are respectively the first and second derivatives of x and z coordinates of the user's position in the environment. In the case of walking trajectories, the speed of locomotion is proportional to the cubic root of the radius of curvature (Vieilledent et al. 2001; Hicheur et al. 2005b) (Equation 4.3):

$$S(t) = K.R(t)^{\frac{1}{3}} \quad (4.3)$$

where $S(t)$ is the horizontal speed at time t , K is a gain speed coefficient, and $R(t)$ is the radius of the local curvature of the trajectory at time t . The coefficient K was empirically determined during pilot tests in which users walked along the lemniscate trajectory while wearing an HMD. We analyzed the mean velocity profiles and we chose the coefficient $K = 0.5$ so that the control law would have similar speed profiles than walking in VEs.

Given this power-law relation, our control law updates the speed and position of the user in the VE at every frame only if the user pressed the trigger button of the hand-held controller as follows:

1. The user speed $S(t)$ was updated according to the 1/3 power law (Equation 4.3) taking into account the local curvature (Equation 4.2) of the trajectory.
2. The user position $P(t)$ was updated using Equation 4.4. The normalized vector \vec{d} is defined by the orthogonal projection of the direction of a user's body segment (head, hand or torso) on the XZ plane (i.e. the floor).

$$P_n(t) = P_{n-1} + (\vec{d} * S(t) * \Delta t) \quad (4.4)$$

Finally, since the power law can only be applied to curved trajectories (in a straight line the radius of curvature is infinite), we first defined a maximum navigation speed of 1.4m/s, which is considered as a comfortable walking speed in REs (Bohannon 1997). However, during the pilot study we observed that, when physically walking in VR, users rarely achieved the speed of

1.4m/s. Therefore in order to ensure that real and virtual navigation achieved similar navigation speeds, we decided to set the maximum navigation speed to 1m/s that better corresponds to walking speeds observed in VR (Fink et al. 2007). Sudden accelerations and decelerations were filtered to avoid abrupt changes in the perceived speed.

4.2.3 Experimental Design

We used a repeated-measures design in which the independent variable was the navigation technique. We considered 5 navigation techniques: (1) **Walking** - 1:1 mapping between the VE and the RE. Users walk in the VE as they walk in the RE. (2) **Torso Steering** - Users navigate by pressing Vive controller trigger. It uses torso direction to specify the direction of travel. Motion speed is defined by the control law described previously. (3) **Hand Steering** - Similar to Torso steering except that the hand defines the direction of travel. (4) **Head Steering** - Similar to Torso steering except that the head defines the direction of travel. (5) **Passive** - The virtual camera followed a path defined as a Gerono lemniscate (Equation 4.1) and the speed of the motion was automatically updated using the control law described before.

The hypotheses guiding our study were:

- [H1] Users similarly perform the trajectory with the different navigation techniques.
- [H2] Gaze anticipation is preserved during navigation in VE for the walking condition.
- [H3] Top-down reorientation strategies differ depending on the navigation technique.

4.2.4 Experimental Protocol

First, participants read and signed the consent form which provided detailed information regarding the experiment. The experiment was divided into five blocks, one for each navigation technique. For each block, participants filled first the Simulator Sickness Questionnaire (SSQ) (Kennedy et al. 1993) and then they were equipped with the HTC Vive trackers and the backpack, placed at the center of the physical workspace, and then equipped with the HMD. For each block, the eye-tracking was calibrated and then participants performed 10 repetitions (where the first two trials were considered as training trials) as follows:

1. The coordinate system of the FOVE and the HTC Vive trackers were first aligned in order to avoid any potential orientation mismatch. The calibration procedure required participants to align their head direction with a virtual red sphere. Once the participant was aligned with the sphere, the two coordinate systems were aligned. This procedure ensured that the alignment error was lower than 1 degree.

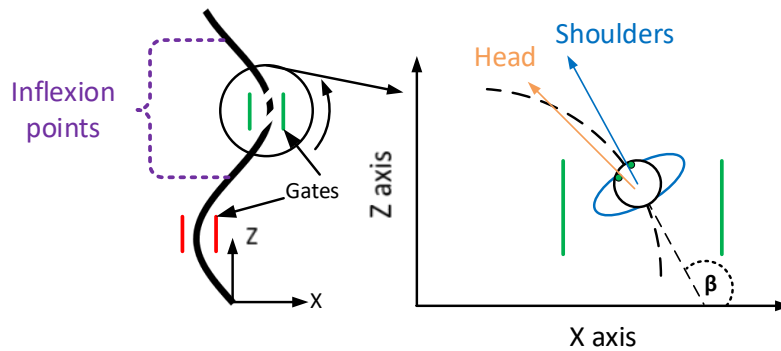


Figure 4.3 – Left - Participants had to perform a eight-shape trajectory in the VE by memorizing it (we displayed any visual information on the floor). Right - Orientation of body segments and heading direction in the horizontal plane. Horizontal angles for each body segments and β for heading are defined as the unwrap tangent function of the ratio X/Z , where X and Z represent positions of the body segment.

2. After the calibration, participants could see the lemniscate trajectory drawn on the floor, a black cross representing the origin of the trajectory, a black arrow indicating their starting orientation, and a text informing the trial number and the sentence « Please press the trigger to start ».
3. Once participants were placed on the black cross and aligned with the black arrow, they could press the controller trigger that started a 3 seconds countdown. When the countdown was over, all the visual information regarding the trajectory was hidden and they could start the task.
4. Participants performed the trajectory using the current navigation technique. The start and endpoints of the trajectory were the same. The trajectory was validated using an invisible checkpoint system which ensured that users performed a valid trajectory. In case of an invalid trajectory, the trial was not recorded and participants had to perform it again.

After each block, the users took off the VR equipment then filled an SSQ questionnaire to monitor their cybersickness and a NASA Task Load Index (NASA-TLX) form ([Hart 1986](#)) to assess mental demand, performance, effort, and frustration. Between blocks, participants had a 5-minute break to minimize potential negative effects of cybersickness. To minimize learning effects, the order of the conditions was counterbalanced using a Latin-square design. In total the experiment duration was one hour. At any time, users could ask for a break or stop the experiment. Yet, this never happened.

4.2.5 Data Measurement

Along with the entire experiment we ensured the maximum frame rate of the FOVE which was 70Hz. We measured the position and orientation of the head and shoulders using the 3 HTC Vive trackers. The reference coordinate system was defined by the HTC Vive tracking system as shown in Figure 4.2. Eye-Gaze orientation was measured thanks to the two integrated infrared eye-trackers in the FOVE HMD which had an error of less than 1° . We also measured the time to perform the trajectory and the distance achieved in the VE and the RE. Regarding the subjective measurements, we measured the changes in the SSQ scores for each condition, the physical and mental effort using the NASA-TLX questionnaire, and the users' subjective feedback for each condition.

4.2.6 Data Analysis

To analyze the temporal sequences between the body segments, we resampled them at a frequency of 30 Hz as done in previous work ([Bernardin et al. 2012](#)), then data were filtered with a Butterworth low-pass filter with a cutoff frequency of 1 Hz to remove oscillations due to stepping activity ([Authié et al. 2015](#)). Participants' trajectory was computed as the displacement of the shoulders barycenter. After assessing that the trajectory direction did not have any effect on the results, we mirrored the trajectories to the right. We then computed participants' speed as the first-time derivative of their position as well as the instantaneous curvature of the trajectory (Equation 4.2).

To study body segments orientation behavior, we computed horizontal angles (in degrees) for each body segment (gaze, head, left shoulder, and right shoulder) and the heading direction as the unwrap arc-tangent function of the ratio X/Z , where X and Z were the coordinates of the vector that defined the orientation of each body segment in the horizontal XZ plane (Figure 4.3). To study temporal synergies, the relative time delay of each body segment was computed by cross-correlations of their horizontal orientation in space.

In total, we collected 1 000 trajectories (20 users, 5 conditions, and 10 trials per condition) during the experiment. We removed the first and second trials from each condition for the analysis because they were considered practice trials. Among the 800 remaining trajectories, we noticed that 28 trajectories (3.5%) were invalid: sometimes participants performed correctly the whole trajectory except at the end where they were not able to go back to the center of the VE and they had to make half turn to end the trial. We, therefore, removed them from the analysis.

For each dependent variable, we first checked their normal distribution with the Shapiro-Wilk

test. Then we did an analysis of variance (ANOVA) with repeated measures to assess the effect of the condition (walking, torso steering, head steering, hand steering, and passive). We considered the threshold $p < 0.05$ as significant. We used pairwise t-tests with Bonferonni corrections for the posthoc analysis when necessary. If the distribution of the dependent variable was not normal, we used the Friedman ANOVA test and posthoc pairwise Wilcoxon tests with Bonferroni corrections.

4.2.7 Results

4.2.7.1 Trajectory Execution

All the participants performed correctly the trajectories during the experiment according to our requirements. Table 4.1 reports the characteristics of the trajectories performed by participants and Figure 4.4 shows the average trajectories achieved by each participant per conditions. Friedman test showed that the navigation technique affected average speed ($\chi^2(4) = 17.72$, $p < 0.01$) as well as average curvature ($\chi^2(4) = 11.6$, $p < 0.05$). Pairwise posthoc comparisons showed that the speed was lower for Torso Steering than for Passive ($p < 0.01$) and that the curvature was lower for Head Steering than for Walking ($p < 0.05$). Even if some difference exists, the absolute difference is low and the trajectories remain similar for each condition in terms of average speed and curvature (see Table 4.1).

Friedman test showed an effect of the navigation technique on the distance achieved in the VE ($\chi^2(4) = 39.8$, $p < 0.001$). Post-hoc tests showed that the smallest traveled distance in VE was observed with passive navigation ($11.56\text{m} \pm 0.23$, $p < 0.05$) and the highest with walking ($14.63\text{m} \pm 1.14$, $p < 0.05$). Distance traveled in the RE during steering or passive conditions was 5 times smaller than the one in VE. All users used at maximum 1m^2 working space to navigate with steering and passive conditions. Friedman test showed an effect of the navigation technique on the distance achieved in RE ($\chi^2(4) = 10.68$, $p < 0.05$) but the post-hoc analysis did not reveal any significant differences. The task completion time was affected by the navigation technique ($\chi^2(4) = 56.8$, $p < 0.001$), pairwise comparisons showed that passive was the fastest (13.18 ± 0.15 , $p < 0.001$) and walking the slowest (18.0 ± 2.74 , $p < 0.01$).

4.2.7.2 Temporal Anticipation of Body Segments

Figure 4.5 shows typical temporal sequences of body segments (gaze, head, shoulders) and heading horizontal turning angle during a trial for each condition. The evolution of these angles differed between conditions. In walking and torso steering, there was a coupling between the

Table 4.1 – Mean and standard deviation for time execution, distance achieved in VE and RE, average speed and curvature for each condition.

	Walking	Torso Steering	Hand Steering	Head Steering	Passive
Average speed (m/s)	0.83 ± 0.11	0.83 ± 0.04	0.85 ± 0.05	0.84 ± 0.06	0.88 ± 0.02
Average curvature (1/m)	0.044 ± 0.015	0.036 ± 0.017	0.037 ± 0.016	0.034 ± 0.022	0.035 ± 0.018
Dist in VE (m)	14.63 ± 1.14	12.83 ± 1.40	13.35 ± 1.62	12.40 ± 1.85	11.56 ± 0.23
Dist in RE (m)	-	2.36 ± 0.44	2.16 ± 0.49	2.43 ± 0.50	2.17 ± 0.30
Time (sec)	18.0 ± 2.74	15.34 ± 1.20	15.7 ± 1.54	14.64 ± 1.52	13.18 ± 0.15

heading and the shoulders (i.e. both curves are overlapped on the figure) whereas the coupling for hand steering and head steering was between the heading and the head. Passive conditions showed no particular coupling between the body segments.

The left chart on Figure 4.6 shows the average temporal anticipation, from gaze and head with respect to the heading direction. During walking, there was an anticipation of gaze (529.23 ms), which precedes the anticipation of the head (204.58 ms) with respect to the heading direction. One way repeated measures ANOVA showed an effect of the condition on gaze anticipation with respect to the heading direction ($F_{3,42,64.98} = 29.47$, $p < 0.001$, $\eta_p^2 = 0.61$) and post-hoc analysis indicated that the anticipation was faster during walking than every other condition ($p < 0.001$), except for torso steering where the effect was not significant ($p = 0.059$). Temporal anticipation of the head with respect to the heading direction was also affected by the condition ($\chi^2(4) = 50.744$, $p < 0.001$). Post-hoc analysis indicated that head anticipation was faster during walking than for the other conditions ($p < 0.001$), except for torso steering where the effect was not significant ($p = 0.12$).

We also investigated the temporal anticipation between body segments horizontal angle (Figure 4.6 right). For the walking condition, there exists a gaze anticipation with respect to the head (167.40 ± 78.2 ms) and the shoulders (639.10 ± 182.11 ms). Temporal anticipation from gaze to head is affected by the condition ($F_{3,16,60.08} = 2.97$, $p < 0.05$, $\eta_p^2 = 0.14$). Pairwise tests showed a faster gaze anticipation related to the head for hand steering than passive ($p < 0.05$). There was also an effect of the condition on the temporal anticipation from head to shoulders ($F_{3,10,58.89} = 20.46$, $p < 0.001$, $\eta_p^2 = 0.52$). This anticipation was significantly faster for walking than all the other conditions ($p < 0.001$). Finally, the condition also affected the temporal anticipation from gaze to shoulders ($F_{3,48,66.16} = 19.81$, $p < 0.001$, $\eta_p^2 = 0.51$) with again a faster anticipation for walking than all the other conditions ($p < 0.001$).

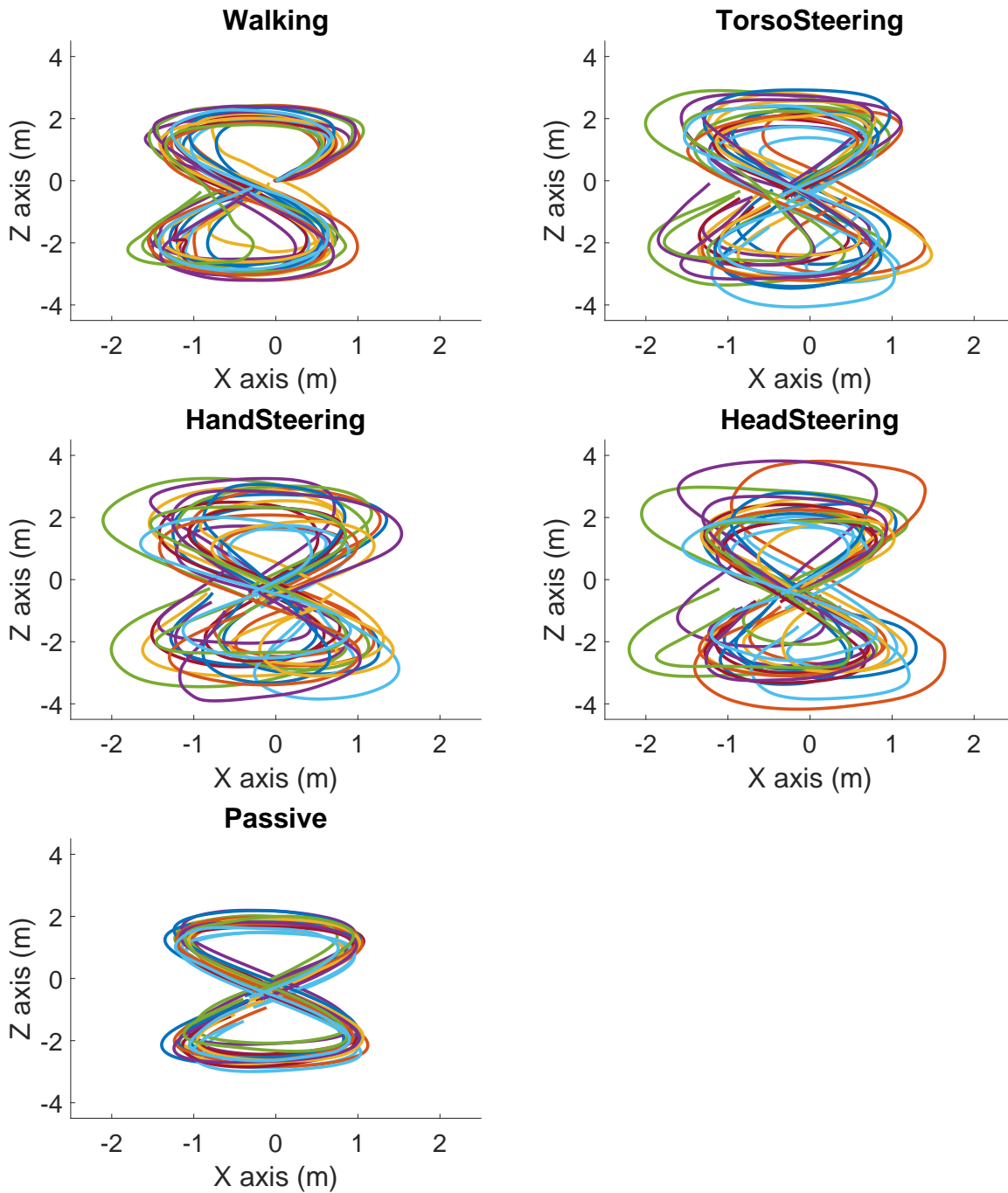


Figure 4.4 – Average trajectories achieved by each participant for all conditions.

4.2.7.3 Subjective Questionnaires

In general, participants did not experience any simulator sickness symptoms during the experiment, which was confirmed by the SSQ scores. Moreover, the navigation techniques had

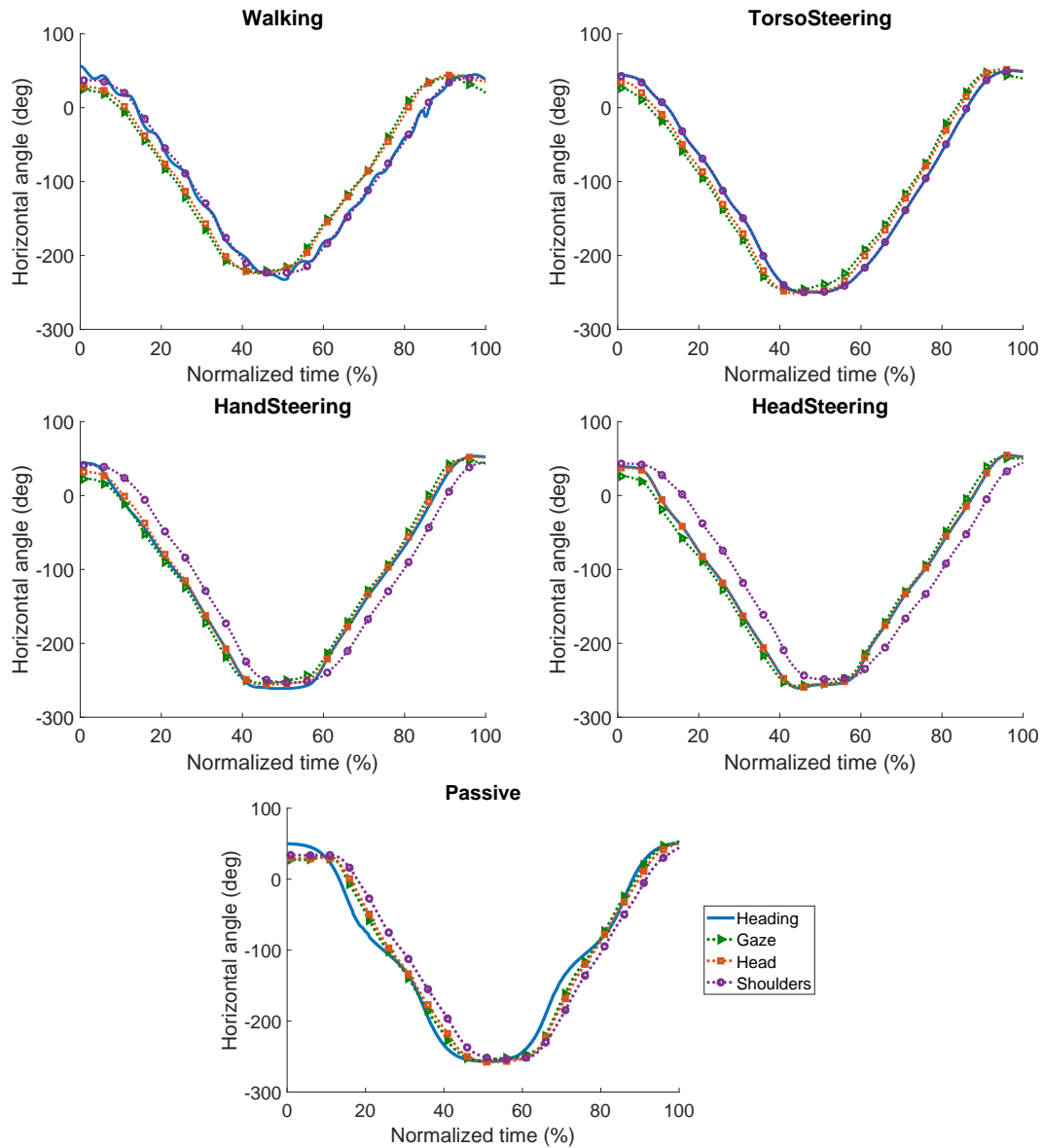


Figure 4.5 – Typical evolution of the average angle of gaze (green), head (orange), shoulders (violet), and heading (blue) while performing the trajectory per condition. For the walking and torso steering conditions, we can notice the coupling between the heading and the shoulders angles (both curves are overlapped) whereas for hand steering and head steering, the coupling is between the heading and the head angles. The passive condition shows no particular coupling between the horizontal angle of body segments. A body segment anticipation can be noticed if the evolution of its horizontal angle is shifted to the left wrt. the heading angle evolution.

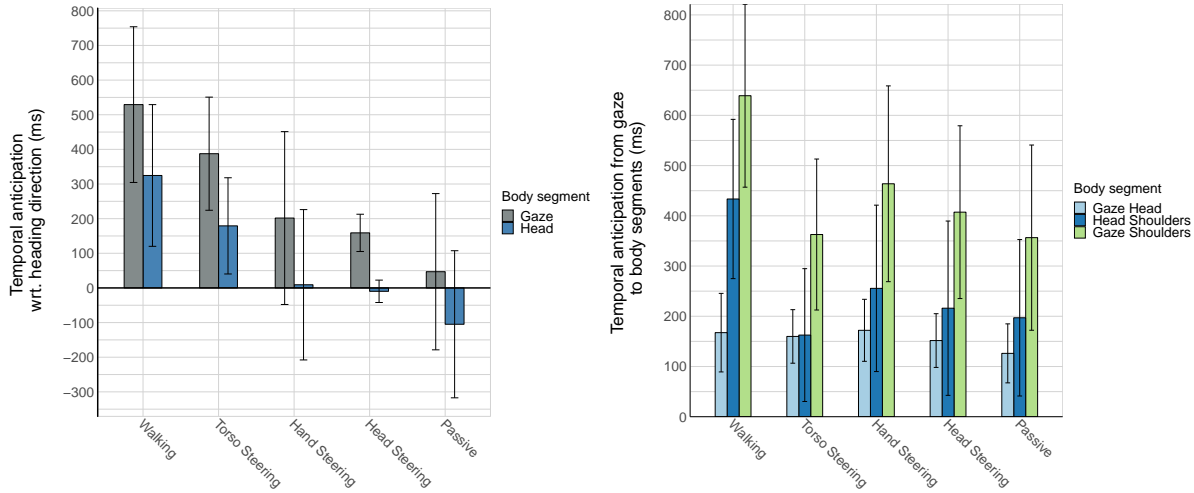


Figure 4.6 – Left - Mean and standard deviation of temporal anticipation (in ms) of gaze and head horizontal angles wrt. the heading direction; Right - Temporal anticipation (in ms) from gaze to head and shoulders horizontal angles for each condition. A positive value means an anticipation of the first body segment on the second one whereas a negative value means an anticipation of the first body segment on the second one.

no effect on the SSQ scores ($\chi^2(4) = 3.9375$, $p = 0.41$) as well as on nausea ($\chi^2(4) = 3.64$, $p = 0.45$), oculomotor ($\chi^2(4) = 7.33$, $p = 0.11$) and disorientation ($\chi^2(4) = 5.1839$, $p = 0.27$) subscales. The TLX-NASA subscales were not significantly affected by the technique except for the physical demand ($\chi^2(4) = 31.471$, $p < 0.001$) where users indicated that walking was more exhausting than the passive navigation ($p < 0.05$). We finally asked users to sort each technique from the most preferred to the least preferred. Walking was globally the most preferred, with half of the participants who ranked it first, followed by the steering techniques, with a higher preference for head and torso than hand steering. Passive was the least preferred with 12 participants who ranked it last.

4.3 Discussion

Our study focused on how user behavior was affected by the navigation technique. In particular, we investigated gaze and body segments anticipation as well as the orientation strategies across several navigation techniques (walking, torso/hand/head steering, and passive). Our main objective was to assess whether gaze anticipation, previously shown during curved trajectories while walking in REs, still exists in VEs and whether there is an influence of the navigation technique used. By combining knowledge from biomechanics and computer science,

we designed an experiment where participants had to perform a lemniscate shape using 5 different navigation techniques. We analyzed the trajectories performed by participants as well as their gaze and body segment temporal reorientation behaviors. Overall, regardless of the navigation technique considered, our results show that participants performed similar trajectories and that they had a top-down reorientation strategy to perform curved trajectories in VR.

4.3.1 Stereotypy of Trajectories is Preserved in VE

Goal-directed locomotion in REs can be characterized as a stereotypic task ([Hicheur et al. 2007](#)): for a given initial and final position and orientation, it was shown that walkers perform this task in a very similar manner, either considering intra and inter individual variability of the trajectory. This property was also demonstrated in VEs using several locomotion interfaces ([Cirio et al. 2013](#)), suggesting common principles that govern the control of the trajectory. Our study, even using a new control law, leads to the same conclusions across all the tested navigation techniques. Trajectories had qualitatively very similar shapes (Figure 4.4) and very small differences were observed in terms of their kinematics. This confirmed our first hypothesis [H1]. This is important for a fair comparison of the body segments' temporal orientation delays since it was previously shown that the reorientation behavior is influenced by the path followed ([Bernardin et al. 2012](#)).

We can however notice a larger variability across participants when considering steering techniques with respect to walking. This may be explained by a higher difficulty of navigating with such techniques that provide less sensory information about motion perception. We can also discuss our VE which was minimalist to avoid any influence on the gaze behavior but the lack of salience points may have led to poor optic flow information. Let's note that in these steering conditions, few users were performing an eight-shape trajectory in the RE as well.

For the purpose of our experimental task, we designed a new control law based on the relation between velocity and curvature during human locomotion. This law was relevant since velocity profiles, as well as the geometry of the path performed, were similar between physical walking and the other techniques. This motivates the use of the knowledge from biomechanics and neuroscience to design new navigation control laws. Future work is needed to evaluate whether such control laws could provide better users' experience and comfort in VEs.

Table 4.2 – Mean and standard deviations of the temporal anticipation (in ms) of gaze and head with respect to the heading direction in VE and RE and gaze related to body segments. Our results refer to walking in VE whereas (Bernardin et al. 2012; Authié et al. 2015) refer to walking in RE.

	Gaze Heading	Head Heading	Gaze Head	Head Shoulders	Head Shoulders
Our results	529.23 ± 224.76	324.65 ± 204.56	167.40 ± 78.20	433.49 ± 158.54	639.10 ± 182.11
(Bernardin et al. 2012)	404.45	182.49	202.66 ± 83.08	212.63 ± 161.99	443.51 ± 202.92
(Authié et al. 2015)	400 ± 50	200 ± 10	-	-	-

4.3.2 Gaze Anticipation during Walking in VE vs. RE

Our experiment was based on previous studies that assessed gaze anticipation behavior during a curved locomotor trajectory in a RE (Bernardin et al. 2012; Authié et al. 2015; Hollands et al. 2002; Courtine and Schieppati 2003). In these previous works, we were able to demonstrate that gaze also anticipates body reorientation when physically walking in VR with an HMD, which confirmed our second hypothesis [H2]. For a deeper comparison, Table 4.2 shows a summary of our results with respect to the literature in RE. Our results for the walking condition in VE had similar order of magnitude than previous works in RE but the delays were higher suggesting that gaze anticipates more the change in heading in VEs than in REs. We hypothesize that higher anticipation could be explained by several reasons: (1) a shorter field of view that requires higher anticipation in order to perform the trajectory. Authié et al. showed that the gaze behavior of people with a shorter FoV (affected by retinitis pigmentosa) have larger head movements (a wider horizontal exploration of the environment) during curved trajectories than the control condition (Authié et al. 2017). A shorter FoV may impact the gaze activity but additional work is needed to assess the impact of FoV in body segments behavior. (2) a « safety » mechanism which forces the user to anticipate more in a VE because participants cannot see their body while walking in the RE. (3) the impact of HMD and trackers weight on participants' head which could modify delays. To investigate these factors, further studies are required.

4.3.3 Reorientation strategies and Navigation techniques

Our results showed that navigation techniques affected temporal anticipation when considering both heading direction (gaze-heading and head-heading) and body segments (gaze-head, head-shoulders, and gaze-shoulders), which confirms our third hypothesis [H3]. Especially, walking in VE induces significantly larger delays than steering and passive techniques. However,

unlikely walking in VE, head-shoulders, and gaze-shoulders delays for steering techniques are closer than Bernardin et al. delays for walking in RE ([Bernardin et al. 2012](#)).

Torso Steering: Gaze heading and head heading delays were different between torso steering compared to the other steering techniques. Moreover, torso steering had the closest behavior about gaze anticipation than walking in RE. One reason could be that the steering direction provided by the torso would be more natural and participants would anticipate more easily thanks to the decoupling between head direction and heading direction which allows the head not to be involved in the steering direction. This hypothesis is discussed in Arechavaleta et al. work in which they showed that human locomotion can be approximated by a nonholonomic system ([Arechavaleta et al. 2008b](#)). They compared different body reference frames (head, shoulders, and pelvis) and their results showed that shoulders can be compared as a steering wheel that steers the human body with a delay of around 200ms. It means that the shoulders' trajectory is less affected by oscillations induced by step alternation. Among the 20 participants, we identified 5 of them where the head shoulders temporal delay was smaller than 50ms. It means that these participants were reorienting the head and shoulders almost simultaneously, resulting in a « en-bloc » reorientation strategy. This behavior has been noticed in RE as well and can be affected by some diseases challenging postural control and locomotion. For instance, in patients with stroke, Lamontagne and Fung ([Lamontagne and Fung 2009](#)) showed changes in the reorientation strategies modifying the amplitude and the timing of the anticipation. Besides, another study showed that physical deficiency like a rupture of the anterior cruciate ligament has an impact on the timing of body segment reorientation ([Reed-Jones and Vallis 2007](#)). Injured participants used a different reorientation strategy where the head anticipated less the trajectory. « En-bloc » strategies would then allow a decrease of the degrees of freedom to control when turning.

Hand Steering: Since torso and head are involved in the reorientation strategy during curved trajectories, we were wondering which would be the users' strategy when the steering control is initiated by the hand. From the 5 participants that had temporal anticipation between head and shoulders smaller than 50ms with torso steering, 4 of them also had head shoulders delay smaller than 50ms with hand steering. These participants had a different strategy: they were putting the controller perpendicular to their torso and simultaneously turned the controller and their torso, which resulted in a « en-bloc » reorientation strategy with a lower head shoulders temporal anticipation. For the others, the controller was not aligned to the trunk and they rotated their wrist to steer, which created a dissociation between the body segments reorientation and the steering direction, and therefore higher head shoulders delays.

Head Steering: This technique is used often in VR applications since it is easy to develop and intuitive for the user. Regarding the temporal anticipation, the head cannot anticipate the trajectory (delay head heading close to 0ms) and the gaze heading delay was lower than in walking and torso steering. However, users with « en-bloc » strategy for hand and torso steering had a normal anticipation synergy with this technique. We can wonder if head steering should be chosen rather than torso steering which is less used but allows anticipation of the head with respect to the future trajectory by preserving the same kinematics properties.

Passive: Regarding temporal anticipation with respect to heading direction, the variability between users suggests that the reorientation strategy could differ. Some of them would anticipate the future trajectory whereas others would reorient their body later. That was especially the case for passive navigation where participants did not have any control over the virtual trajectory, meaning that they had to figure out when the turns would occur.

We noticed a difference for gaze head delays only between hand steering, where gaze anticipates faster related to the head, and the passive condition. It means that gaze temporal anticipation related to the head remains rather consistent during the navigation but the coupling head-shoulders differs according to the navigation technique as described before. From the perspective of designing navigation techniques based on the synergies of body segment orientations, this result suggests that gaze-based steering might not be necessary as the head orientation closely follows the gaze orientation.

We investigated the relationship between the delays and the users' preferences. We could have expected that the closer the delays are to walking in RE, the more users prefer the navigation technique. However, temporal anticipation from gaze to head and shoulders were similar between steering techniques, and head steering (which is the second most preferred) had the shortest delays with respect to heading after passive navigation (which is the least preferred technique). Although we identified different behaviors according to the navigation technique, we did not notice any correlation between anticipation and cybersickness.

4.4 Conclusion

In this chapter, we described an experiment that evaluated gaze and body segments behavior while navigating along an eight-shaped trajectory. The experiment considered five navigation techniques exhibiting different levels of fidelity and control. First, compared to real-world locomotion behaviors ([Bernardin et al. 2012](#); [Authié et al. 2015](#)), the results confirmed that a temporal top-down reorientation strategy was preserved while walking in the VE but also for

the three virtual steering navigation techniques evaluated. Second, the results showed that the navigation technique had a significant effect on anticipation mechanisms. In a nutshell, virtual navigation techniques are not able to generate the same anticipation mechanisms that the ones observed in real and virtual walking, yet, the potential impact on the user has still to be explored. Nevertheless, we believe that by gathering knowledge about how users interact and behave in VEs, researchers and practitioners will be able to design new navigation techniques and control laws, based on laws governing human motor control, which could improve user comfort and the overall experience in VR.

«I hated myself and the world because I had failed to face and accept the limitations of my self and of life. In literature this refusal is called romanticism; in psychology, neurosis. »

Luke Rhinehard, The Dice Man

5

Does the Control Law Matter? Characterization and Evaluation of Control Laws for Virtual Steering Navigation

5.1 Motivations

The evaluations of navigation techniques ([Bowman and Hodges 1999](#); [Bowman et al. 1998](#); [Bowman et al. 2001b](#)) mostly focus on the two first components without considering the last one, hereafter referred to as the control law. Some exceptions can be identified, such as redirected walking methods in which the control law is the main design component. In contrast, for virtual steering methods, only the analysis of angular speed with head rotation gains has been formally studied ([Sargunam et al. 2017](#)) but not the linear speed control. Since spatial steering techniques are commonly used methods due to their simplicity, it is essential to thoroughly study the potential impact of linear speed control on users' behavior. For example, considering that the linear speed has a direct impact on the actual users' motion, it can potentially have an influence on the quality of the navigation as well as users' experience while being immersed in the VE.

The contributions of this chapter are two-fold. First, we propose a formal characterization of control laws for virtual steering techniques. This characterization aims at encouraging reproducibility in future experiments and provides clear guidelines for VR practitioners. Second, we designed a user study assessing how the linear speed update on virtual steering techniques can impact the users' behavior in a navigation task. In particular, three linear speed control laws (discrete, continuous, adaptive) were evaluated in a virtual slalom navigation task considering different curvature conditions (low, medium, and high curvature turns). The users' behavior was assessed through an analysis of the spatial-temporal characteristics of their trajectories and their level of comfort was evaluated through subjective questionnaires. We found that the control law had an impact on the way users performed the navigation task. We noticed differences in users' linear and angular speed profiles, and also differences in perceived physical demand and effort between the control laws. Taken together, our results contribute to the understanding of human behavior in VEs and argue that evaluating and comparing different control laws is necessary to improve their design.

5.2 Characterization of Control Laws

The control law defines how the navigation states (e.g. linear and rotational speed) are updated at each time step considering users and system inputs. Most of the existing classifications and taxonomies tend to overlook the details of the control law and mainly focus on navigation metaphors and input mechanisms, except for a few examples ([Bowman et al. 1998](#); [Anthes et al. 2004](#); [Nabiyouni and Bowman 2016](#)). Thus, researchers and practitioners are faced with the need to design the control law and manually adjust its parameters (e.g. maximum speed, acceleration/deceleration rate) for each experiment or application. The goal of this section is to characterize navigation control laws to encourage reproducibility in future experiments and provide clear guidelines for VR practitioners. Furthermore, we present three full examples corresponding to the control laws that we evaluated in our user study (see Section 4).

5.2.1 Main Components

When characterizing a control law, two major components should be defined: the input data and the transfer function. The input data comprise the user's input and the system state. The transfer function determines a new navigation state, using the input data. The navigation state encloses all the elements that are involved in the computation of the next virtual camera position

and orientation: tangential speed/acceleration, rotational speed/acceleration, camera position, and orientation. The navigation state can be also an input for the transfer function.

5.2.1.1 Input Data

User's input data is provided by input devices (e.g. tracking data, buttons, or joysticks). The input data determines the actions that the user has to perform to operate the navigation technique and its degree of control. For further information about the wide variety of existing input devices for virtual steering techniques, please refer to (LaViola et al. 2017). **State input data** is extracted by the current and/or the past state of the system. State input data can range from the curvature of the current trajectory (Brument et al. 2019), the scale of the environment (McCrae et al. 2009), the viewpoint quality (Freitag et al. 2016) or the user's perceived motion (Argelaguet 2014). State input data is commonly used in adaptive techniques.

5.2.1.2 Transfer Function

A transfer function defines the mapping between the input data and the next navigation state (Frohlich et al. 2006). When navigating in VEs, the transfer function is responsible for updating the kinematics of the virtual camera, therefore updating the following navigation states:

- **Heading** - The current direction of the motion. For steering techniques, the navigation direction is generally determined by a user's body segment such as the head, the hand, or the torso, and defined by pointing or looking to the desired direction, although it can also be updated according to the rotation speed and acceleration.
- **Linear speed** - The velocity of the virtual camera is tangential to the heading direction. In most implementations, the tangential speed is set to a constant value or it is computed with a linear function that takes into account the user's input.
- **Linear Acceleration** - The acceleration of the virtual camera. Generally, the acceleration is computed as the time derivative of the tangential speed.
- **Position** - The position of the virtual camera. The camera position is normally updated using either a constant translation or defined by the linear speed and acceleration.
- **Rotation speed** - The rotation speed of the virtual camera. Although the virtual camera orientation, in an HMD context, is in most cases equal to the user's head orientation, redirected techniques or joystick-based navigation require transfer functions to update the camera's orientation.
- **Rotation acceleration** - The rotation acceleration of the virtual camera. As the linear

acceleration, it can be a derivative of the rotation speed or manually defined.

The following section illustrates the design of control laws based on the linear speed transfer function.

5.2.2 Control Law Design Example

The design constraints are that the user should be able to control the linear speed using a 1DoF input device and the heading is defined with an isometric mapping with respect to the user's torso orientation (i.e. torso steering). A generic transfer function is presented in Algorithm 1. This function computes at every frame the current speed (S_t) and acceleration (A_t) taking into account the user input (in our experiment, the trigger's pressure from the HTC Vive controller, $trig \in [0; 1]$; where 0 means the trigger is released and 1 entirely pressed) and the simulation time (Δt). When the user is providing input (Lines 2 to 8), the algorithm computes a target speed (S_t) and limits the generated acceleration (Line 4 and 8) to avoid potentially high accelerations. If the user is not providing input (Lines 10 to 14) the acceleration is set to stop the motion. For practical reasons, we only considered forward motions in our user study. Finally, the computed acceleration is used to define the final speed (S_t) and the specific case handling the motion end. Three constants are required: the maximum and minimum linear speed ($S_{max} = 1.4m/s$, $S_{min} \approx 0$) and the maximum and minimal linear acceleration ($A_{max} = 1m/s^2$, $A_{min} = -1m/s^2$). The maximum navigation speed and acceleration are set to match a comfortable walking speed in a real environment. Regarding the main behavior of the transfer function (Line 2), we focused on three alternatives with different degrees of control: constant, linear, and adaptive.

The **constant** transfer function has a binary behavior, either the user is not moving (i.e. not pressing the controller's trigger) or he is navigating at S_{max} (i.e. pressing the controller's trigger). Therefore the function always outputs S_{max} :

$$S_t \leftarrow S_{max} \quad (5.1)$$

The **linear** transfer function takes into account the continuous nature of the input data and sets the speed according to the controller's trigger pressure ($trig$):

$$S_t \leftarrow trig * S_{max} \quad (5.2)$$

Finally, for the **adaptive** transfer function, we chose a function that takes into account the relationship between the speed and the curvature of the actual trajectory in human walking (Bru-

Algorithm 1 General Speed Transfer Function

```

1: if  $trig \neq 0$  then
2:    $S_t \leftarrow \text{SpeedTransferFunction}(S_{max}, trig)$ 
3:    $A_t \leftarrow (S_t - S_{t-1}) / \Delta t$ 
4:   if  $A_t > 0$  then
5:      $A_t \leftarrow \text{Min}(A_t, A_{max});$ 
6:   else
7:      $A_t \leftarrow \text{Max}(A_t, A_{min});$ 
8:   end if
9: else
10:  if  $S_{t-1} > S_{min}$  then
11:     $A_t \leftarrow -A_{max}$ 
12:  else
13:     $A_t \leftarrow 0$ 
14:  end if
15: end if
16:  $S_t \leftarrow S_{t-1} + A_t \Delta t$ 
17: if  $S_t < S_{min}$  then
18:    $S_t \leftarrow 0$ 
19:    $A_t \leftarrow -S_{t-1} / \Delta t$ 
20: end if

```

ment et al. 2019). During a continuous trajectory, the instantaneous speed varies according to the local radius of the curvature (Equation 5.3) as a power law (Equation 5.4):

$$R_t = \frac{(\dot{x}^2 + \dot{z}^2)^{\frac{3}{2}}}{\dot{x}\ddot{z} - \ddot{x}\dot{z}} \quad (5.3)$$

where \dot{x} , \dot{z} , \ddot{x} and \ddot{z} are respectively the first and second derivatives of x and z coordinates of the user's position in the environment. This function derives from the control of human walking trajectory in a curve, where the speed of locomotion is, in the case of walking trajectories, proportional to the cubic root of the radius of curvature (Vieilledent et al. 2001; Hicheur et al. 2005b):

$$S_t = K.R_t^{\frac{1}{3}} \quad (5.4)$$

where S_t is the horizontal speed at time t , K is a gain speed coefficient, and R_t is the radius of the local curvature of the trajectory at time t . We set the coefficient $K = 0.6$. Therefore, we computed the virtual speed according to user's position in the VE using Equation 5.4.

5.2.2.1 Acceleration Update

Then, the control law computes the user's acceleration $A(t)$ based on the speed computed at the previous frame and the new estimated speed (algorithm 1-2). If the acceleration is positive it means the user is in the acceleration phase and it is negative then the user is in the deceleration phase. The acceleration is bound based on research work on acceleration analyses in REs ([Jian et al. 1993](#)) ($A_{min} \leq A(t) \leq A_{max}$, where A_{min} and A_{max} are respectively equal to -1 and $1m.s^{-2}$).

5.2.2.2 Final Speed Update

Final speed $S(t)$ is updated with respect to the previous frame final speed $S(t-1)$, the current acceleration $A(t)$ and the delta time Δt between the two frames (algorithm 1-3).

5.2.2.3 Direction Update (\vec{d})

As we consider an isometric torso steering technique, the heading will match the projection of the torso direction on the ground plane. The normalized heading vector \vec{d} is then defined by the cross product between the orthogonal projection \vec{bs} (i.e torso's direction) on the XZ plane (i.e. the floor) and the normal of the XZ plane. We decided for two reasons to choose the torso as the body segment \vec{bs} that defines the future direction. On one hand, it does not constrain users' head rotation during the navigation task and on the other hand, it has been shown that the use of physical rotation can provide a better navigation experience ([Riecke et al. 2010](#)).

5.2.2.4 Position Update (P_t)

Finally, the user position (P_t) is updated using the previous position (P_{t-1}), the previous speed (S_{t-1}), the acceleration (A_t) needed to reach (S_t) and the delta time (Δt) between two frames:

$$P_t = P_{t-1} + \vec{d} \left[S_{t-1} * \Delta t + \frac{1}{2} A_t * \Delta t^2 \right] \quad (5.5)$$

Such characterization allows practitioners to design every element that a control law must provide. In the next section, we assess the potential impact of different control laws on the user's behavior.

5.3 User Study

The goal of this experiment was to investigate the effects of control laws on users' behavior and preferences during a navigation task with curved trajectories. We wanted to study in particular the way users perform a different types of turns (by varying the trajectory's curvature) with virtual steering techniques. To this end, we designed a slalom task as it involves continuous navigation with several turns, therefore inducing speed and orientation adaptations. The considered task, although it does not represent an ecologic task in a VE, allows assessing the control laws in a controlled and standardized manner.

5.3.1 Participants and Apparatus

18 participants (16 males and 2 females) aged between 22 and 31 years old (25.11 ± 2.39 , mean \pm SD) without any ocular or locomotion disorders volunteered to this study. 14 participants reported using VR on a weekly or daily basis, 3 few times and 1 never. All participants except one had regular experiences with videos games. They were naive to the purpose of the experiment and signed an informed consent form. The study was conformed with the standards of the declaration of Helsinki. We use a Vive HMD to immerse the users in the VE and 2 HTC Vive trackers, fixed to a backpack carried by the participants, to track users' shoulders. The reference coordinate system was defined by the HTC Vive tracking system. During the whole experiment, we guaranteed the maximum frame rate of the HMD. The cables of the HMD were hanging from the ceiling to prevent users from being bothered by them. The VE was a large plane with a noisy texture in order to generate motion flow from participants' rotations but without any salient features. The virtual slalom consisted in 12 turns defined as a sinusoidal-like trajectory (Figure 5.1). We set up three slaloms with the same amplitude ($a = 2m$) but with different frequencies f to modify the trajectory's curvature and alter the task difficulty: Small Curvature (SC), $f = 1$; Medium Curvature (MC), $f = 1.5$ and High Curvature (HC), $f = 2$. To indicate the path to follow without constraining too much the trajectory, participants had to go through virtual gates (1x2.3x1 meters) located at the peaks of the sinusoidal trajectory (Figure 5.1). The beginning of the trajectory was indicated by a black cross displayed on the ground. Only the ground and the gates were displayed during the task.

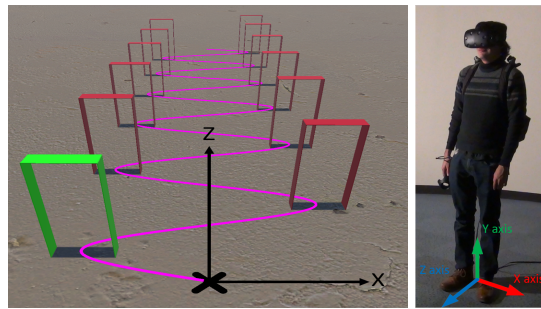


Figure 5.1 – Left - The VE used for the experiment. Users started from the black cross and performed a 12 gates slalom. The order of the gates is shown by the pink path, only represented here for explanatory purposes. The green gate represented the next gate to cross. Right - Participant equipped with the HTC Vive HMD, a backpack, the HTC Vive trackers and controller.

5.3.2 Design and Hypotheses

We used a repeated-measures design in which the independent variables were the **control law**: constant (C), linear (L) or adaptive (A) and the **curvature type**: small (SC) medium (MC) and high (HC). Our hypotheses were: **[H1]** The control law and the curvature would influence the performance (e.g. time, distance) and the spatio-temporal parameters (e.g. speed, acceleration, and angular profiles) of the trajectories. **[H2]** Users would report better comfort and subjective results with the adaptive control law. With these hypotheses, we suggest that the control law, but also the type of trajectory, could influence users' navigation. In particular, we expect that the adaptive control law would be better suited for the task, especially for high curvature turns, since its design is based on the biomechanics of natural walking.

5.3.3 Procedure

First, participants read and signed the consent form which provided detailed information regarding the experiment. The experiment consisted of three randomized blocks, one for each control law. Each block considered 1 training trial to get familiar with the task and 12 randomized experimental trials (4 trials per curvature type). Each trial involved participants performing 6 left and 6 right turns. The experiment, therefore, resulted in a total of 39 trials (3 control laws x 13 trials), namely 468 turns (39 trials x 12 turns) per participant. Before the beginning of each block, participants filled a Simulator Sickness Questionnaire (SSQ) ([Kennedy et al. 1993](#)). Each experimental trial followed the procedure described hereafter. Participants were facing at the gates and started their trajectory at the black cross in the VE (Figure 5.1). Once placed on the black cross, they could trigger a 3 seconds countdown by pressing the touchpad before starting

the trial. Then, they performed the slalom using the control law defined for the current block. At the end of the trial, we asked them to answer the question « How comfortable the trial was? » on a 7-point Likert scale, where 1 was « not comfortable at all » and 7 « very comfortable ». After each block, the users took off the VR equipment, then filled an SSQ questionnaire, a NASA Task Load Index (NASA-TLX) form ([Hart 1986](#)) and the USE questionnaire ([Lund 2001](#)) (considering only the *Ease of Learning* dimension. Between blocks, participants had a 5 minutes break. The order of the conditions was counterbalanced using a Latin-square design. In total, the experiment took approximately one hour.

5.3.4 Data Analysis

We removed the first and last turns from each trial since we wanted to analyze the behavior during the continuous trajectory, therefore not considering the beginning and the end of the trajectory. We conducted two main analyses, one focusing on the trajectory performed during the entire trial (global) and a second considering only the slalom turns (local). We defined a turn as the trajectory between two inflexion points of the sinusoidal-like trajectory. We resampled positions and orientations of head and shoulders, and then applied a Butterworth low-pass filter with a cutoff frequency of 1 Hz and finally temporally normalized them to evaluate the effect of our experimental conditions over time. We gathered the time required to perform the task and computed distances achieved in both VE and RE. We computed participants' trajectories in the VE as well as their physical movements in the RE (i.e. their torso rotation and translation) as the shoulders' barycenter trajectories (CG). During the pilot studies, we observed that some participants tended to drift over time (unintentional positional drift). Although they do not have to physically walk, they might end up to few meters away from the starting point. Thus, we considered that their motion in the RE could be valuable. We then computed participants' linear speed and acceleration as respectively the first and second-time derivatives of the CG. To evaluate the effect of our independent variables on average kinematics of the trajectories, we performed a two-way analysis of variance (ANOVA) with repeated measures when the distribution of the dependent variables was normal or an Aligned Rank Transformation (ART) ANOVA test if not ([Wobbrock et al. 2011](#)). Normality was assessed using the Shapiro-Wilk test. Greenhouse-Geisser adjustments to the degrees of freedom were applied, when appropriate, to avoid any violation of the sphericity assumption. Post-hoc analysis was based on pairwise t-tests with Bonferonni corrections. To evaluate the effect of the experimental factors over time (time normalized over 1 turn), we used the Statistical Parametric Mapping (SPM) method ([Friston et al. 2007](#)). This analysis allows comparing time-series data of different trials taking into account

their variability at each time-step. Finally, to analyze subjective data from the questionnaires, we used the Friedman test and post-hoc pairwise Wilcoxon tests with Bonferroni corrections.

5.3.5 Results

5.3.5.1 Trajectories, Time and Distance

Figure 5.2 shows the average virtual path followed by participants depending on the control law and the curvature type. It illustrates the great similarity regarding the path followed for a given curvature across the 3 control laws. In addition, Table 5.1 reports average spatio-temporal characteristics of the trajectories. ART ANOVAs showed that the control law ($F_{2,34} = 62.22$, $p < 0.001$), as well as the curvature type ($F_{2,34} = 44.76$, $p < 0.001$) had an effect on trial duration, being longer with the adaptive control law ($p < 0.05$), and when performing the SC condition ($p < 0.05$).

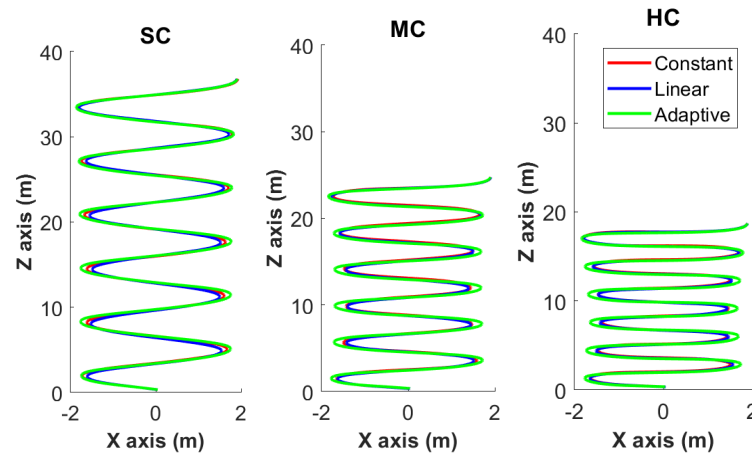


Figure 5.2 – Average path (after filtering the data) followed by participants depending on control law and curvature type.

We found an effect of the curvature type on the distance achieved in the RE (i.e. displacement of the CG) ($F_{2,34} = 3.49$, $p < 0.05$), where the bigger the curvature was, the higher the users movement achieved in the RE were ($p < 0.05$). Besides, we noticed that the displacement from the starting position in both X and Z axes were higher when performing the HC condition than the others ($F_{2,34} = 3.50$, $p < 0.05$ for X axis, $F_{2,34} = 54.15$, $p < 0.001$ for Z axis).

Table 5.1 – Mean and standard deviation, reported as M (SD), for time execution, distance achieved in VE and RE for each control law and curvature type for the whole trial. The two effect columns report respectively whether there was a significant effect of the control law or of the curvature type on the studied variables (* for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$). Post-hoc tests (with Bonferonni corrections) for main effects are reported using superscripts. Two levels sharing the same superscript are not significantly different.

	Constant	Linear	Adaptive	Effect	SC	MC	HC	Effect
Time execution (sec)	40.74 (3.93) ¹	41.262 (5.26) ¹	48.80 (4.56) ²	***	42.49 (6.41) ¹	42.66 (5.96) ¹	45.65 (4.73) ²	***
Distance VE (m)	55.93 (4.48)	55.50 (4.66)	55.83 (5.70)		60.01 (3.43) ¹	54.31 (3.99) ²	52.94 (4.48) ³	***
Distance RE (m)	6.39 (2.18)	6.72 (2.31)	6.62 (2.55)		5.98 (2.40) ¹	6.65 (2.21) ²	7.09 (2.32) ³	***
Linear speed (m.s ⁻¹)	1.37 (0.07) ¹	1.36 (0.10) ¹	1.14 (0.05) ²	***	1.32 (0.11) ¹	1.29 (0.13) ²	1.26 (0.07) ²	***
Acceleration (m.s ⁻²)	0.033 (0.004) ¹	0.032 (0.005) ¹	0.019 (0.002) ²	***	0.028 (0.006) ¹	0.029 (0.008) ²	0.029 (0.009) ²	***
Angular speed (rad.s)	0.83 (0.14) ¹	0.82 (0.15) ¹	0.678 (0.10) ²	***	0.625 (0.06) ¹	0.81 (0.09) ²	0.90 (0.12) ³	***

5.3.5.2 Linear Speed, Acceleration and Angular Speed

Figure 5.3 shows the average and standard deviation of the temporal evolution of the linear speed, acceleration, and angular speed depending on the curvature type and the control law. SPM analysis showed an effect of the control law on these time-series during the turn. Post-hoc tests demonstrated that the linear speed, acceleration, and angular speed were smaller for the adaptive control law than the constant or linear ones ($p < 0.05$) during the turn. However, no difference was observed between constant and linear that had similar profiles.

Mean linear speed — An interaction effect was found ($F_{4,68} = 14.20$, $p < 0.001$) in which the control law had an effect on the mean linear speed for the entire trial ($F_{2,34} = 75.90$, $p < 0.001$) as well as the curvature type ($F_{2,34} = 41.40$, $p < 0.001$). Post-hoc comparisons showed that participants' linear speed was slower with the adaptive control law than the constant or linear ones ($p < 0.05$) and faster during the SC than the MC or HC ($p < 0.05$). However, during the turns, we reported only an effect of the control law ($F_{2,34} = 63.13$, $p < 0.001$) where participants' linear speed was slower with the adaptive control law than the others ($p < 0.05$).

Mean acceleration — We noticed an effect on the control law ($F_{2,34} = 95.152$, $p < 0.001$), the curvature type ($F_{2,34} = 8.733$, $p < 0.001$) and an interaction effect ($F_{4,68} = 10.65$; $p < 0.001$). Post-hoc analysis determined on one hand that, the adaptive control law provided slower acceleration than the constant or the linear control laws ($p < 0.05$) and on the other hand that the higher the curvature type was, the higher the mean acceleration was ($p < 0.05$).

Mean angular speed — We observed an effect of the control law ($F_{2,34} = 89.416$, $p < 0.001$), the curvature type ($F_{2,34} = 238.88$, $p < 0.001$) and an interaction effect ($F_{4,68} = 15.62$, $p < 0.001$). Post-hoc tests showed that the lower the curvature type is, the lower is the mean angular speed and the adaptive control law produced lower angular speed profiles than the

constant or linear control laws.

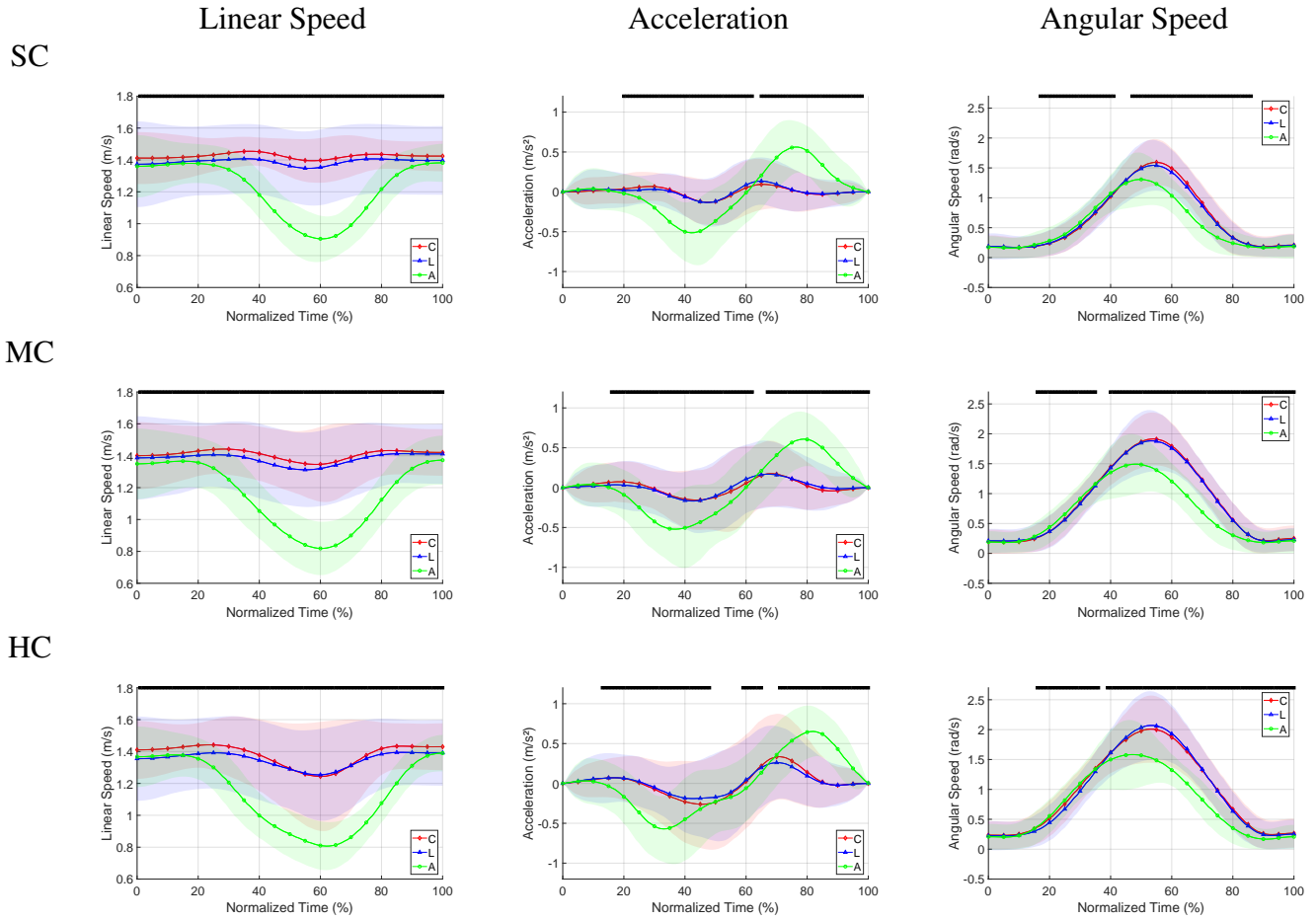


Figure 5.3 – This figure shows averaged temporal evolution of mean and standard deviation of linear speed, acceleration and angular speed for each control law (constant (C) in red, linear (L) in blue and adaptive (A) in green) and curvature type (SC on first row, MC on second and HC on third) during turns for all participants. Each sample of the temporal sequence is a dependant variable. The part where the control law has an effect is represented by the black line meaning that the F value for this variable is higher than the F^* computed. We can notice that there is an effect of the control law on the variables during most of the turn duration. Besides, the linear speed, acceleration and angular speed profiles differ according to the curvature type.

5.3.5.3 Subjective Questionnaires

None of the participants experienced simulator sickness symptoms and we did not report any effect of the control law on the average SSQ scores. We also noticed no effect on the average values of the USE (*Ease of Learning dimension*) questionnaire. TLX-NASA questionnaire scores

presented an effect on the physical demand subscale ($\chi^2(2) = 6.65$, $p < 0.05$), but post-hoc comparison showed no effect between the different control laws (Figure 5.4). Besides, the effort subscale showed an effect on the control law ($\chi^2(2) = 7.84$, $p < 0.05$) but post-hoc comparison did not show effect between the different control laws (Figure 5.4). Regarding the question asked at the end of each trial, we found an effect on the curvature type ($F_{2,34} = 16.37$, $p < 0.001$), where the SC appeared the most comfortable curvature type and the HC the least comfortable ($p < 0.05$).

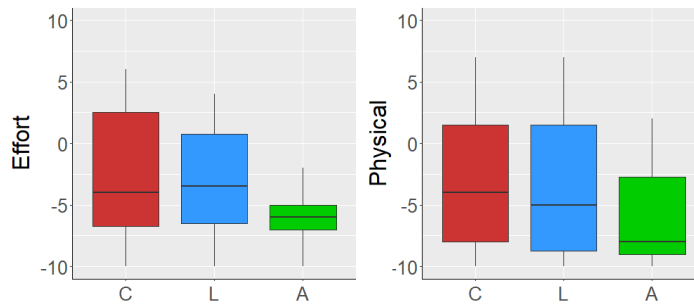


Figure 5.4 – Boxplots of the TLX results per control laws (C for constant, L for Linear and A for Adaptive) for Effort and Physical Demand subscales. -10 indicates a very low effort or physical demand whereas 10 indicates a very high effort or physical demand.

5.4 Discussion

Our objective was to assess whether the control laws could influence how users perform navigation in VEs. We designed an experiment where participants had to perform virtual slaloms with different curvature types using 3 different control laws. Our results showed an effect of the control law, that generated different users' movements for a given slalom, but also an effect of the curvature type where the curvature influenced the way users performed the slalom task.

5.4.1 Influence of Curvature on Users Movements and Trajectories

Considering the movements in the RE, we showed that the higher the curvature, the higher the user's displacements in the RE. These movements results in unintentional positional drift, where the users were drifting from their initial position in the RE while navigating in the VE. Some participants had high unintentional positional drift in the RE, almost reaching the limits of the physical workspace. Yet, we did not observe any effect of the control law. Then, we suggest that the drift could be more dependent on the amount of physical rotation required, and in particular

to perform high curvature trajectories. This result has strong relevance for VR setups with a limited workspace size as it suggests that, even for steering techniques, users might reach the physical boundaries of the workspace after a short navigation period. This could affect the users' safety and may break their presence in the VE. While methods to avoid such situations have been largely explored for full gait techniques, such as redirected walking (Razzaque et al. 2001) or resetting techniques (Williams et al. 2007), it remains unexplored for virtual steering techniques. An additional observation concerns the possibility to manually modulate the navigation speed with the linear control law, where users can increase or decrease their speed using the trigger controller. Yet, our results showed that they did not use this possibility. We did not find the difference between linear and constant speed profiles as shown in Figure 5.3, meaning that they were always pressing the trigger to its maximum to reach the maximum navigation speed (1.4mm/s). We could have set a higher maximum speed for the linear law, allowing participants to continuously modulate the current virtual speed instead of clamping it, but it would have introduced a bias in our experimental design since the three control laws would not have had the same maximum values. Future work can further investigate if users take advantage of linear control laws, in which they can dynamically update their tangential speed, during complex navigation maneuvers.

5.4.2 Control Laws Can Alter Kinematics

Regarding the comparison of the control laws, Figure 5.3 summarizes the typical temporal evolution of linear and angular speed for each control law. We can notice different variability in the **linear speed** profiles according to the curvature type for the constant and linear conditions (HC generates more variability for these control laws than the MC or SC ones), where this variability is lower for the adaptive one (more similar profiles regardless of the curvature type). Research on the biomechanics of walking in REs showed a relation between the trajectory curvature and the walking speed (Vieilledent et al. 2001). Since the adaptive control law is based on this relation, we suggest that participants better adapted their behavior with this one than the others. One reason is that this law generated similar linear speed profiles than walking in REs, allowing users to keep a consistent behavior across the different curvature types. We also noticed a significant difference for each curvature type between the **acceleration** profiles produced by the adaptive control law, and both constant and linear laws. This can be explained by the fact that most of the participants were navigating at the maximum speed during turns, resulting in acceleration profiles close to 0m/s^2). In contrast, the adaptive law generated deceleration profiles before the turns and acceleration profiles after them. Besides, acceleration profiles variability

can be explained by the users' physical motion. For example, we can notice in Figure 5.3 that higher curvatures generated higher variability in the acceleration profiles, where it remained consistent for the adaptive one. Finally, the **angular speed** profiles were also altered by the control law and the curvature type. Figure 5.3 shows that participants rotated faster their torso with the constant and linear control laws than the adaptive one. For the adaptive law, as the speed was adjusted according to the curvature of the user's trajectory, it enforced lower speeds. This adaptation generated a change in turning behavior, inducing lower angular speeds. However, for the constant or linear ones, where the linear speed profiles were higher, participants preferred to compensate for the higher speed by rotating faster their torso in order to turn faster (involving higher angular speed profiles) than releasing the controller trigger to decrease the virtual speed and cross the gates with a lower angular speed. We argue that having control laws that provide lower angular speed could improve users' navigation because fast body rotations may degrade users' trajectories and could increase cybersickness (Farmani and Teather 2018). Overall, these results confirmed our first hypothesis [H1], for a given task, the control law and the curvature type can influence the spatio-temporal parameters (displacements in RE, linear speed, angular speed, and acceleration profiles) of the trajectory.

5.4.3 Towards Control Laws Based on Human Behavior?

The TLX-NASA analysis revealed a main effect of the control law on the physical demand and effort subscales. Although post-hoc comparisons could not confirm it, a visual inspection of the results (see Figure 5.4) suggests that participants had a lower perception of physical and effort demand for the adaptive law. This can be explained by the lower angular speed profiles generated with the adaptive control law that decreases the turning effort to perform slaloms. Therefore, the different TLX scores between the adaptive control law and the constant or linear ones can have two interpretations: (1) the lower angular speed profiles provided somehow more comfort resulting in lower effort to perform the task, or (2) the perception of the trajectory motion generated by the adaptive law seemed similar to an equivalent trajectory performed by real walking. These hypotheses might be explained by a higher locomotion fidelity for the adaptive control law than the others. Yet, further research is required to validate these suggestions. An interesting point about users' behavior, is that we noticed that had different strategies while navigating, resulting in different physical body rotations and translations. However, this behavior was consistent for each user across the three control laws. We informally reported four typical behaviors: (1) No translations in the RE with full-body rotation (including feet) during the turns. (2) No translations in the RE but only upper-body rotations (only the torso was rotating). (3)

Translations in the RE with full-body rotations. (4) Translations in the RE with upper-body rotations. We suggest that participants shifted in the RE either with forward translations to navigate faster (i.e. to follow the forward virtual translation in the VE) if they felt comfortable to perform the navigation task, or backward to counterbalance the high curvature turns (i.e. stepping back in the RE to be able to cross the gate without collisions in the VE) if they felt uncomfortable to perform the navigation task. Regarding the orientation, we noticed that high curvature implied full-body rotations and it was difficult for participants to only rely on upper-body rotations. Nevertheless, more investigation is required to better understand in which situations users tend to use one of these patterns and if every participant had the same behavior according to the control law and curvature type. These results, although they do not fully support [H2], provide insights on how the control law can alter users' experience while navigating. Taken together, our experiment showed that a navigation task involving turns and body rotations could alter user behavior. Developers should then consider control laws with respect to the type of trajectories users should have in the VR application. While constant and linear laws are popular in VR applications and can be still creditable for straight trajectories, our results would recommend the use of adaptive control laws when trajectories involve high curvature turns, as they could improve users' comfort.

5.5 Conclusion

In this paper, we first proposed a characterization of control laws for spatial steering navigation in VEs, and second, we described an evaluation of three different control laws in a virtual slalom task. While the characterization aims at encouraging reproducibility in future experiments and providing guidelines for VR practitioners on the design of control laws, the experiment explored the impact that the control law might have on user's performance and behavior. Our results showed that the control law and the type of trajectory altered the spatio-temporal parameters of the trajectories, in particular the angular speed profiles. The adaptive control law showed encouraging results that arouse interest in the potential use of control laws based on human locomotion for trajectories that require high curvature turns. However, future studies should consider VEs that better represent ecological situations, as well as evaluations of the control law at the individual level. These works could improve the existing control laws by being more adapted to the user and the task. To sum up, these results highlight the relevance that the control law can have on virtual steering and that human motor control knowledge is a promising research avenue to improve its design.

6

Understanding, Modeling and Simulating Unintended Positional Drift during Repetitive Steering Navigation Tasks in Virtual Reality

6.1 Motivations

Several studies have shown that even navigation techniques that do not require physical movements when used in combination with a Head-Mounted Display (HMD) yield unintended physical movement of the user (i.e. moving physically forward, leftward, rightward, or backward in the workspace while virtually navigating in the VE). This phenomenon referred to as *Unintended Positional Drift* (Nilsson et al. 2013b) (UPD), can be problematic since a user may come near the physical boundaries or obstacles in the workspace without noticing it. However, while previous works have assessed UPD while using Walking-In-Place (WIP) techniques (Nilsson et al. 2013a; Nilsson et al. 2013d; Nilsson et al. 2014a), little is known about UPD during steering navigation in VEs. Yet, UPD could have a negative impact on the user's experience as it can increase the risk of collisions with real obstacles and decrease presence if the application needs

to overtly reposition the user in the workspace. Besides, having a better understanding of UPD behaviors has the potential to improve the design of navigation techniques to minimize UPD and avoid or minimize such adverse effects.

In this chapter, we propose for the first time an analysis of UPD during a repetitive navigation task using a virtual steering technique. The chapter aims at, on one hand, presenting a characterization and models of a user's UPD while navigating in a VE, and on the other hand, an assessment of these models for a given task. Based on experimental data of users performing a slalom task in a VE using a torso-steering technique, we introduce two models (linear regression and Gaussian mixture) encoding the UPD based on the movement of the users. We designed a simulation framework that supports simulations of users navigating and drifting with a steering technique. The purpose of the simulator is to approximate realistic conditions for comparing ground truth data with simulated data. Simulations have been frequently used for assessing new navigation techniques ([Hodgson and Bachmann 2013](#); [Thomas and Rosenberg 2019](#); [Bachmann et al. 2019](#)). These evaluations often rely on simulated user paths to test new redirection techniques. Yet, they often use unrealistic navigation paths such as random walks with perfectly straight path segments and in-place turns, which do not necessarily correspond to ecological navigation performed in VR setups. In this chapter, we then reproduced the same experimental task in a simulation framework to assess our UPD models. We showed that our simulator can produce reliable UPD behavior in line with that observed with real users for the given repetitive steering navigation task. The results contribute to the understanding of UPD while navigating in VEs and our methodology could open new perspectives to new designs and assessments of navigation techniques that could reduce UPD.

In summary the contributions of this chapter are:

- Analyses of the UPD during a repetitive virtual navigation task when using a virtual steering navigation technique.
- UPD models characterizing users' motion in the workspace based on their movements.
- The design and validation of a virtual simulation system able to reproduce the characterized UPD.

6.2 UPD analysis during steering navigation

In this section, we describe how we analyzed UPD while using a virtual steering technique to navigate in VEs.

6.2.1 Navigation Task

6.2.1.1 Dataset

We analyzed the dataset gathered in chapter 5. Users had to perform a virtual slalom task while wearing an HMD. They were following three different sinusoidal-like trajectories (with low, medium, and high curvature) using a torso-steering navigation technique with three different control laws (constant, linear, and adaptive). The virtual movement was provided by pressing a controller's trigger (allowing virtual translation) and the heading direction was provided by the user's torso orientation. The control laws differ by their speed update and the implementations are described in chapter 5. The curvature type of the trajectory and the control law were randomized within-subjects variables. 18 users participated in the user study. We considered the whole dataset for analyzing UPD because we wanted to assess if the UPD could be influenced by the type of trajectory or the control law to update virtual motion in the VE.

During the experiment, users were immersed in the VE with an HTC Vive HMD, and two HTC Vive trackers were used to track users' shoulders. The HTC Vive tracking system was used as the reference coordinate system. In the rest of the chapter, we define the X axis of the HTC Vive tracking system as the *mediolateral* (ML) axis and the Z axis as the *anteroposterior* (AP) axis. The virtual slalom consisted of a sinusoidal trajectory composed of twelve turns, either starting with a left turn or a right turn. Three different curvature types were used for the slalom, with a sine amplitude of 2 meters. Curvature type was defined by different frequencies f to alter the task difficulty: Small Curvature (SC), $f = 1$; Medium Curvature (MC), $f = 1.5$ and High Curvature (HC), $f = 2$. They were based on curvature chosen in previous work done in REs ([Bernardin et al. 2012](#)). The path to follow was indicated through virtual gates ($1 \times 2.3 \times 1$ meters) located at the peaks of the sinusoidal trajectory. Users had to go through the gates to perform the navigation task. There was one block per control law, that consisted of twelve randomized trials (four per curvature type). Users performed six left and six right turns in each trial. In total, each user performed 36 trials ($3 \text{ control laws} \times 12 \text{ trials}$), resulting in 432 turns ($36 \text{ trials} \times 12 \text{ turns}$).

The dataset consists of data recorded for each frame of every trial. It contains the frame identifier, the execution time, head and shoulders position, and orientation in both VE and workspace.

6.2.1.2 Pre-processing

The UPD is defined as the physical displacement of the user in the workspace while navigating in the VE with a virtual steering technique. To analyze only the UPD behavior during the continuous trajectory, we removed the first and last turns from each trial as they were respectively the beginning and the end of the slalom in which users were mainly performing rather straight-line trajectories than curvilinear. We considered a turn as a piece of trajectory between two inflection points of the slalom (Figure 6.1). To evaluate the UPD over time, we first resampled the dataset, then filtered data with a Butterworth low-pass filter (1Hz cutoff frequency) to remove natural body oscillations when turning (Hicheur et al. 2005a) and finally temporally normalized them. Users' movements in the workspace were calculated by considering the barycenter of the shoulders' trajectories. We computed the amplitude of users' shoulders as the unwrap arc-tangent function of the ratio between the coordinates of the shoulders' orientation vector in the ML/AP plane (Figure 6.1). To evaluate the effect of our independent variables on average kinematics of the trajectories, we performed a two-way analysis of variance (ANOVA) with repeated measures when the distribution of the dependent variables was normal or an Aligned Rank Transformation (ART) ANOVA test if not (Wobbrock et al. 2011).

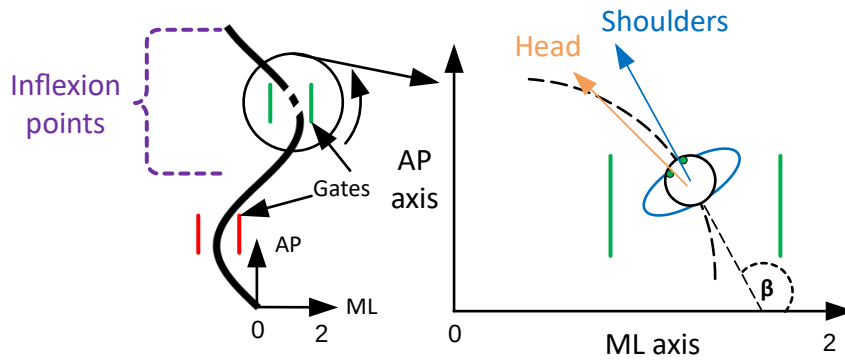


Figure 6.1 – Left: users performed a virtual slalom by going through gates. A turn is defined as the trajectory between two inflection points. Right: Orientation of body segments in the horizontal plane. Horizontal angles for each body segment are defined as the unwrap tangent function of the ratio ML/AP, where ML and AP represent orientations of the body segment.

To avoid any violation of the sphericity assumption, we used Greenhouse-Geisser adjustments to the degrees of freedom. T-tests with Bonferroni corrections were used as post-hoc analyses. To evaluate the temporal evolution of UPD, we used the Statistical Parametric Mapping (SPM) method (Friston et al. 2007), which allows comparing time-series data considering the variability

over time.

We performed two different analyses to gain a better understanding of how the users drift in the workspace:

1. Global Analysis: We quantified the UPD as the difference between the position of the user at the beginning and the end of the virtual turn. We wanted to confirm first that the users drift after performing one turn.
2. Continuous Analysis:
 - Whole turn: We evaluated the temporal evolution of the UPD during the whole virtual turn by computing the cumulative sum of the UPD both on ML and AP axes. We aimed to assess when UPD occurs within the turn.
 - Sliding window analysis: We aimed at explaining the UPD by relating the cumulative sum of the UPD on a specific period of time with other variables such as the amplitude of the rotation.

6.2.2 Global Analysis of UPD

For each turn performed, we gathered its first and last point and computed the displacement of users in the workspace on both ML and AP axes. Figure 6.2 shows the density map of users' positions at the end of a left turn and a right turn. We can notice that after a left turn, the UPD on the ML axis is negative whereas it is positive for right turns. It means that the users drifted towards the direction of the turn (a virtual left turn provokes displacements towards the left in the workspace and a virtual right turn towards the right in the workspace). The static analysis showed that, on average, users drifted on the ML axis -0.22m ($SD = 0.13$) for left turns and 0.22m ($SD = 0.14$) for right turns (Figure 6.3). Regarding the AP axis, it is hard to determine whether users tend to drift rather forwards or backward. On average, users showed no drift on this axis, even though we can notice in Figure 6.2 that there are some points spread along the AP axis.

Statistical analyses confirmed our first observations. First, we observed that the turn number (from the 2nd to the 11th completed in the slalom) did not influence the UPD that remained consistent across the turns. Therefore we aggregated all the turns together. Then we performed a three way ANOVA (control law \times curvature type \times turn side) and we noticed an effect of the turn's direction on the UPD on the ML axis ($F_{1,17} = 73.74$, $p < 0.001$, $\eta_p^2 = 0.80$), where post-hoc analysis showed that users tend to drift more leftwards (UPD $x < 0$) during a left turn and more rightwards (UPD $x > 0$) during a right turn ($p < 0.05$). However, we

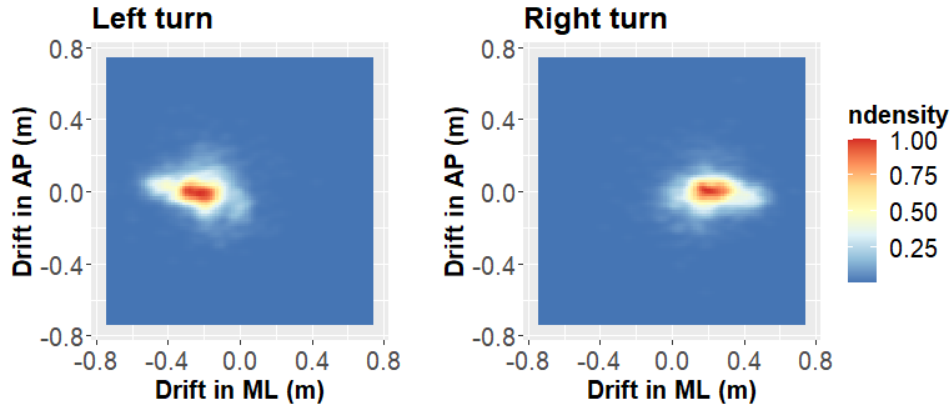


Figure 6.2 – Density map of users' UPD in the workspace at the end of a left or right turn.

did not notice an effect of the control law ($F_{1.73,29.34} = 0.28, p = 0.72$) nor the curvature type ($F_{1.55,26.41} = 1.18, p = 0.31$) on the UPD on the ML axis. Regarding the AP axis (Figure 6.3), we found an effect of the control law ($F_{1.66,28.20} = 8.48, p < 0.05$), where post-hoc analysis showed that users tend to slightly drift more backwards with the adaptive control law than the constant or the linear ones ($p < 0.05$). However, we did not find an effect of the curvature type ($F_{1.24,21.11} = 3.28, p = 0.07$) nor the turn direction ($F_{1,17} = 0.78, p = 0.38$) on UPD on AP axis.

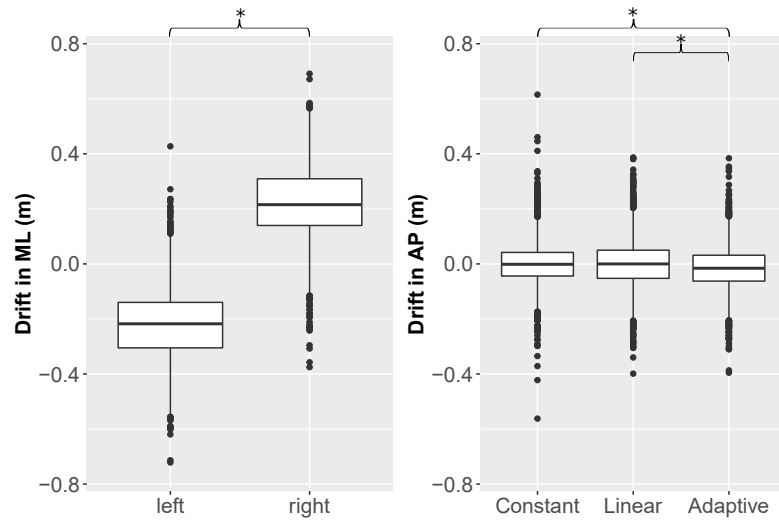


Figure 6.3 – Boxplots of UPD on the ML axis per turn direction (left, right) and on the AP axis per control law (constant, linear, adaptive). The whiskers indicate pairwise comparisons (* $p < 0.05$).

This first analysis showed the existence of UPD when performing a turn in VR while using

steering techniques. The next step is then to understand the temporal aspects of the UPD by taking into account the temporal variability.

6.2.3 Temporal Evolution of UPD

6.2.3.1 Whole Turn Analysis

Figure 6.4 shows the average and standard deviation of the temporal evolution of accumulated UPD on ML and AP axes for both right and left turns, depending on the curvature type and the control law. SPM analysis showed a consistent UPD behavior with no effect of the control law nor the curvature type on these time-series during the turn. For each sample of the turn trajectory (each turn consisted of 375 samples), the critical threshold of the paired samples t-test statistic was never exceeded, indicating no significant difference of accumulative UPD across conditions.

Also, it is interesting to notice that the temporal evolution of the accumulated UPD on the ML axis follows a similar pattern for both left and right turns. During the first 40% of the trajectory, the UPD is opposite to the turn direction (i.e. it decreases during the left turn and increases during the right turn) before evolving in the opposite direction from the 40% point until the end of the trajectory (i.e. it increases during the left turn and decreases during the right turn). Regarding the AP axis, we can notice that the average accumulated UPD remains close to 0, but a negative UPD (backwards movement) seems to appear during the turn (40%–60% of the normalized time).

The fact that there are no effects between the experimental conditions would support us in aggregating the data together in order to create our UPD models. In the following subsection, we deepen the analysis in order to get the final results and generate our UPD models.

6.2.3.2 Sliding Window Analysis

In the previous analyses, we noticed the existence of UPD, and we confirmed that UPD differs according to the turn direction. Considering the UPD as a continuous variable allows us to understand how UPD occurs over time while considering the trajectory variability. For instance, users' amplitude during a turn can vary based on the turn strategy (e.g. regarding the foot placement). Since this information is not available with the global analysis (considering only the first and last data point of a turn), the use of a sliding window is required. In this section, we want to analyze the possible relationship between UPD and the difference in the shoulders' amplitude during the turn (i.e. if the amount of turn can explain how users drift). For each turn, instead of computing the difference between the first and the last point of the turn, we computed the difference of amplitude and the UPD between points with different sliding windows. Since

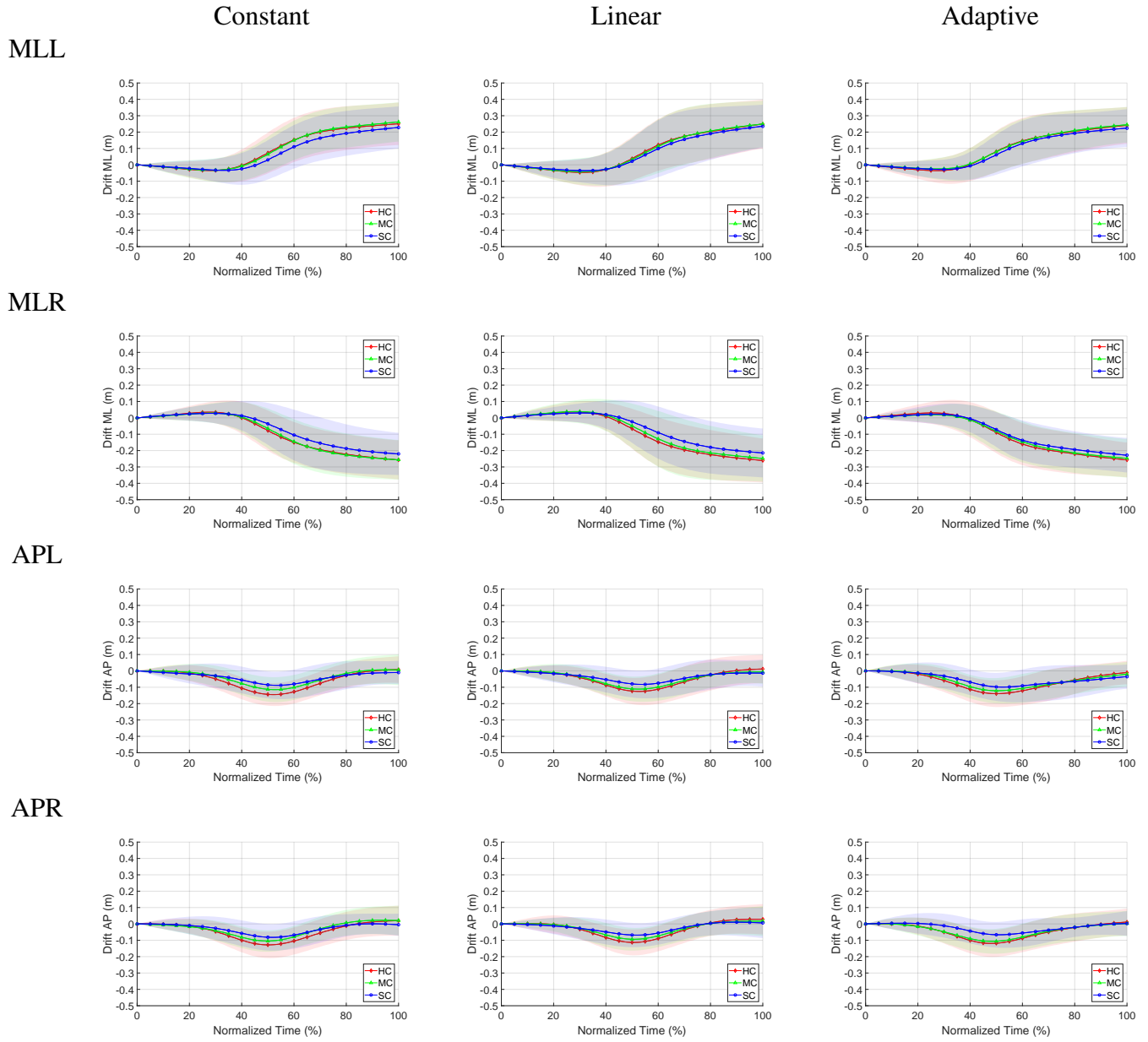


Figure 6.4 – This figure shows the averaged temporal evolution of means and standard deviations of the accumulated drift on the ML axis for left (MLL) and right (MLR) turns (top rows) as well as on the AP axis for left (APL) and right (APR) turns (bottom rows) for all users. The colors indicate the curvature types: high (HC) in red, medium (MC) in green, and small (SC) in blue. The columns indicate the control laws: Constant in first column, Linear in second, and Adaptive in third column. Each sample of the temporal sequence is a dependent variable (each turn had 375 samples). We found no effect of the control law on the variables during a turn, i.e., the critical threshold of the paired samples t-test statistic was never exceeded.

the average time of a turn is around 4 seconds, we decided to test windows ranging from 0.5 to 2 with a step of 0.5 seconds. We selected the best dataset for the analysis based on the following criteria: (1) The histogram of the UPD on X follows a normal distribution; (2) The distribution is separated into two clusters based on the amplitude (left and right turns since we noticed a difference between them); (3) The difference of amplitude covers more high values than close to zero values. These criteria are dependent on the task and trajectories we had. It is important to keep in mind that the choice of the sliding window is dependent on the trajectory. In our example, increasing the sliding window helped us discretize the distribution of points. We finally decided to choose the window of 2 seconds as it fulfilled at best the criteria mentioned above.

Then, we plotted the UPD on the ML axis based on the difference of amplitude (all conditions grouped) to determine which type of regression we would use in our UPD models (Figure 6.5). We were able to identify different UPD patterns. First, we confirmed that, like users 1 and 2 in Figure 6.5, users drifted in general in the turn direction (i.e. $UPD < 0$ when the difference of amplitude is < 0 and $UPD > 0$ when the difference of amplitude is > 0).

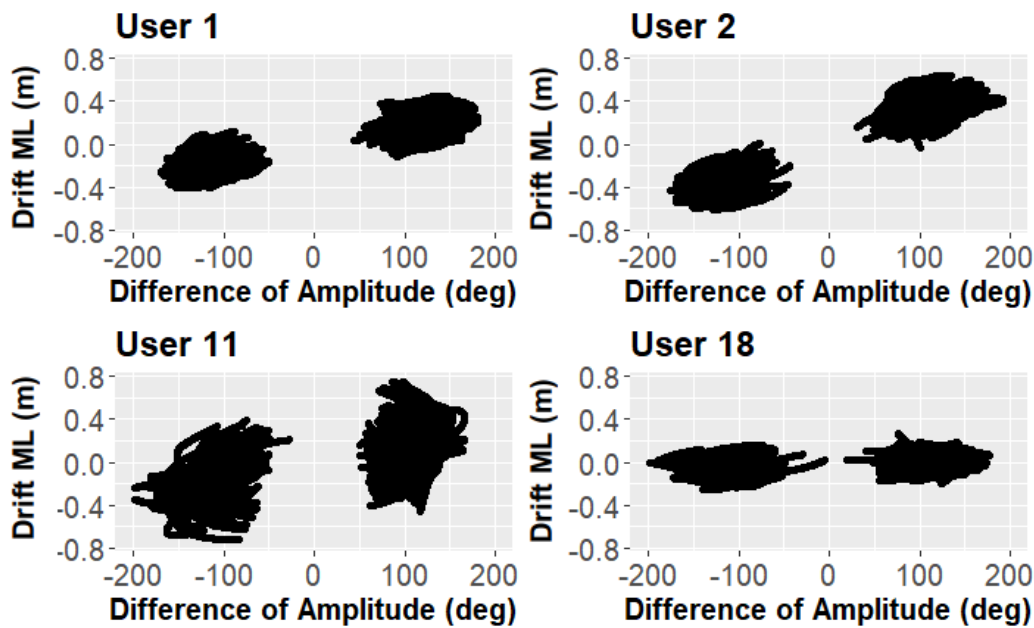


Figure 6.5 – Selected representative examples of mediolateral UPD patterns based on the difference of amplitude for all conditions. We can identify three different patterns: (1) Users 1 and 2 drift towards the direction of the turn, where user 2 drifted more than user 1; (2) User 11 shows a random drift pattern, sometimes drifting to the opposite of the turn direction; (3) User 18 shows almost no drift.

Yet we also had three users (like user 11) in which the patterns were impossible to determine,

since they were sometimes drifting either in the turn direction or its opposite. Moreover, one participant (user 18) almost showed no UPD at all (UPD close to 0). Regarding the AP axis (Figure 6.6), for both turn directions, the UPD seems either forward or backward. We checked visually the distribution of the UPD on the AP axis, and we noticed that it was following a normal distribution centered on 0.

Based on these observations, we decided to consider the difference of amplitude as our main metric to model UPD and we split the data between the 9 conditions ($3 \text{ control laws} \times 3 \text{ curvature type}$) to see if the patterns would differ across conditions.

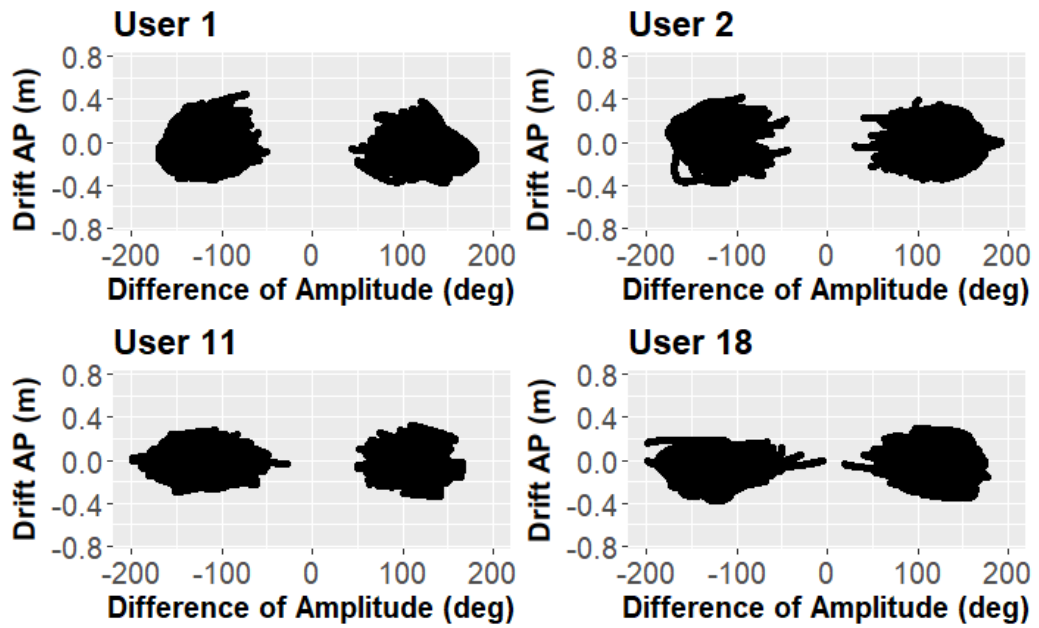


Figure 6.6 – Examples of anteroposterior UPD patterns based on the difference of amplitude for all conditions.

6.3 Generating the UPD Models

Based on visual exploratory analysis, we determined that linear and Gaussian Mixture Model (GMM) were two alternatives that seemed to be well adapted to our data. Our objective was to compare a simple approach (linear model) with a more sophisticated one (GMM) that could both suit our data. In this section, we describe these UPD models that encompass how users drift in the physical workspace.

6.3.1 Linear Model

Even though at first sight, the relation between the difference of amplitude Δamp_t and UPD on the ML axis does not seem to be linear, we wanted to investigate whether a first simple approach with a linear regression could be a reasonable approach to model UPD. For each user, condition and turn direction, we computed a linear regression of the UPD for each axis based on the difference of amplitude (Equation 6.1 for ML axis, Equation 6.2 for AP axis).

$$ML_t = 0.0016 \cdot \Delta amp_t + 0.002 \quad (6.1)$$

$$AP_t = 1.80 \cdot 10^{-5} \cdot \Delta amp_t + 0.03 \quad (6.2)$$

Regarding the ML axis, a 3-way ANOVA (control law \times curvature type \times turn direction) showed that neither the control law ($F_{1.95,33.19} = 1.17$, $p = 0.32$), the curvature type ($F_{1.27,21.56} = 1.95$, $p = 0.17$), nor the turn direction ($F_{1,17} = 0.04$, $p = 0.83$) had a significant impact on the slope. We found similar observations for the intercept. Therefore we compute the parameters of our linear model as respectively the mean of the slope and the mean of the intercept between conditions and users. We used the standard deviation of the slope to model noise in the final UPD output (0.01 for ML and 0.002 for AP). Since the data we gathered is based on the difference of amplitude, information for the $[-100,100]$ range is missing. We hypothesized that the UPD will follow the same behavior in this range and extrapolated the model. Figure 6.7 shows the linear fit for each user. We found $R^2 = 0.25$ for ML fit and $R^2 = 0.1$ for AP fit.

6.3.2 Gaussian Mixture Model

Figure 6.5 and Figure 6.6 show that UPD on both ML and AP axes is divided into two clusters depending on if the difference of amplitude Δamp is either negative or positive. We noticed that the distribution of Δamp , UPD on ML and AP axes followed a normal distribution, therefore we learned a probabilistic model from these data with a Gaussian Mixture Model (GMM) (Reynolds 2009). In particular, we estimated the parameters of the mixtures using the Expectation-Maximization (EM) implementation from the *mixtools* package in R to compute the two mixtures of our multivariate normal distributions (Benaglia et al. 2009). We were able to generate a GMM model giving the probability of UPD on ML and AP axes for each user and condition. Each mixture provides for the following variables (Δamp , UPD on ML and AP axes) their mean (μ), standard deviation (σ), and covariance matrix (Σ).

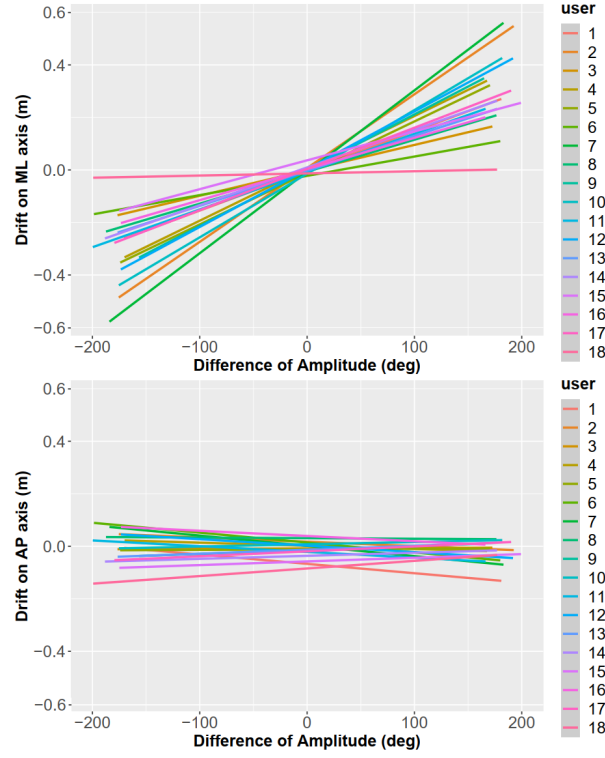


Figure 6.7 – Linear regression modeling the mediolateral and antero-posterior UPD based on the difference of amplitude. Each regression line corresponds to one user.

Regarding the μ parameter, a 2-way ANOVA (control law \times curvature type) showed that the curvature type had a significant effect on μ_A for both mixtures (left turn: $F_{1.15,6.92} = 1333.58$, $p < 0.001$, $\eta_p^2 = 0.99$; right turn: $F_{1.16,6.96} = 588.96$, $p < 0.001$, $\eta_p^2 = 0.99$), where post hoc analyses showed the higher the curvature, the higher μ_a for left turns and the lower for right turns ($p < 0.05$). We noticed the same result for μ_{ML} (left turn: $F_{1.19,7.14} = 5.58$, $p < 0.05$, $\eta_p^2 = 0.24$; right turn: $F_{1.17,7.03} = 2.95$, $p < 0.05$, $\eta_p^2 = 0.33$), where the higher the curvature, the higher μ_{ML} for left turns and the lower for right turns ($p < 0.05$). Yet, we did not notice an effect of μ_{AP} for left turns ($F_{1.27,7.64} = 0.19$, $p = 0.73$) nor right turns ($F_{1.57,9.41} = 2.38$, $p = 0.15$).

Regarding the σ parameter, a 2-way ANOVA (control law \times curvature type) showed that the curvature type had a significant effect on σ_A for both mixtures (left turn: $F_{1.41,8.46} = 25.36$, $p < 0.01$, $\eta_p^2 = 0.80$; right turn: $F_{1.25,7.49} = 22.36$, $p < 0.01$, $\eta_p^2 = 0.78$), where post hoc analyses showed the higher the curvature, the higher σ_a for left turns and the lower for right turns ($p < 0.05$). We did not notice any effect of the control law or the curvature type on σ_{ML} for both turns. Yet, we did notice an effect of the curvature type for σ_{AP} (left turns: $F_{1.05,6.28} = 8.85$, $p < 0.05$, $\eta_p^2 = 0.59$; right turns: $F_{1.09,6.54} = 15.19$, $p < 0.01$, $\eta_p^2 = 0.71$), where post hoc

analyses showed the higher the curvature, the higher σ_a for left turns and the lower for right turns ($p < 0.05$).

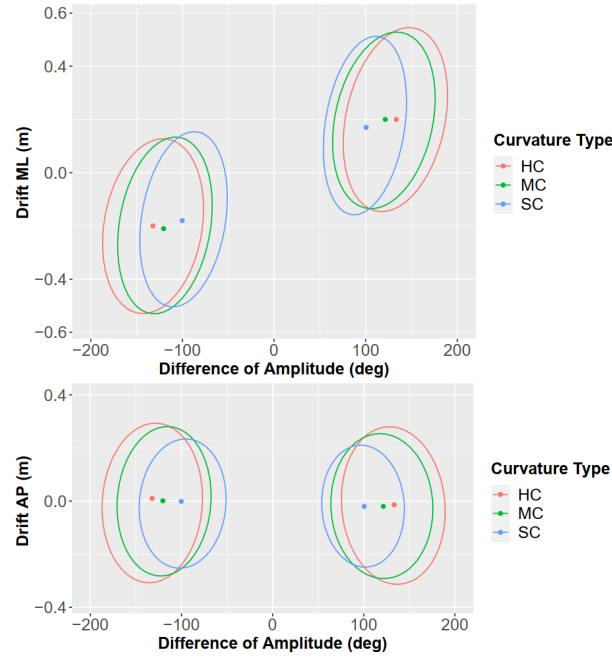


Figure 6.8 – Ellipses of the mixtures plots fit with GMMs for modeling UPD on the ML and AP axes given the difference of amplitude for each curvature type: high (HC) in red, medium (MC) in green, small (SC) in blue.

Since we noticed an effect of the curvature type on the GMM parameters but not the control law, we decided to have 3 GMMs (one for each curvature type) where μ , σ , and Σ are computed as the mean of all GMMs generated per user and curvature type. Figure 6.8 shows the ellipses computed in our analysis, Table 6.1 and Table 6.2 show the GMM estimated parameters for each variable and curvature type for both ML and AP axes. We used the following procedure to compute UPD based on this model. First, we select the best mixtures based on the input Δamp : this can be easily determined by the curvature type of the slalom and the estimated parameters μ_a , where we choose the mixture that minimizes $|\Delta amp - \mu_a|$. In case no mixtures correspond, we can extrapolate our model by creating a new multivariate normal distribution by transforming the closest mixtures to Δamp into a new normal distribution with an affine transformation. Yet, this was not required in our model since the implementation of the UPD in our simulator will never face cases like this one. Then, we compute the conditional distribution of UPD (on both ML and AP axes) given Δamp . In a bivariate case where UPD is partitioned into two random variables (in our case A for the amplitude, X for UPD on ML axis, and Z for UPD on AP axis),

Table 6.1 – Mean, standard deviations and covariance matrix of estimated parameters (amplitude, UPD ML axis) from GMMs for both turn directions and each curvature type: high curvature (HC), medium curvature (MC), small curvature (SC).

	Left Turn	Right Turn
HC	$\begin{pmatrix} -131.57 \\ -0.20 \end{pmatrix} \begin{pmatrix} 501.03 & 0.70 \\ 0.70 & 0.01 \end{pmatrix}$	$\begin{pmatrix} 133.03 \\ 0.20 \end{pmatrix} \begin{pmatrix} 426.83 & 0.61 \\ 0.61 & 0.01 \end{pmatrix}$
MC	$\begin{pmatrix} -118.93 \\ -0.19 \end{pmatrix} \begin{pmatrix} 390.41 & 0.57 \\ 0.57 & 0.01 \end{pmatrix}$	$\begin{pmatrix} 120.26 \\ 0.19 \end{pmatrix} \begin{pmatrix} 413.55 & 0.56 \\ 0.56 & 0.01 \end{pmatrix}$
SC	$\begin{pmatrix} -98.38 \\ -0.17 \end{pmatrix} \begin{pmatrix} 325.05 & 0.54 \\ 0.54 & 0.01 \end{pmatrix}$	$\begin{pmatrix} 99.83 \\ 0.17 \end{pmatrix} \begin{pmatrix} 245.66 & 0.45 \\ 0.45 & 0.01 \end{pmatrix}$

Table 6.2 – Mean, standard deviations and covariance matrix of estimated parameters (amplitude, UPD AP axis) from GMMs for both turn directions and each curvature type: high curvature (HC), medium curvature (MC), small curvature (SC).

	Left Turn	Right Turn
HC	$\begin{pmatrix} -132.17 \\ 0.01 \end{pmatrix} \begin{pmatrix} 78.29 & 0.18 \\ 0.18 & 0.01 \end{pmatrix}$	$\begin{pmatrix} 133.48 \\ -0.014 \end{pmatrix} \begin{pmatrix} 65.56 & -0.2 \\ -0.2 & 0.01 \end{pmatrix}$
MC	$\begin{pmatrix} -120.49 \\ 0.001 \end{pmatrix} \begin{pmatrix} 56.86 & 0.09 \\ 0.09 & 0.008 \end{pmatrix}$	$\begin{pmatrix} 121.45 \\ -0.02 \end{pmatrix} \begin{pmatrix} 71.35 & -0.08 \\ -0.08 & 0.006 \end{pmatrix}$
SC	$\begin{pmatrix} -100.23 \\ -0.001 \end{pmatrix} \begin{pmatrix} 57.06 & 0.07 \\ 0.07 & -0.001 \end{pmatrix}$	$\begin{pmatrix} 100.53 \\ -0.02 \end{pmatrix} \begin{pmatrix} 62.24 & -0.05 \\ -0.05 & 0.006 \end{pmatrix}$

the conditional distribution of UPD X (or Z) given A is computed through Equation 6.3 and Equation 6.4. Last, we sample a value from this new normal distribution and we apply the UPD on both ML and AP axes.

$$X|A = a \sim \mathcal{N}(\mu_{ML} + \frac{\sigma_{ML}}{\sigma_A} \Sigma_{A,ML}(a - \mu_A), (1 - \Sigma_{A,ML}^2) \sigma_{ML}^2)) \quad (6.3)$$

$$Z|A = a \sim \mathcal{N}(\mu_{AP} + \frac{\sigma_{AP}}{\sigma_A} \Sigma_{A,AP}(a - \mu_A), (1 - \Sigma_{A,AP}^2) \sigma_{AP}^2)) \quad (6.4)$$

where μ_A , μ_{ML} , μ_{AP} , σ_A , σ_{ML} , σ_{AP} are the mean and standard deviation of the mixtures and $\Sigma_{A,ML}$, $\Sigma_{A,AP}$ respectively the correlation coefficient between A and X or A and Z .

6.4 Simulating Drift During Steering Navigation

The previous section aimed at characterizing the user's UPD when virtually navigating. In this section, we describe a simulation framework that aims at using such characterization to simulate new navigation data which could be used to assess virtual navigation tasks and serve as a testbed to propose UPD compensation methods. First, we describe the simulation framework, then we analyze how the simulation framework allows us to reproduce the navigation task considered in section 6.2.

6.4.1 Simulation Framework

Our framework enables simulation of virtual agents navigating through VEs using a virtual steering technique for a given navigation task. It is divided into two different components: the navigation task and the agents' (virtual and real) behavior. The framework aims at simulating the actual user behavior (real agent) given a constrained virtual navigation task, where control mechanisms enable updating position and orientation of both agents during the simulation.

The navigation task considers the virtual area where the virtual agent will navigate, as well as the actions required to perform it. It can represent for example a user wearing an HMD with a limited tracking space and even physical obstacles inside this area. The framework simulates two agents, one virtual representing its position and its orientation in the VE and a second one representing its position and its orientation in the RE. Both agent behaviors can be independent, can consider the physical drift model, and can also consider redirection heuristics. The simulation can be performed at any fixed framerate to be equivalent to VR setups. The position and orientation of the agents should be updated at each frame of the simulation, regarding the navigation task. Any kind of navigation tasks can be embedded (e.g. performing a slalom, finding the exit in a maze, traveling in a virtual forest and pickup objects, etc.). For more comprehensive analysis, the simulator can record several metrics at each frame (e.g. time, distance achieved in VE and RE, position and orientation of agents, linear and angular speed, etc.). The simulator enables to visualize virtual and real trajectories of an agent in real-time, but it also allows to run the simulation in test mode, where the rendering pipeline is not including to speed up the simulation calculations.

6.4.2 Simulation of Slalom Task

In order to simulate the slalom task discussed in subsection 6.2.1, we considered the following constraints when defining the trajectories of the virtual agent. First, we considered a constant velocity of the virtual agent of 1.3 m/s, which was the mean velocity during the navigation task. Second, we modeled the virtual slalom trajectory with a parametric formulation by using cubic Bézier curves (Equation 6.5). The virtual agent will follow this trajectory and their orientation will be defined by the tangent at a given position. The trajectories between two gates were computed using the following equation:

$$P(t) = (1-t)^3P_0 + 3(1-t)^2tP_1 + 3(1-t)t^2P_2 + t^3P_3 \quad (6.5)$$

where P_0 is the previous gate the agent crossed, $P_1 = P_0 + \alpha$, P_2 the next gate the agent should cross, $P_3 = P_2 + \alpha$. To add variability in the trajectories, we used a 2D vector α where $\alpha_x = 0$ and $\alpha_z \sim \mathcal{N}(1, 0.25)$.

Adjustments of real agents' heading direction were based on the pose of the virtual agent. The simulation was performed with a fixed framerate of 90 frames per second (framerate of the HTC Vive used in the user study). We embedded our models (linear, GMM) to simulate the UPD of the real agent based on the behaviour of the virtual agent. UPD was simulated with respect to the sliding window we used in our analysis. Therefore, UPD was computed with a two-second sliding window. If the real agent reached the limits of the workspace (2×2 meters, same as the one used in the user study), a reset was performed: we automatically replaced the agent at the center of the workspace. We reproduced the experimental protocol from chapter 5 by simulating 18 users performing each condition.

6.4.3 Analyses of Simulated Data

We used the same methodology as described in section 6.2 to analyze the simulated data. We estimated linear regression and GMM parameters for each simulated user. Using global analysis (difference between end and beginning of turn), a one way ANOVA with the type of data as dependant variable (simulated linear, simulated GMM or real data) showed no significant effect on UPD on the ML axis after a turn ($F_{1,34,22.82} = 0.15$, $p = 0.77$), but we noticed an effect on the AP axis ($F_{1,13,19.24} = 41.09$, $p < \mathbf{0.001}$, $\eta_p^2 = 0.51$), where post-hoc analyses showed that the linear model generated on average more backwards drift than the GMM or real ones ($p < \mathbf{0.05}$).

For the linear model, Table 6.3 shows parameters of estimated linear regressions between simulated and real data. Regarding the UPD on the ML axis, a one way ANOVA with the type of data as dependant variable (simulated or real data) showed no significant effect on the linear regression parameters (slope: $F_{1,17} = 1.73$, $p = 0.20$, intercept: $F_{1,17} = 0.12$, $p = 0.73$). Regarding the UPD on the AP axis, a one way ANOVA with the type of data as dependant variable (simulated or real data) showed no significant effect on the linear regression parameters (slope: $F_{1,17} = 0.001$, $p = 0.97$, intercept: $F_{1,95,33.19} = 2.47$, $p = 0.13$).

For the GMM model, Table 6.4 shows the parameter of estimated mixtures between simulated and real data for both axes. Regarding the μ parameter, a one way ANOVA with the type of data as dependent variable (simulated or real data) showed an effect of type of data on μ_A for both mixtures (left turn: $F_{1,5} = 15.01$, $p < \mathbf{0.01}$; right turn: $F_{1,5} = 12.77$, $p < \mathbf{0.01}$, $\eta_p^2 = 0.72$), where post hoc analyses showed respectively lower and higher μ_A for left and right turn with simulated data than real data ($p < \mathbf{0.05}$). We noticed the same result for μ_{ML} (left turn: $F_{1,5} = 11.99$,

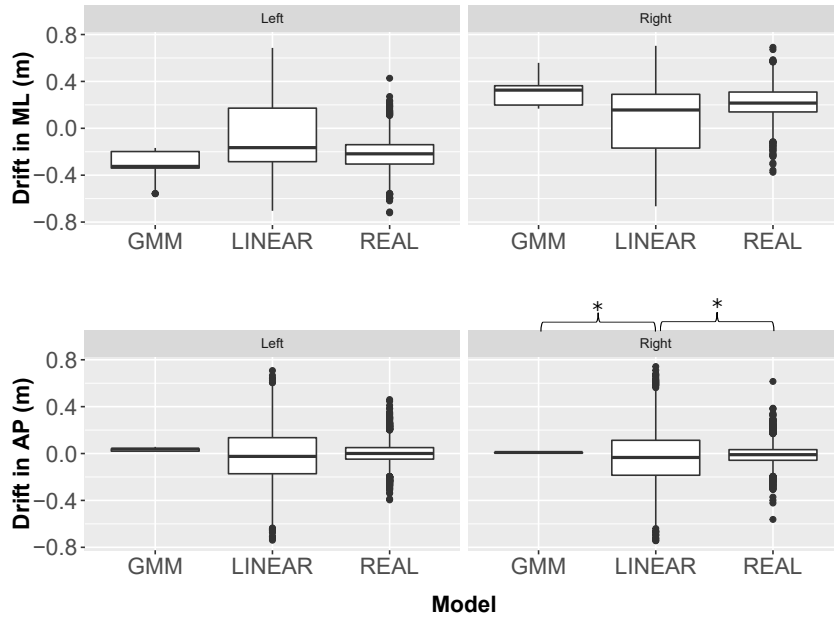


Figure 6.9 – Boxplots of UPD on the ML and AP axes per turn direction (left, right) for each type of data (simulated, linear, GMM). The whiskers indicate pairwise comparisons (* $p < 0.05$).

Table 6.3 – Average estimated parameters $mean(SD)$ (slope, intercept) from linear regression for each type of data (real and simulated) and each drift axes (ML, AP). No significant differences were found between the type of data for both axes.

	X		Z	
	Slope	Int.	Slope	Int.
Real	0.016(0.01)	0.002(0.13)	$1.80 \cdot 10^{-5}(0.02)$	0.03(0.17)
Sim.	0.013(0.01)	-0.002(0.16)	$1.55 \cdot 10^{-5}(0.002)$	0.006(0.05)

$p < 0.05$, $\eta_p^2 = 0.70$; right turn: $F_{1,5} = 14.55$, $\eta_p^2 = 0.74$, $p < 0.05$), where simulated μ_{ML} was lower for left turns and right turns ($p < 0.05$). Yet, we did not notice an effect of μ_{AP} for left turns ($F_{1,5} = 1.74$, $p = 0.23$) nor right turns ($F_{1,5} = 2.05$, $p = 0.20$).

Regarding the σ parameter, a one way ANOVA with the type of data as dependent variable (simulated or real data) showed that the type of data had a significant effect on σ_A of the amplitude for both mixtures (left turn: $F_{1,5} = 37.76$, $p < 0.001$, $\eta_p^2 = 0.83$; right turn: $F_{1,5} = 55.15$, $p < 0.001$, $\eta_p^2 = 0.90$), where post hoc analyses showed higher σ_A for real data than simulated ($p < 0.05$). We did notice an effect of type of data on σ_{ML} for both turns (left turn: $F_{1,5} = 165.13$, $p < 0.001$, $\eta_p^2 = 0.97$; right turn: $F_{1,5} = 297.90$, $p < 0.001$, $\eta_p^2 = 0.98$),

Table 6.4 – Averaged estimated parameters ($\mu(\sigma)$) from mixtures (left/right) for each type of data (real and simulated) and drift axes (ML,AP).

	X		Z	
	Real	Simu	Real	Simu
μ_A	-116.33/117.15	-126.63/126.62	-116.34/117.15	-126.63/126.62
μ_X	-0.19/0.19	-0.11/0.11	-	-
μ_Z	-	-	-0.005/-0.02	0.01/0.007
σ_A	292.13/311.03	198.32/198.94	292.15/311.01	198.35/198.99
σ_X	0.008/0.008	0.016/0.017	-	-
σ_Z	-	-	0.009/0.009	0.00003/0.00002

where post hoc analyses lower higher σ_{ML} for real data than simulated ($p < 0.05$). We also noticed an effect of type of data on σ_{AP} (left turns: $F_{1,5} = 9.77$, $p < 0.05$, $\eta_p^2 = 0.62$; right turns: $F_{1,5} = 14.49$, $p < 0.01$, $\eta_p^2 = 0.70$), where post hoc analyses showed lower σ_{AP} with simulated data than real ($p < 0.05$).

6.5 General Discussion

If UPD is accumulated over time, it may become problematic for two main reasons: (1) safety purposes where users could reach the limits of the workspace or collide with obstacles within, (2) repositioning users to the center would break immersion. It is important to be aware of the effects of UPD, to gain a better understanding of it, and to find potential solutions that could minimize it. In this chapter, we aimed to characterize for the first time UPD patterns for a given steering navigation task. We aimed to raise awareness of this yet undisclosed phenomenon and provide first insights into UPD challenges to foster research in this direction among the research community. We presented a methodology to analyze UPD and create UPD models. In addition, we presented the first results of simulated UPD with virtual agents. Our results showed the existence of UPD during steering and the possibility to simulate it. Yet, it is important to consider that our approach is a first step towards establishing UPD models for virtual steering navigation, using the virtual slalom task as an example. Therefore, this contribution is not providing a generalizable model, but a proof of concept of how to construct and assess models (e.g. the linear and GMM ones we used).

6.5.1 Understanding UPD During Steering Navigation

We demonstrated the existence of UPD while using a steering navigation technique. During a navigation task, users may unintentionally move into the workspace without noticing it. In particular, we characterized UPD patterns and noticed that users tended to drift on the ML axis towards the direction of the turn: performing a virtual left turn resulted in leftwards UPD whereas a virtual right turn resulted in rightwards UPD (Figure 6.3). Besides, we observed UPD on the AP axis, but we were not able to determine any particular patterns or reasons that could lead to forward or backward UPD. Our initial hypothesis is that UPD during slalom turns may depend on the user's turn strategy.

Performing quick whole-body rotations while still maintaining balance and some momentum can be difficult. There exist two main strategies to perform a turn ([Hase and Stein 1999](#)): (1) To turn to the right when the right foot is placed in front, subjects generally altered direction by spinning the body around the right foot (spin turn); (2) To turn left when the right foot is in front, subjects shifted weight to the right leg, externally rotated the left hip, stepped onto the left leg, and continued turning until the right leg stepped in the new direction (step turn). We suggest that the turn strategy influenced UPD on the AP axis: a step turn strategy resulted in backwards UPD and a spin turn in forward UPD. However, it is important to keep in mind that the task was constrained by gates with a given position and orientation.

We hypothesize that the UPD may be task dependent, meaning that the UPD patterns we observed in the slalom task may differ for other navigation tasks (e.g. free navigation without constraints). Then, considering UPD as a temporal variable (e.g. with a sliding window analysis) may be necessary to understand it across different navigation tasks, since UPD differed with respect to the slalom curvature type. Future work should explore additional navigation tasks (and in particular trajectories with sharp corners that may require manual labeling instead of automatic detection) to compare whether the UPD patterns remain similar or not, but also improve the robustness of the temporal analysis. In addition, recording foot placement could provide additional insights to analyze the footstep strategy and their potential relation to the characteristics of UPD, for example, foot dominance can alter postural balance ([Alonso et al. 2011](#)). One advantage of our analysis methodology is that it can be applied to any kind of navigation technique requiring less physical movement (WIP, teleport-based). We could therefore imagine in the future studying UPD for any techniques that require « turning-in-place » movements, as this motion may be one major source of UPD.

6.5.2 Modeling UPD During Steering Navigation

Based on the UPD patterns observed in the considered dataset and visual exploratory analysis, we determined that linear and Gaussian Mixture Models were 2 alternatives that seemed to be well adapted to our data., we presented two models, linear regression and GMM, to encode the UPD on both ML and AP axes based on users' rotations. We suggested that UPD may be related to the amount of physical rotation performed during the navigation task. The linear model hypothesized that the higher the user's rotation, the higher the UPD. The GMM model considers the marginal distribution of a user's rotation and given UPD observed in real data, generates UPD accordingly. Overall, while these models provide a first relevant approximate of UPD patterns, we are aware that they could be improved.

For instance, the linear model tends to generate more variability than the GMM since the noise added during the simulation was based on the standard deviation of the estimated parameters of the regression, whereas the GMM parameters had very low standard deviations. This suggests that our models are not entirely encoding the subtleties of the real UPD behavior and that additional features should be added to the model. Linear regression was an interesting option to describe overall the UPD patterns without considering intra-individual variability. The GMM model should rather be considered at the individual level. To improve the modeling of UPD, other solutions could be explored. Recent research work showed that deep learning or reinforcement learning could be promising avenues to outperform models that rely on human-engineered logic ([Silver et al. 2016](#); [Mnih et al. 2015](#)). In addition, other metrics such as path curvatures, angular speed, or additional tracked body parts should be considered to improve UPD models. Finally, it is worth noticing that UPD may also introduce intra-subject variability. We tried to find models that explain UPD for a given task based on visual exploratory analysis. We determined that linear and Gaussian Mixture Models were 2 alternatives that seemed to be well adapted to our data. However, we are aware that these models are not generic to describe UPD in steering navigation. Other types of models could be assessed and individual UPD models for each user could be learned on the fly while gathering live data in order to have UPD based on user behavior.

6.5.3 Simulating UPD During Steering Navigation

Using simulation-based evaluations is interesting for two major objectives: (1) assessing and validating the UPD models and (2) generating and testing hypotheses about physical UPD. Due to the current COVID-19 pandemic, performing in-person user studies can be a major challenge for VR researchers. Thus, simulation-based evaluations can be an interesting alternative means

to assess and validate scientific research questions as they do not require researchers to perform experiments with real users. In our contribution, we used a simulation to compare generated UPD with ground-truth data from an experiment with real users. Results from simulation showed that it is possible to generate similar UPD behavior observed with real data. However, one main challenge about simulation-based evaluations is to reproduce virtual trajectories that resemble a real user's movements while navigating. We suggest that future work should consider how to add variability from the input (trajectories and movements performed by the agents) to the output (variability in the models).

Moreover, the simulation framework could be extended and generalized in order to perform more simulations. For instance, one solution would be to use existing datasets from other studies, analyzing their UPD, creating new UPD characterizations, and assessing them through simulation. Then, the simulation framework would enable the reproduction of user studies just by reproducing the experimental protocols used in the experiments. Still, in-person user studies would be required in future works to gather new datasets about users' behavior when performing different tasks with different navigation techniques.

6.5.4 Reducing UPD During Steering Navigation

Drift from the center of the workspace may increase over time and distance traveled in the VE. Then, compensating its effect during steering navigation could be an interesting option in order to keep the user the closest to the center of the workspace. What could be the navigation methods which could decrease UPD? To answer that question, we may take inspiration from existing redirection techniques used while walking. One approach could be to use existing solutions such as the freeze-and-turn resetting ([Williams et al. 2007](#); [Cirio et al. 2009](#)) or providing visual or auditory warning feedback to the user. Although these solutions are easy to implement, they may decrease the sense of presence.

Subtle approaches could also be considered. A lot of research work addressed the potential use of gains to redirect users with navigation technique ([Rietzler et al. 2018a](#); [Congdon and Steed 2019](#)). So far, few works considered reducing UPD with walking by scaling up translation gains based on the discrepancies between real and virtual movements ([Montano-Murillo et al. 2019](#)) or gesture-based techniques ([Nilsson et al. 2014a](#)) trying to optimize legs movements that could reduce drifting forward while using WIP. Using gains with steering techniques could be possible as well. In the example of the slalom task, we noticed that UPD depends on the direction of the turn and the amplitude of body movement. Then, one approach could be to reduce this amplitude in order to reduce UPD. By applying a constant rotational gain on the

virtual camera, we could either decrease (if gains > 1) or even increase (if gain < 1) the user's amplitude, resulting in an eventual different UPD. Other types of gains could be considered such as translation ([Interrante et al. 2007](#)), curvature ([Grechkin et al. 2016](#); [Bölling et al. 2019](#)) or even displacement gains ([Steinicke et al. 2009](#)) that could be adapted to steering.

These suggestions remain hypothetical since we do not know the effect of rotational gains on UPD, and also require prior knowledge of the navigation task. Still, the use of gains could be promising to control participant orientation in the workspace and find new heuristics that could minimize UPD during steering navigation, and consequently reduce workspace required to navigate, as already studied for redirected walking ([Messinger et al. 2019](#); [Azmandian et al. 2015](#)).

6.5.5 Perspectives

The analysis of UPD in this chapter provided interesting effects and insights into how users drift while using virtual steering techniques, with practical implications for different applications and potential vistas for future work to compensate for UPD. However, there are also a few limitations of our current work, which may lead to additional research ideas that may be investigated in future work. To improve knowledge about UPD, further analyses should be done using different navigation tasks. For instance, it could be interesting to study the eventual link between UPD and other factors such as the sense of presence or cognitive load ([Bruder et al. 2015](#)) as they might influence UPD. In addition, other approaches (e.g. machine-learning-based, using other metrics) for modeling UPD should be considered to improve the existing models. The simulation-based analysis could enable to have insights about UPD by performing fewer user studies. We intend to improve the simulation framework, by including a more flexible architecture that can be extended by VR practitioners, so that it could become in the future a testbed for studying UPD in VEs. Regarding the use of gains to compensate UPD, future work is required to study the effects of gains on UPD so that they can be used with steering techniques.

6.6 Conclusion

The analysis of UPD in the literature remains scarce, yet, the practical implications of UPD are diverse, from the breaks of presence that require reset mechanisms and potentially dangerous situations that would result from reaching the boundaries of the workspace. This chapter has proposed a first characterization of the user's UPD while navigating in virtual

environments. This characterization, in addition to shedding insight into this phenomenon, aims to enable the simulation of the user's behavior to assess and potentially propose UPD correction methods. Thus, a simulation framework was presented, first to provide a proof of concept of how such a system should be conceived, but also to provide experimental validation of the proposed characterizations. The simulation results showed that the simulation framework was able to reproduce UPD from real user data. However, this is only a first step towards the precise characterization of the UPD, as several limitations remain, such as the generalization to other navigation tasks, the consideration of other drift predictors, and the personalization of UPD models to account for user variability. This work opens new perspectives about understanding UPD that could become a key component when designing new navigation techniques, as its aftereffects are still unexplored. We believe that the simulation framework could be an efficient tool in order to explore UPD mitigation strategies paving the way for novel navigation techniques able to efficiently reduce the UPD without impacting the users' experience.

Conclusion

In this part, we first showed a study of the impact of the navigation technique (walking versus steering versus passive motion) on users' gaze and body segments coordination during curvilinear trajectories in VEs chapter 4. We demonstrated that there was a similar ordered top-down sequence of reorientation of the gaze, head, and shoulders during curved trajectories between walking in REs and VEs (for all the evaluated techniques). However, the anticipation mechanism was significantly higher for the walking condition compared to the others.

Then, we investigated the influence of the control law in virtual steering techniques, and in particular the speed update, on users' behavior while navigating in virtual environments chapter 5. The results show that users' trajectories and behaviors were significantly affected by the shape of the trajectory but also by the control law. In particular, users' angular velocity was higher with constant and linear laws compared to the adaptive law.

Finally, in chapter 6 we noticed that during navigation in VEs with virtual steering techniques, users might unintentionally move in the physical workspace while navigating, resulting in Unintended Positional Drift (UPD). We characterized and analyzed the UPD with our dataset, gathered from the previous experiment, containing the positions and orientations of eighteen users performing a virtual slalom task using virtual steering techniques. We analyzed the performed motions and proposed two UPD models: the first based on linear regression analysis and the second based on a Gaussian Mixture Model (GMM) analysis. Then, we assessed both models through a simulation-based evaluation where we reproduced the same navigation task using virtual agents. Our results indicate the feasibility of using simulation-based evaluations to study UPD.

All together, these results contribute to the understanding of how navigation techniques, and in particular spatial steering ones, can influence users' movements during locomotion tasks in terms of body segment coordination, kinematics, and unintended positional drift during goal-directed navigation tasks involving curvilinear trajectories.

PART III

Altering Perception of Rotation Gains in Virtual Environments

Introduction

This part details the second research axis of the manuscript in which we investigated how the perception of rotation gains can be altered in VR (Figure 6.10). Perception of rotation gains has been widely studied in VR, but we noticed that some experimental conditions have not been assessed yet.

We present two psychophysical studies that have been published in two research papers. The first one entitled « Influence of Dynamic Field of View Restrictions on Rotation Gain Perception in Virtual Environments » is a conference paper presented at the International Conference on Virtual Reality and Augmented Reality (EUROVR20) that investigated the impact of vignetting (i.e. its shape or visual effect) on the perception of rotation gains.

The second contribution, « Studying the Influence of Translational and Rotational Motion on the Perception of Rotation Gains in Virtual Environments » has been accepted to the Symposium on Spatial User Interaction (SUI '21) and will be presented in November. It assessed the impact of the presence or absence of virtual translational motion, as well as the rotational motion (i.e. at which angular speed users rotate) on the perception of rotation gains but also on users' movements and in particular the gaze activity.

These results contribute to the understanding of human perception in VR (in particular perception of rotations) and provide guidelines about the design and improvements of rotations gains in VR.

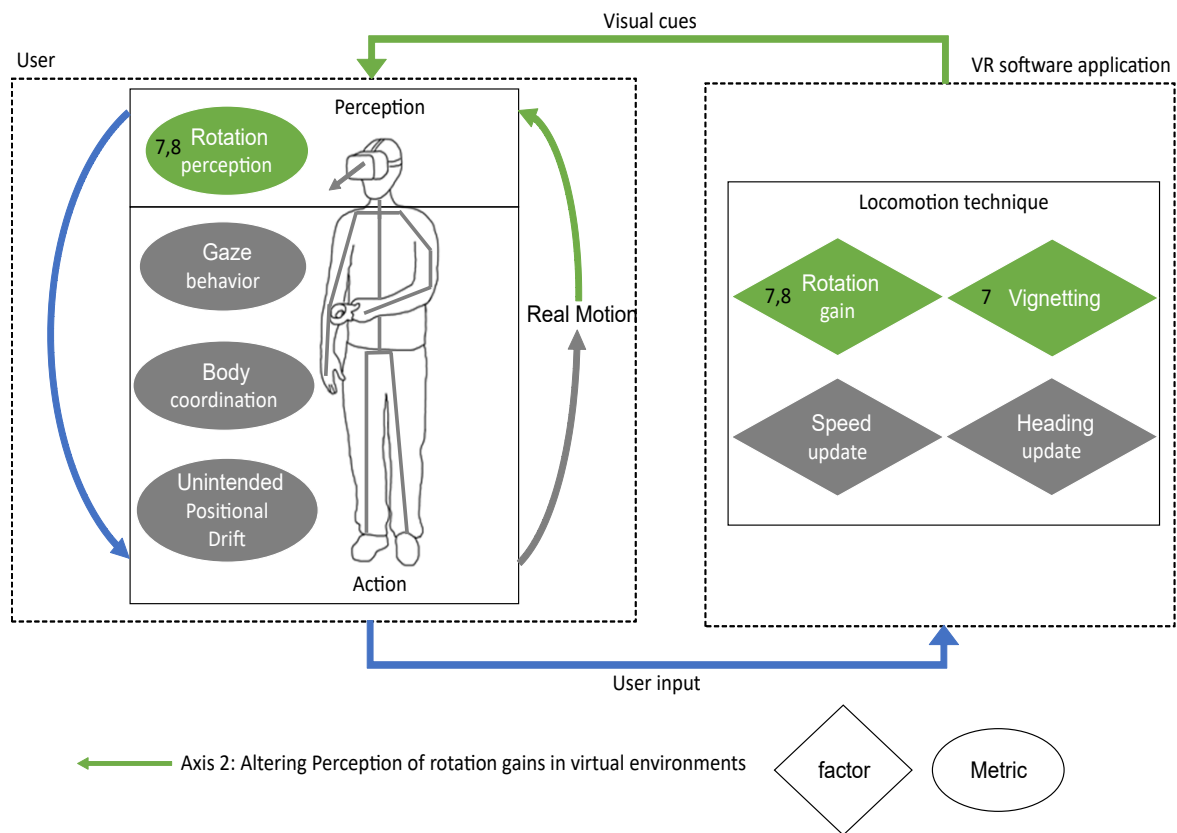


Figure 6.10 – Factors (green rhombuses) and metrics (green ellipses) studies in this part. The number referred to the chapter where the factors and metrics were investigated.

« It's one thing to question your mind; it's another to question your eyes and ears. But, then again, isn't it all the same? Are our senses just mediocre inputs to our brain? Sure, we rely on them, trust they accurately portray the real world around us, but what if the haunting truth is they can't? That what we perceive isn't the real world at all, but just our mind's best guess? That all we really have is a garbled reality, a truly fuzzy picture we will never make out? »

Mr. Robot, S2E12

7

Influence of Dynamic Field of View Restrictions on Rotation Gain Perception in Virtual Environments

7.1 Motivations

Redirection techniques rely on detection thresholds (DTs) gains, which define the limit the user can detect or not the rotation gain. Numerous studies have been done to estimate the DTs of different types of gains such as rotation ([Steinicke et al. 2010](#); [Jerald et al. 2008](#); [Bruder et al. 2009](#)), translation ([Neth et al. 2012](#); [Nguyen et al. 2017](#); [Hopper et al. 2019](#)) or curvature gains ([Steinicke et al. 2010](#); [Bölling et al. 2019](#)). In this chapter, we will only focus on rotation gains. Imperceptibility of rotation gains for redirected walking implementations is a challenge and an active topic of research in VR. When using rotation gains, VR designers have to be careful in their implementations of redirection techniques: they have to use gains that would be subtle enough in order to not disturb users experience (high gains might be noticeable or make the navigation more difficult) and comfort (high gains may provoke more cybersickness). While the

research focused on how to increase the DTs without breaking presence, it is also important to consider the usability and factors that could influence the perception of rotation gains.

For instance, modern HMDs, such as the HTC Vive or the Oculus Rift, offer Field of Views (FoVs) up to 100 degrees. Recent work conducted with these HMDs has shown that FoV can alter motion perception (Nilsson et al. 2014b; Jones et al. 2013). However, related studies mostly focused on visually induced illusory self-motion known asvection (Riecke et al. 2006; Riecke et al. 2005b). Little is known about the relation between the FoV and the perception of rotations gains in VEs. Some recent work showed differences between large and narrow FoV (Williams and Peck 2019) on DTs, but no one explored the impact of dynamic FoV modifications on the perception of rotation gains. Such results could be important for VR developers to design new redirection techniques considering FoV restrictions for a wide audience since the FoVs vary between HMDs.

In this chapter, we present a perceptual study assessing participants' ability to discriminate changes between virtual and real rotations under different FoV restrictions, hereinafter referred as vignetting. Participants had to perform rotations in a virtual forest with different vignetting configurations (see Figure 7.1). Two factors were considered, the shape of the restriction (horizontal, global) and the visual effect (darkening and blur). We evaluated the participants' perception of rotation gains by computing the Point of Subjective Equality (PSE) and the DTs for each condition. Our main hypothesis was that vignetting could reduce participants' ability to determine whether a rotation gain was applied or not, therefore increasing the DTs. Our results contribute to the understanding of human perception in VEs and discuss the usability of vignetting for redirection techniques.

7.2 Dynamic Field of View Restrictions Design

7.2.1 Description

In our experiment, we wanted to investigate the effect of several FoV restriction types. To design each vignetting, we followed models already designed to dynamically modify the FoV with respect to users' head angular speed (Bolas et al. 2017; Norouzi et al. 2018), but we adapted them in order to propose a generic vignetting model that allows any type of FoV restrictions and visual effects. Two different design choices were considered: (1) the restriction shape (i.e. the area of the FoV which is affected by the vignetting) ; (2) the effect type (i.e. the visual effect applied to the restricted area).

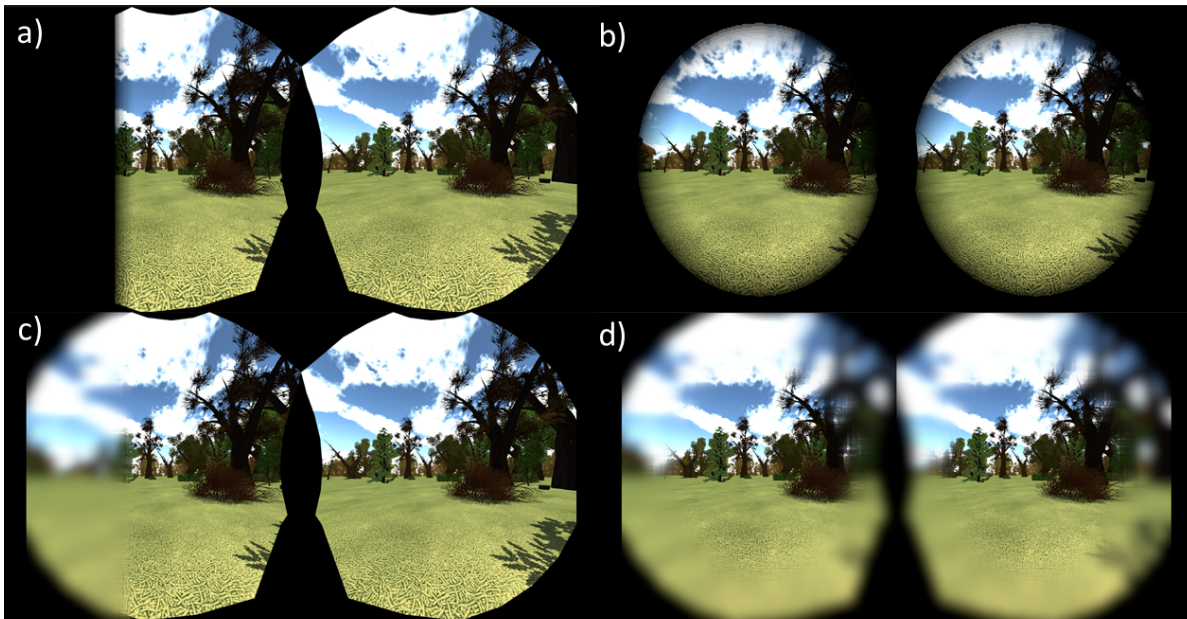


Figure 7.1 – Illustration of the 4 different FoV restrictions (vignetting) during the same rightwards rotation: (a) Horizontal Luminance ; (b) Global Luminance ; (c) Horizontal Blur ; (d) Global Blur.

Regarding the restriction shape, most studies used a circular restriction (an annulus defined by an inner and outer circle, hereafter referred as **Global** vignetting). In this contribution, we also propose an **Horizontal** vignetting that reduces the user's FoV to the opposite head rotation direction. The horizontal mode is inspired by the human anticipation behaviors in REs in which gaze will anticipate the head rotation during a turn (Bernardin et al. 2012). Therefore, the Horizontal vignetting only hides the peripheral vision to the opposition gaze direction. The motivation to design this Horizontal vignetting is to reduce the amount of information and is more subtle than the Global one since the restriction is not applied in both eyes.

Regarding the effect type, we considered two methods that reduce the optical flow in the restricted area. A **Luminance** effect which decreases the contrast in the restricted area and a gaussian **Blur** effect which decreases visual saliency in the restricted area. While the Luminance effect is the most widely used in VR applications using vignetting, we wanted to see whether Blur could provide similar perceptual results while less disturbing. This resulted in 4 different configurations: *Global Luminance*, *Global Blur*, *Horizontal Luminance* and *Horizontal Blur* (see Figure 7.1).

7.2.2 Implementation Details

Given a pixel position p in normalized screen coordinates and the current restriction angle (R_t), we first define whether the pixel falls within the restriction area:

$$Shape(p, R_t) \in [0, 1] \quad (7.1)$$

Zero means that the pixel is outside the restriction zone, one that the pixel is in the restriction zone and $]0, 1[$ is the transition zone. R_t is defined by the yaw head rotation w and Equation 7.1 has to be defined both for the Global, and the Horizontal restriction shapes.

The amount of restriction, R_t , is calculated using Equation 7.2 where α_{max} and α_{min} respectively represent the maximum and minimum values to apply the restriction. When $R_t(\omega) = \alpha_{max}$ there is no restriction applied, and when $R_t(\omega) = \alpha_{min}$ the restriction is maximal. Users FoV is reduced as ω increases.

$$R_t(\omega) = \alpha_{max} - Min(\omega, \alpha_{max} - \alpha_{min}) \quad (7.2)$$

In our model, α_{max} and α_{min} were respectively set to 56 and 18 degrees for the Horizontal restriction and 64 and 30 for the Global restriction. α_{max} was defined considering the HMD used in the study (HTC Vive), while α_{min} was defined empirically. For the Global restriction, the minimum FoV was 60 ($\alpha_{min} \times 2$) while for the Horizontal restriction the minimum horizontal FoV was 74 degrees (asymmetric).

To decrease jitter for the head rotations speed, a hysteresis was applied based on the instantaneous head rotation speed (ω_t). We empirically found that $\gamma = 0.4$ worked best to ensure that the FoV restriction would not jitter due to small head movements.

$$\omega = \gamma * \omega_t \quad (7.3)$$

Then, the cut-off is defined by an inner and outer radius that together form an annulus for the Global type and a rectangle for the Horizontal one. The opacity of the cut-off increases linearly from completely transparent to completely opaque (mask). The mask is calculated using Equation 7.4, while $angle(p)$ defines the viewing angle of the pixel p , and $\epsilon_\alpha = 10$ defines the transition zone.

$$Shape(p, R_t) = \frac{R_t - angle(p)}{\epsilon_\alpha} \in [0, 1] \quad (7.4)$$

Finally, we apply the restriction effect to the pixel, where $Shape(p, R_t)$ defines the strength

of the applied effect. The color of the pixel p in normalized screen coordinates is computed as the linear interpolation between the pixel color and the visual effect (i.e. either the black color for the Luminance effect or the result of the gaussian blur for the Blur one) where the interpolant is the result of $Shape(p, R_t)$.

7.3 User Study

The goal of this experiment was to investigate the effect of vignetting on the detection threshold of amplified head rotations. We considered the previously defined vignetting types and effects. This experiment was inspired by a similar protocol already performed to assess the perception of rotation gains without (Steinicke et al. 2010) or with FoV restriction (Williams and Peck 2019).

7.3.1 Design and Hypotheses

We conducted a 3 (**Vignetting Type**: none, horizontal, global) x 2 (**Vignetting Effect**: luminance, blur) x 2 (**Rotation**: 60°, 90°) user study to estimate the perception threshold depending on the FoV restrictions. Vignetting Type and Rotation were within-participants factors whereas Vignetting Effect was a between-participant factor. We decided to test two different rotations because most of the studies only assessed 90° turns, and Bruder et al. showed that perception of rotation gains can differ depending on the amount of rotation performed (Bruder et al. 2009). Besides, in navigation, shorter rotations than 90° can occur and it is important to understand how participants could perceive gains during a shorter exposition.

For each Vignetting Type and Rotation, we tested 9 times each gain used in the experiment. The gains used in the experiment ranged from 1 (90° physical rotation resulted in a 90° virtual rotation) to 1.4 (54° physical rotation resulted in a 90° virtual rotation), incremented in steps of 0.1. We only applied gain on the yaw axis. Excluding practice session, this resulted in 3 vignetting x 2 rotations x 5 gains x 9 trials, totaling 270 trials per participant. The trials were randomized per block for each participant.

Note that, unlike similar protocols (Steinicke et al. 2010; Bruder et al. 2009; Williams and Peck 2019), we did not assess gains below than 1. These gains were not tested because our interest was to assess whether FOV manipulations could provide a higher gains perception threshold. The task trials were stimuli (gain applied) two-alternative forced-choice (2AFC) tasks. 2AFC tasks avoid participant response bias as participants are forced to guess even when they

are unsure of virtual head amplification. On average, when participants do not know the answer, if participants answer randomly, they will be correct 50% of the time. Our hypotheses for this experiment were:

- [H1] Detection thresholds would be higher when applying vignetting.
- [H2] Detection thresholds would differ depending on the vignetting effect.
- [H3] Detection thresholds would be higher for the 60° turn than the 90° one.
- [H4] Users would report no discomfort while using the FoV vignetting.

These hypotheses were motivated by our suggestions that vignetting could alter participants' perception and therefore allow to add more imperceptible rotational gains. It means that we want to determine whether dynamic modification of FoV with different effects or restrictions could influence the way users perceive rotation with or without head amplifications.

7.3.2 Participants and Apparatus

24 participants (18 males and 6 females) aged between 22 and 37 years old (26.67 ± 3.62 , mean \pm SD) without any ocular or locomotion disorders volunteered to this study. 14 participants reported using VR on a weekly or daily basis, 6 few times and 4 never. All participants except 4 had regular experiences with videos games. They were naive to the purpose of the experiment and signed an informed consent form. The study was conformed with the standards of the declaration of Helsinki.

We developed the application with Unity3D and we use a Vive Pro HMD, that has a resolution of 1440 x 1600 pixels per eye and a 110 degrees diagonal FoV. The reference coordinate system was defined by the HTC Vive tracking system. During the whole experiment, we guaranteed the maximum frame rate of the HTC Vive HMD (90Hz). We use the Vive Wireless Adapter¹ in order to prevent users from being bothered by cables, as it could potentially influence users behavior during their rotations.

The VE was a large outdoor forest with grass, trees, and rocks. We designed it with the Green Forest Unity 3D asset². This VE was chosen to generate motion flow from participants' while physically rotating. We also added a black cross located on the ground and a virtual sphere for calibration purposes.

1. <https://www.vive.com/eu/accessory/wireless-adapter/>

2. <https://assetstore.unity.com/packages/3d/environments/fantasy/green-forest-22762>

7.3.3 Procedure

First, participants read and signed the consent form which provided detailed information regarding the experiment. They had a training session to get familiar with the task, the rotation gains, and the different vignetting conditions. Then, the experiment consisted of 9 randomized blocks, 3 for each vignetting (none, horizontal, global). Each block consisted of 30 trials (3 trials x 5 gains x 2 rotations), with a break after every 3 blocks were completed. The experiment, therefore, resulted in a total of 270 trials (9 repetitions x 3 vignetting type x 5 gains x 2 rotations) per participant. At the beginning and the end of the experiment, participants filled a Simulator Sickness Questionnaire (SSQ) ([Kennedy et al. 1993](#)). After filling the first demographic questionnaire (age, gender, amount of experience playing video games and exposure to VR), we assessed their dominant eye and measure their interpupillary distance (IPD). Then, they were placed at the center of the physical workspace and were equipped with the HMD and the controller.

A trial consisted of rotating the whole body in place (not just the head or the torso but also the feet) either 60 or 90° clockwise or counterclockwise. We randomly ordered clockwise and counter-clockwise rotations during the experiment. Participants could visualize the turn to perform thanks to an arrow indicating the rotation direction. Before starting the trial, they had to calibrate by looking at a red sphere that was displayed in front of them. Once they were staring at it, the sphere turned green and participants could press the controller's trigger to start the trial. Then, participants rotated until a red sphere appeared at the center of their vision, signaling that they should end their rotation by facing at this sphere until it turned green indicating successful trial completion. Participants had to confirm the trial by pressing the controller's trigger. If the participant rotated past the virtual rotation, the green sphere's color changed to red, and participants had to correct and maintain their orientation such that the sphere changed to blue-green. At the end of the trial, the VE faded to black and participants had to answer the following 2AFC question: "My movement in the virtual world was greater than my physical movement: (yes or no answer)".

To prevent unintentional positional drift during the experiment, we ensure that the user started each trial around 50cm to the center of the physical workspace, if the participants were not located nearby, they had to move towards a black cross displayed on the VE floor. Trials where the participants turned too quickly, slowly, or inconsistently were rejected. For speed, participants were required to turn physically at between 45 and 180 degrees per second averaged across the entire turn. Trials were tested to ensure participants did not turn against the desired direction of motion. If a turn had failed, the trial would have been rejected and the 2AFC question would

have been skipped and the participant got feedback about the failure.

After a block of 30 trials, we asked participants to answer the following question « On a scale of 0-10, 0 being how you felt coming in, 10 is that you want to stop, where are you now? » (Rebenitsch and Owen 2014). This question ensured that participants did not feel severe sickness during the experiment, since doing a series of rotations with gains could lead to cybersickness. After every three blocks, the users took off the VR equipment and had a 5-minute break to minimize the potential negative effects of cybersickness.

At the end of the experiment, we asked participants to rate the comfort of each Vignetting Type to perform the task from 1 (not comfortable at all) to 7 (very comfortable). We also asked them to rank the Vignetting Type by their preferences (the one they preferred the most ranked 1st and the one they least preferred ranked 3rd). In total, the experiment took approximately an hour. At any time, users could ask for a break or stop the experiment.

7.3.4 Data Analysis

We recorded 6 480 trials (24 users x 2 Vignetting Effects x 3 Vignetting Types x 5 Gains x 9 Repetitions) during this experiment. Practice trials before the experiment and between blocks were not included in the analysis. Preliminary data analysis revealed that there were no side effects between leftwards and rightwards rotations. We, therefore, mirrored the leftwards turns in order to remove the side factor from the analysis.

We computed for each participant the probability $P(g_n; \text{yes})$ of responding “Yes” for a given gain to the question “My movement in the virtual world was greater than my physical movement”, for each gain, turn and vignetting type. Then, a psychometric curve was fit to each participant’s data, and the Point of Subjective Equality (PSE), 25% and 75% threshold gains were computed with the Quickpsy package in R (Linares and Lopez-Moliner 2016). It fits by direct maximization of the likelihood psychometric functions of the form $\psi(g_n) = \gamma + (1 - \gamma) * F(x)$, where γ is the guess rate and F the cumulative normal distribution function. We excluded 4 participants from the analysis because we were unable to fit a psychometric curve from their data (they mostly never answered “yes”).

Before analyzing the positions and orientations of head and shoulders, we first resampled them and then applied a Butterworth low-pass filter with a cutoff frequency of 1 Hz to remove oscillations due to the potential users’ displacements in the RE. We temporally normalized the evolution angular speed over the trials in order to analyze rotation behavior regarding the experimental conditions. We used the Statistical Parametric Mapping (SPM) method (Friston et al. 2007) to analyze the angular speed across the experimental conditions. This analysis allows

comparing time-series data of different trials taking into account their variability at each time step. In order to evaluate the effect of the Vignetting Effect, Vignetting Type, Rotation on PSEs and DTs, we performed a three-way analysis of variance (ANOVA) with repeated measures. We tested the normal distribution of the data with the Shapiro-Wilk test. Greenhouse-Geisser adjustments to the degrees of freedom were applied, when appropriate, to avoid any violation of the sphericity assumption. Post-hoc analysis was based on pairwise t-tests with Bonferroni corrections. Only significant post-hoc comparisons are reported in the next section. Finally, to analyze subjective data from the questionnaires, we used the Friedman test and post-hoc pairwise Wilcoxon tests with Bonferroni corrections.

7.3.5 Results

We found no significant effect of the vignetting type or gain on the evolution of the angular speed during a trial ($p > 0.05$). This means that participants' rotation behavior remained similar across experimental conditions and trials (Figure 7.2). Besides, we noticed no effect of SSQ scores between the luminance and blur effects, and no fast SSQ average answers remained below 3 for each block during the experiment. These results are important for a fair comparison of DTs since the way participants perform the rotation and cybersickness could alter the perception of the rotation gains.

Psychometric curves were fit to the pooled results of participants' data by Vignetting type, Vignetting Effect, and Rotation (Figure 7.3). Table 7.1 summarizes the PSEs and DTs computed for each experimental condition based on participants' individual fits. We compared $P(g_n; \text{yes})$, the probability of responding "yes" at a given gain g_n , with a 4-way ANOVA (Vignetting Type x Vignetting Effect x Rotation x Gain). There was a significant main effect of Gain ($F(2.32, 51.05) = 177.68, p < .0001, \eta^2 = .89$), where post-hoc analyses showed that the higher the gain, the higher the probability of answer "greater" ($p < 0.05$).

To evaluate the effect of experimental conditions on PSEs, we performed a 3-way ANOVA (Vignetting Type x Vignetting Effect x Rotation). We found a significant effect of the Vignetting Type on the PSEs ($F(1.90, 30) = 3.99, p < 0.05, \eta^2 = .20$) and DTs ($F(1.45, 23.25) = 8.11, p < 0.01, \eta^2 = .34$), where post-hoc analyses showed that PSEs and DTs were higher with the Global vignetting than the baseline one (None). We found neither effect of Vignetting Effect ($p = 0.41$) nor Rotation ($p = 0.13$) on the PSEs and DTs.

A 2-way (Vignetting Type x Vignetting Effect) ANOVA showed an effect of the Vignetting Type on comfort ($F(1.30, 20.74) = 5.00, p < 0.05, \eta^2 = .24$), where Global vignetting was less comfortable than the None and the Horizontal ones ($p < 0.05$). Figure 7.4 shows the number

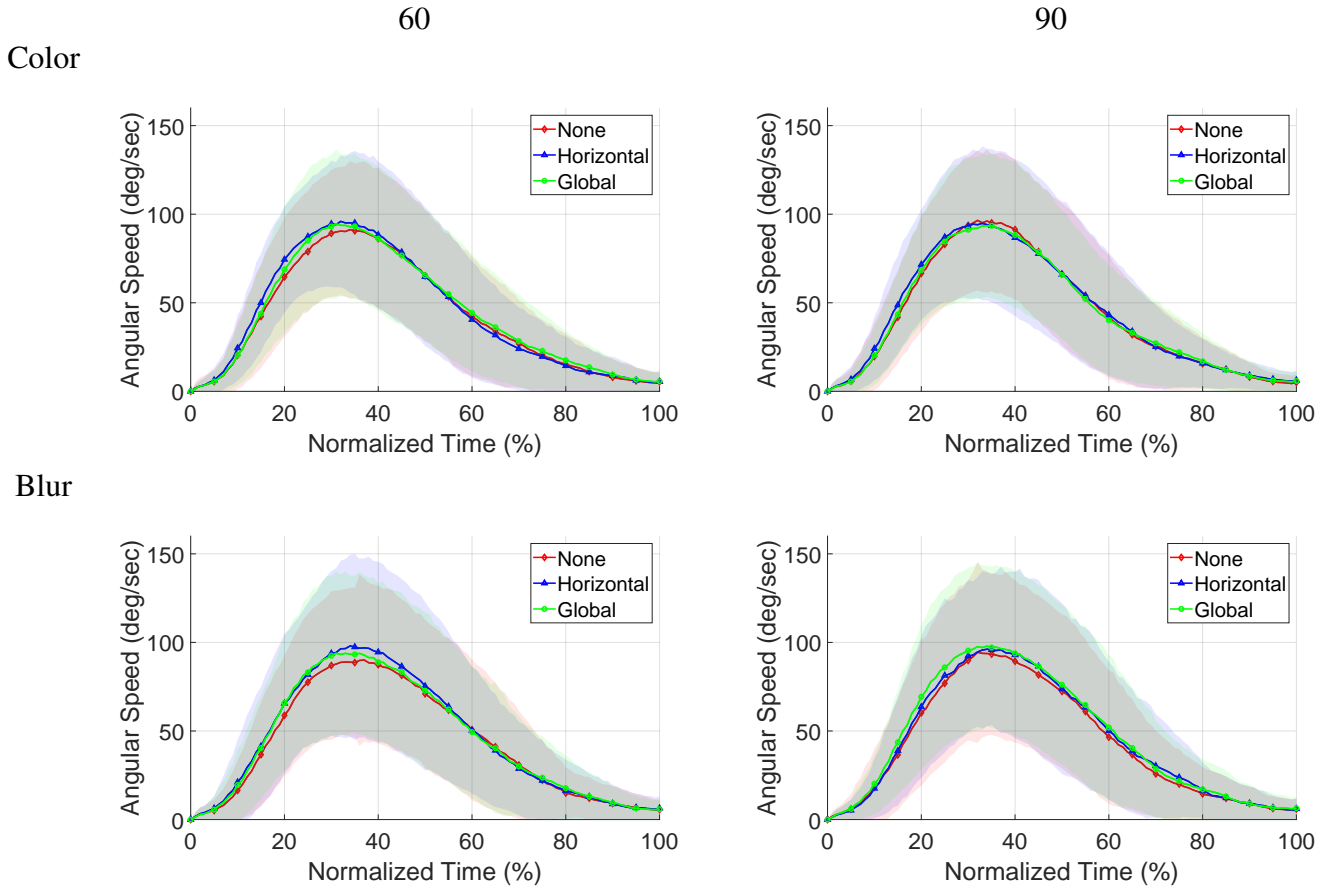


Figure 7.2 – This figure shows the typical temporal evolution of mean and standard deviation of angular speed for each Vignetting type (None in red, Horizontal in blue and Global in green), Vignetting Effect (Color on the first row and Blur on the second) during 60° and 90° turns. Each sample of the temporal sequence is a dependent variable. No effect was found across the conditions.

of votes regarding vignetting type preferences (the most preferred ranked 1st and the least preferred ranked 3rd). A chi-square test showed that the Vignetting Effects were not independent ($\chi^2(8) = 18.595, p < 0.05$). Overall, participants ranked the baseline (None, no vignetting) as the most preferred than the Horizontal and finally the Global.

7.4 Discussion

Our main objective was to assess whether vignetting (either its type or its effect) could alter the perception of rotation gains in virtual environments. More precisely, we designed an experiment where participants had to perform 60 or 90 degrees turns where we applied

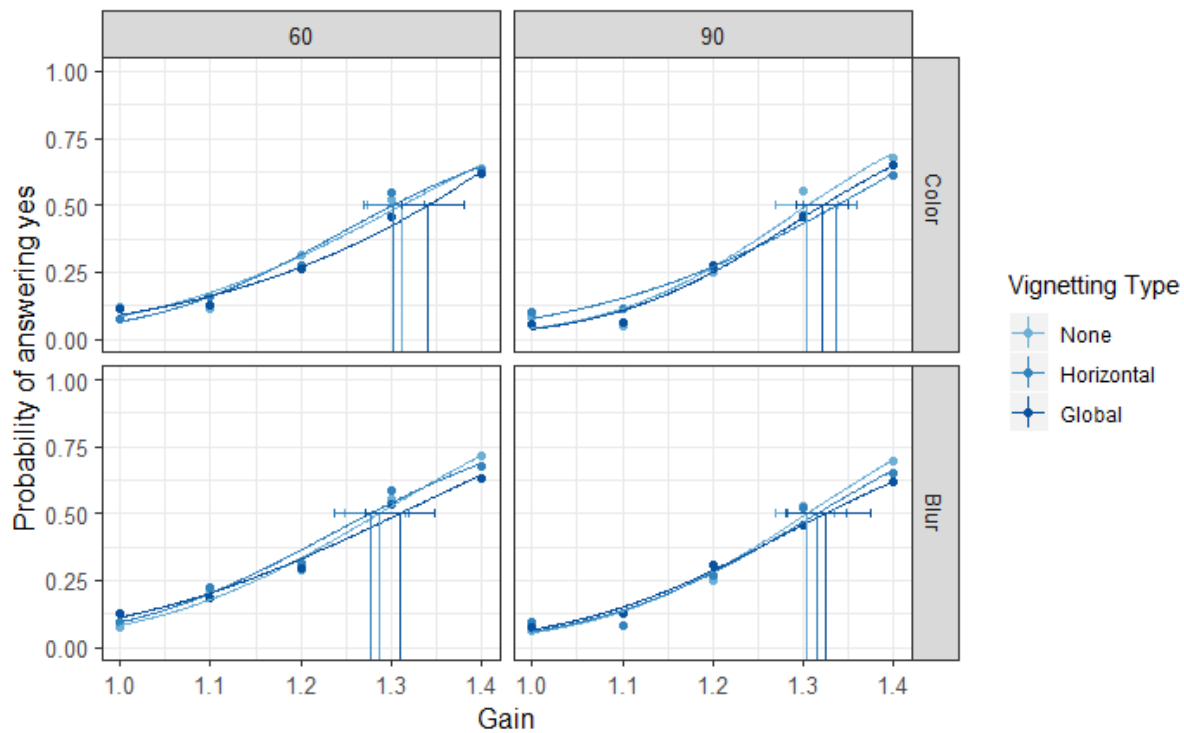


Figure 7.3 – Psychometric functions computed from the pooled results for each Vignetting Type (None in red, Horizontal in green, Global in blue). The x-axis shows the gain applied and the y-axis the probability of answering "yes" to the question "My movement in the virtual world was greater than my physical movement". Results are grouped by Rotation (60,90) and Vignetting Effect (Color, Blur).

Table 7.1 – The 25%, PSE, and 75% threshold gains derived from the psychometric curves. Results are grouped by Vignetting Effect, Type and Rotation.

Effect	Type	Rotation					
		60		90			
		25%	PSE	75%	25%	PSE	75%
Color	None	1.13(0.11)	1.23(0.10)	1.32(0.11)	1.15(0.05)	1.24(0.05)	1.33(0.06)
Blur	None	1.11(0.08)	1.20(0.07)	1.29(0.06)	1.15(0.11)	1.22(0.08)	1.30(0.07)
Color	Horizontal	1.13(0.13)	1.23(0.08)	1.32(0.09)	1.12(0.08)	1.25(0.04)	1.40(0.09)
	Global	1.13(0.06)	1.25(0.08)	1.38(0.12)	1.16(0.07)	1.26(0.06)	1.35(0.08)
Blur	Horizontal	1.10(0.10)	1.20(0.09)	1.29(0.07)	1.13(0.08)	1.24(0.05)	1.35(0.07)
	Global	1.08(0.11)	1.20(0.07)	1.35(0.06)	1.12(0.12)	1.24(0.07)	1.33(0.07)

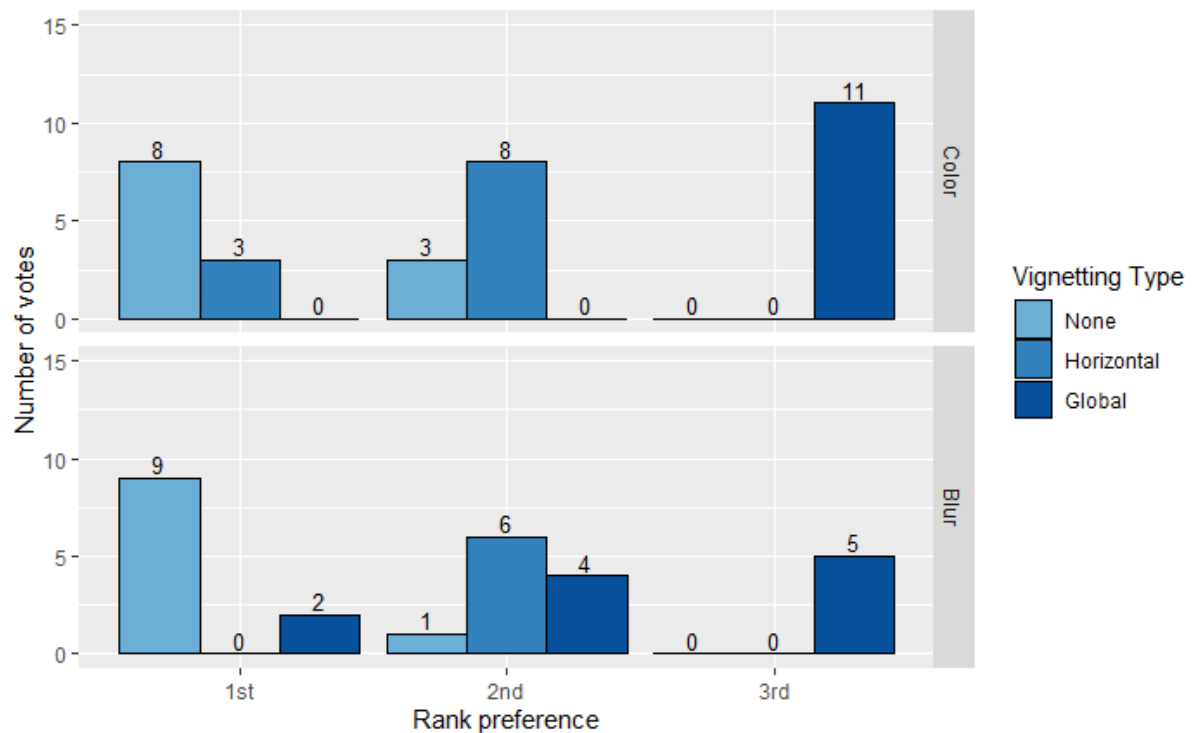


Figure 7.4 – Distribution of participants vignetting preferences (grouped by Vignetting Effect). At the end of the experiment, we asked participants to rank from their most to their least preferred vignetting.

different rotation gains (from 1 to 1.4) and vignetting (None, Horizontal, Global). We analyzed participants' ability to detect or not the gains by computing their PSEs and DTs. While we observed an effect of the Vignetting Type on the PSEs variable of the experiment, our results showed that the average values remain similar.

Regarding **[H1]**, we were expecting that restricting the participants' FoV by applying a vignetting would make the detection of rotation gains more difficult, resulting in higher PSEs and DTs. This hypothesis was motivated by the fact that peripheral vision could help to disambiguate the perception of self motion (Lappe et al. 1999). We extended this statement by supposing peripheral vision could also help to detect or not a rotation gain. We wanted therefore to check how users would be able to determine a rotation gain with less information on the VE. Even though we found an effect of the Vignetting Type on the PSEs and DTs, Table 7.1 shows that the average PSEs per condition remained quite similar (around 1.20 and 1.26). We guaranteed in our vignetting model that the amount of restriction between the Horizontal and Global was similar, but the restricted regions were different. Restricting both eyes (Global vignetting) seemed to be

more efficient for disturbing the detection of rotation gains than restricting the eye opposite to the participant's rotation (Horizontal vignetting). One explanation could be that, during the rotation, the eyes were staring at the opposite direction of the region where the Horizontal vignetting was applied, while the Global one also covered the peripheral region opposite to the rotation's direction. Then, Global vignetting tended to be more efficient in disturbing the detection of rotation gains than the others conditions.

In our experiment, we had the Vignetting Effect as a between-group variable. Half of the participants tested the Luminance effect and the other half the Blur one. We wanted to see whether different visual effects could alter the perception of gains, as it was demonstrated that they can alter users' self-motion perception (Bruder et al. 2012a). We did not see differences between both effects, rejecting [H2]. While most of the vignetting effects used in VR applications are based on a black texture decreasing the contrast in the restricted area, we wanted to see whether a blurring effect, that could be less noticeable to the user, could provide similar or higher PSEs and DTs. Finally, our experiment showed that both visual effects were similar. We could therefore consider different effects with respect to users' preferences.

While most studies on the perception of rotation gains considered mainly 90° rotations, we wanted to see if the detection of rotation gains could be more difficult with a shorter rotation (60° in our experiment). With [H3], we expected differences in PSEs and DTs between both turns. Bruder et al. showed that participants were better at discriminating rotations when the virtual turning angle is rather large (Bruder et al. 2009). Even though we did not find a significant effect of Rotation on PSEs and DTs, Figure 7.3 shows that, for 60° turns, the PSEs for the Global Vignetting Type is higher than the two others for both Vignetting Effects (the blue curve is slightly shifted to the right compared to the others). Thus, the use of vignetting and rotation gains might be interesting to manipulate user rotations during shorter rotations than 90°.

Subjective questionnaires showed that users preferred to perform the rotation task without vignetting. While some research work showed the benefits of vignetting to reduce cybersickness (Fernandes and Feiner 2016), participants did not prefer the use of vignetting to perform navigation tasks (Sargunam and Ragan 2018; Norouzi et al. 2018). Thus, it is hard to determine the benefits of vignetting regarding user preferences and we believe that vignetting based on head movements is not appropriate for all users in VR. For instance, all participants that reported using VR on a weekly or daily basis noticed both vignetting effects, while the participants that experienced VR for the first time did not notice them. Besides, most of the "expert" participants did not recommend the vignetting effects, reporting that it was too constraining and uncomfortable. Few of them also reported that they were not affected by the vignetting since they were

focused on the detection task. Thus, it could be interesting to consider the vignetting with respect to the user VR experience. Our results demonstrated the opposite of our hypothesis [H4]. We could have expected that the blurring effect (that mimics the natural blurring in the peripheral vision) would be more comfortable than the luminance one (that hides the peripheral vision). However, the Horizontal vignetting seemed more appreciated by participants than the Global vignetting. One reason could be that it was less noticeable, thus participants were less bothered during the tasks.

The literature notes that during a sensory conflict between visual and vestibular cues, the visual information is predominant on the vestibular and the proprioceptive ones during locomotion. During the task, participants had to compare their perceived virtual rotation with their real rotation. The vignetting restricted information in the peripheral region, generating less visual information than in the baseline condition. Yet, since the rotations asked were constant, the amount of extra-retinal information received by participants remained the same across vignetting conditions (i.e. constant optical flow). Then, we believe that the similar PSEs and DTs across conditions can be explained by three external factors that we could explore in future experiments:

1. **Optic flow** can be used to control heading direction ([Warren Jr et al. 2001](#)) while walking. Research work showed that offsetting the location of the Focus of Expansion (FoE) alters gait behavior, resulting in a walking path that is deviated at in a direction opposite to the FoE ([Warren Jr et al. 2001](#); [Sarre et al. 2008](#)). Besides, asymmetric optic flow can alter the steering behavior, some studies showed that when there is an inconsistency between the speed of two corridors' walls, the chosen trajectory is the one that reduces the difference between those regions (participants drift towards the slower moving wall) ([Kountouriotis et al. 2013](#); [Chou 2005](#)). Thus, manipulation of optic flow could alter the perception of rotation gains. It can be interesting to have a look at these manipulations since optic flow is a major component in the perception of self-motion. Besides, in our experiment, as only rotation was considered, the optic flow was constant for each pixel. Introducing a translation component could help to determine whether the amount of optical flow could disturb the detection of rotational gains or not.
2. **Saccades (and vestibulo-ocular-reflex)** could contribute to the detection of rotation gains. Saccadic suppression of image has been already used to subtly reorient participants in the VE. They take advantage of the inability to detect changes in the location of a target when the change occurs immediately before, during, or shortly after the saccade ([Bridgeman et al. 1975](#)). Bolte and Lappe suggested that participants are more sensitive to scene rotations orthogonal to the saccade than in the same direction of this

saccade (Bolte and Lappe 2015). Sun et al. implemented a redirected walking controller that rotates up to 0.14 degrees/frame the virtual camera when a saccade is detected (Sun et al. 2018b). Moreover, Langbehn et al. assessed the threshold of translation and rotations offset during participants' blinks (Langbehn et al. 2018b). They reported that it is possible to apply a $\pm 5^\circ$ reorientation in the transverse plane along the line of gaze during saccades $> 15^\circ$ (and users tend to fail to detect translations shift from range 4-9 cm). Therefore, it is easier to apply a gain during a saccade than during a fixation. In our experiment, participants had to stare at a sphere at the end of the rotation task. When a gain was applied, the mismatch between the gaze direction and the sphere position in the VE might have been noticeable and therefore have contributed to detect the gain. Recording gaze activity during such an experiment would help to determine whether gaze behavior is different according to the gain.

3. **Proprioception** is an important cue while navigating. In our experiment, participants could have relied on computing the amount of rotation done in RE (with their feet orientation) and check if it matches with the final orientation in the VE. Marlinsky showed that blindfolded people tend to overestimate rotations of lower magnitudes and underestimate those of higher magnitudes (Marlinsky 1999). Besides, they overestimated passive rotations and this estimation was linearly related to the magnitude of turn. Research work showed the importance of neck proprioception in the perception of body orientation and motion (Pettorossi and Schieppati 2014; Panichi et al. 2011). It may be difficult to assess the impact of proprioception because we cannot isolate this factor. We could, for instance, ask participants the amount of physical rotation they performed at each trial and measure the rotation error with and without gain. We could then see whether the proprioception information was prior to the visual one or not.

7.5 Conclusion

In this chapter, we proposed to study the impact of different vignetting implementations on the perception of rotation gains during virtual turns in VE. The results of our experiment showed a difference of the Vignetting Type on the PSEs and DTs, but no effect for the Vignetting Effect nor Rotation. Yet, the average PSEs and DTs remained quite similar across the different conditions, and the results of our experiment might suggest that vignetting could not necessarily alter the perception of rotation gains. It is difficult to conclude that our results encourage the use of vignetting in order to increase the gains used in redirected techniques since they allow

an only slight increase of rotation gains while altering users' comfort. Nevertheless, we believe that the use of FoV manipulations could be considered an interesting option for VR applications. Vignetting should therefore be designed with a user-centered approach in order to make it affordable in redirection techniques implementations.

« Jeder sieht die Grenzen seines Gesichtsfeldes als die Grenzen
der Welt an. »

Arthur Schopenhauer

8

Studying the Influence of Translational and Rotational Motion on the Perception of Rotation Gains in Virtual Environments

8.1 Motivations

Detection Thresholds (DTs) are important for implementing redirected walking controllers as they provide insights about the perceptibility of gains as they must be subtle to users. Since rotation gains can be influenced by several factors such as the amount of rotation to perform ([Bruder et al. 2009](#)) or the Field of View ([Williams and Peck 2019](#)), they remain an active topic in VR research. Most of the experiments assessing the perception of rotation gains are based on physical rotations where users could rotate at their desired pace without any virtual translational motion added. Neth et al. showed that users are less sensitive to curvature gains while walking in VR at slower speeds ([Neth et al. 2012](#)). In contrast, little is known about the sensitivity to rotation gains under particular experimental conditions: (1) while varying the rotational speed and (2) in the case of a virtual translation combined with users' rotational motion. In addition, recent studies

have investigated the impact of rotations gains in 360° video-based telepresence systems ([Zhang et al. 2018](#); [Matsumoto et al. 2020](#)). In such systems, the combination of virtual translation of the mobile platform and user rotation in the workspace could occur, but they only investigated separately their impact. Thus, it remains unclear the potential influence of combined virtual translational and rotational motion on the perception of rotation gains.

This chapter presents a perceptual study assessing the perception of rotation gains, in which participants had to discriminate the difference between their virtual and real rotations across several translational and rotational motions. Participants performed physical rotations in a virtual forest with two types of virtual translational motion (with or without) as well as three different rotational motions (20, 30, and 40 degrees per second). We recorded their body movements and gaze activity in order to study the effect of the experimental conditions on users' behavior. We assessed each participant and conditions their gain DTs. Our main hypothesis was that the translational and rotational motions would impact participants' DTs and users' behaviors. The results of this study contribute to the understanding of human perception in VEs and provide insights about potential improvements in redirection techniques controllers, and in particular implementation of rotation gains in VR systems.

8.2 User Study

In this experiment, the goal was to assess the effect of translational and rotational motions on the perception of rotation gains. It was inspired by a similar user study performed to assess the perception of rotation gains without ([Steinicke et al. 2010](#); [Bruder et al. 2009](#)) or with translation ([Neth et al. 2012](#)).

8.2.1 Design and Hypothesis

We conducted a 2 **Translation Speed** (no Translation (nT): 0m/s; with Translation (T): 1.4m/s) x 3 **Rotational Speed** (20°, 30°, 40° per seconds) within-subjects experiment to estimate DTs of rotation gains with or without virtual translation and varying the rotational speed. While most of the previous studies have assessed the perception of rotation gains by turning in place without virtual translation motion, we decided to investigate whether virtual translation could influence the perception of rotation gains, as it has been demonstrated that perception of curvature gain is influenced by the walking speed ([Neth et al. 2012](#)). Moreover, most previous studies did not control the speed at which users performed the rotation. That is why we decided to

control this factor by varying the rotational speed. We wanted to see whether turning faster or slower could influence the perception of rotation gains. The experiment only considered two translational conditions, as they relate to more common cases during VR locomotion, either stop or at comfort locomotion speed. In order to guarantee not too long experiment session, we decided to rather have more rotational speed to assess than translational speed for several reasons. We believed that the rotational speed would have more impact than the translational speed and therefore we wanted to have more values to assess regarding the rotational speed. In addition, since the impact of virtual translation has not been assessed yet, we wanted to first investigate only one translational speed in order to have a first comparison between with or without translational speed.

Six rotational gains ($g \in [0.5, 0.7, 0.9, 1.1, 1.3, 1.5]$) were considered in the experiment. For each combination (translation speed *times* rotation speed *times* gain) we considered four repetitions (two leftwards and two rightwards). Table 8.1 reports the amount of rotations participants had to perform in both real and virtual environments depending on the rotation speed and the gain. Based on our analysis, we hypothesized that translational and rotational speeds could alter participants perception and precisely: **[H1]** adding a virtual translational motion would help users to better discriminate the rotation gains; **[H2]** the slower the rotation speed, the higher the PSE and DTs are; **[H3]** gaze and body segments behavior would be modified by the translational and rotational speeds as well as the gains.

Table 8.1 – Real rotation (in degrees) that participants had to perform with respect to the rotational speed and the gain. Since each trial lasted 3 seconds, the virtual rotations to perform were respectively 60, 90 and 120 degrees for the 20°, 30° and 40° rotational speed conditions.

Rotational Speed / Gain	0.5	0.7	0.9	1.1	1.3	1.5
20° (60° virtual rotation)	120	85	67	55	46	40
30° (90° virtual rotation)	180	129	100	82	69	60
40° (120° virtual rotation)	240	171	133	109	92	80

8.2.2 Participants and Apparatus

14 participants (8 males, 6 females) aged between 21 and 53 years old (26.43 ± 7.4 , mean \pm SD) achieved the experiment. 5 participants reported having regular use of VR and HMD, 7 few times, and 2 never. Half of the participants had regular experiences with 3D videos games. We assessed their dominant eye and dominant foot through the questionnaire proposed by (Coren et al. 1979). 10 participants had right eye and foot dominance whereas 4 had left dominance.



Figure 8.1 – Left - User wearing the HTC Vive Pro Eye HMD equipped with a wireless module, one HTC Vive tracker located at the pelvis and one HTC Vive controller. Right - User's point of view of the VE during the experiment. The black arrow indicates the direction of the turn. The sight and pink sphere were used for calibration purposes).

They signed an informed consent form and were naive to the purpose of the experiment. The study conformed to the standards of the declaration of Helsinki. All participants were able to finish the experiment.

The virtual environment was developed with Unity3D. We used a Vive Pro Eye HMD (resolution of 1440 x 1600 pixels per eye and a 110 degrees diagonal Field of View). The experimental platform was guaranteed to run at a minimum of the HMD frame rate (90Hz). We used the Vive Wireless Adapter¹ to avoid cables, as it could eventually disturb participants while performing the task (Figure 8.1).

The VE consisted of a large forest designed with Green Forest Unity 3D asset². The VE enabled the generation of motion flow during virtual translations applied while participants were physically rotating. A virtual black cross on the ground indicated the center of the physical workspace and was used for calibration purposes between trials. A virtual sphere with a diameter of 2.5cm was displayed in the VE and represented the target that participants had to follow.

8.2.3 Procedure

In our experiment, participants had to perform two different tasks: a proprioception task to assess the ability of users to estimate turning without any instructions and a perception task where we assessed the perception of rotation gains with and without virtual translation. The perception task was the main purpose of our study, in which we investigated the perception of gains whereas the proprioception task was to guarantee that users were able to accurately perform rotations before the perception task. We used a One Alternative Forced Choice (1AFC) task in

1. <https://www.vive.com/eu/accessory/wireless-adapter/>

2. <https://assetstore.unity.com/packages/3d/environments/fantasy/green-forest-22762>

which users are exposed to one stimulus (i.e., a rotation gain lower or higher than 1) and they are forced to choose an answer from a question with two potential answers, in our case determining whether the virtual rotation was **faster** or **slower** (Prins et al. 2016). To avoid cybersickness due to the use of rotational gains and a high number of trials, we separated the experiment into two sessions separated each of at least 24 hours. Each session included one proprioception task and one condition (nT or T) of the perception task.

8.2.3.1 Beginning of session

Participants started by reading and signing a consent form that described the experimental protocol. Then, they filled a Simulator Sickness Questionnaire (SSQ) (Kennedy et al. 1993) and a demographic questionnaire (age, gender, amount of experience playing video games, and exposure to VR).

8.2.3.2 Proprioception task

Participants started with the proprioception task. Participants were immersed in a virtual forest and were asked to perform leftwards or rightwards (direction) 90 degrees turns with or without vision (vision mode). In the without vision mode, the screen was blacked-out so that users did not have any visual cues from the environment. They performed 8 trials (2 repetitions x 2 directions x 2 vision mode) with the following procedure: (1) Participants were placed at the center of the workspace (indicated by the virtual black cross); (2) They had to align their body with a virtual sphere placed two meters in front of them (i.e. two meters forward from the black cross and position and at the user's height). A virtual black sight following head movements was displayed to help participants to aim at the sphere; (3) A text indicated the vision mode condition (with or without) and a black arrow indicated the direction of the turn (left or right). Once this calibration phase was done, they had to press the Vive controller's trigger to notify that they were ready to perform the trial; (4) After a one-second countdown, the sphere, the text, and the direction arrow were hidden and participants could start their 90 degrees rotation; (5) They had to press again the controller's trigger to indicate they finished their turn.

8.2.3.3 Perception task

Participants performed the first 4 training trials using the maximum and the minimum gains in order to guarantee that they understood the task. Then, they performed four randomized blocks of 18 trials (3 rotational speeds x 6 gains, each combination is tested once per block). Leftwards

or rightwards rotations were randomized during the task. Before each block, the eye-tracking system was calibrated using the native calibration procedure. Each trial followed the following procedure: Steps 1 and 2 are the same as for the proprioception task; (3) We indicated during one second with a virtual black arrow the direction of the sphere movement, then the direction arrow disappeared and the automatic motion started according to the translation condition (nT or T):

- nT - the sphere moved during 3 seconds leftwards or rightwards at the given rotational speed set for the trial. Participants had to align their whole body in order to always be facing the sphere until the sphere movement was done.
- T - an automatic constant virtual translation (1.4m/s) was added during the trial. The sphere and the participants started to perform a 2 meters forward virtual translation, then the sphere starting to move for 3 seconds leftwards or rightwards at the given rotational speed set for the trial. Participants had to align their whole body in order to always be facing the sphere until the sphere movement was done. To end the motion, we added a 1-second forward virtual translation.

For both nT and T conditions, we guaranteed that the user's full body was aligned with the sphere by checking during the trial user head and pelvis orientation with the virtual sphere. At the end of the trial, the VE faded to black and participants had to answer the following forced-choice question: « I felt that my virtual rotation speed was (faster or slower) than my real one. ». After a block, participants had to answer the following question: « On a scale of 0-10, 0 being how you felt coming in, 10 is that you want to stop, where are you now? ». This question was first introduced in a research work assessing users' susceptibility to cybersickness ([Rebenitsch and Owen 2014](#)) and was reused in other experiments assessing cybersickness during navigation (e.g., [Fernandes and Feiner 2016](#)). In our experiment, this question allowed us to monitor during the experiment users comfort between blocks. We refer to this question as Fast-SSQ in the rest of the paper. After two blocks, participants had to take at least a 5 minutes break to mitigate cybersickness.

8.2.3.4 End of session

At the end of the session, participants filled a post-SSQ. Then, we asked participants a multiple choice question: "Which information did you prior the most to detect the rotation gain?" with the following answers: Body orientation; The ability to gaze the sphere; Motion of the sphere; My rotation speed; Rotation of the virtual environment; Salient elements of the virtual environment; Steps done during the task. The objective was to identify which features participants would rather rely on to perform the perception task. In total, one session took approximately 45

minutes.

8.2.4 Data Analysis

In the proprioception task, we collected in total 224 trials (14 users x 2 sessions x 2 vision modes x 2 directions x 2 trials). For each participant, condition, and body segment (head and pelvis), we computed the relative error (in degrees) of the estimation of 90 degrees rotations. In the perception task, we collected in total 2 016 trials (14 users x 2 translation types x 3 angular speeds x 6 gains x 2 directions x 2 trials).

For each participant, we computed the probability of answering “Faster” from the 1AFC question $P(g_n; faster)$ for each gain, translation type, and rotational speed. We used the Quickpsy package in R (version 0.1.5.1) to compute participant’s PSE and 25% and 75% DTs ([Linares and Lopez-Moliner 2016](#)). It allows fitting psychometric curves based on the experimental data by direct maximization of the likelihood. These psychometric functions follow the form $\psi(g_n) = \gamma + (1 - \gamma - \lambda) * F(x)$, where γ is the guess rate, λ the lapse rate and F the cumulative normal distribution function. We set γ at 0 and the lapse rate was estimated as a parameter of F .

To analyze the head orientation, we computed the amplitude of the head as the unwrap arc-tangent of the head orientation. Then we resampled at 90Hz the data and performed a temporal normalization to study the evolution of head amplitude over time and analyze the participants turning behavior through the different experimental conditions. To this end, we used the Statistical Parametric Mapping (SPM) method ([Friston et al. 2007](#)). This analysis allows comparing time-series data of different trials taking into account their variability at each time step. We computed the baseline movement of the sphere that was constant across experimental conditions in order to compare the conditions with respect to the theoretical movement participants should have performed. We also recorded the delay (in degrees) participants had at the end of the trial (i.e. how far from the sphere they were when this one ended its trajectory).

Eye-tracking data was captured at 90Hz and filtered using a Butterworth low-pass filter of order 4 to filter high-frequency artifacts (higher than 15Hz). Instead of using the raw eye-tracking data, our analysis considered the angular error between the center of the sphere and the eye direction. For each block, the first second for all the trials in the T condition, in which users were instructed to gaze at the target sphere while it was describing a forward motion, was used to correct any rotational offset that could be introduced by an inaccurate calibration. The offset was computed by averaging all data points (30s of data per user). Using the corrected angular error data, for each trial we computed the ellipse that fitted the 95% of the data samples. The ellipse fit provides insights into the spread and accuracy of the user’s gaze. The eye-tracking data from

one user was not exploitable due to errors in the recordings and two users were excluded from the analysis as they presented unique behaviors (higher variability and lower precision). From the remaining data, 40 trials were excluded from the analysis when the width and x-offset were higher than 3 standard deviations. The total number of observations was 1541.

From the pre and post SSQ data gathered before and after each session, we computed the pre and post SSQ score accordingly to the methodology described in (Kennedy et al. 1993). We also computed a delta SSQ score for each scale (i.e., post-SSQ score minus pre SSQ score) to have insights about the cybersickness variations after each session.

Assessing the effect of the experimental conditions (translation speed, rotational speed) on independent variables, we performed analyses of variance (ANOVA) with repeated measures. To analyze and compare PSE and DTs across conditions, we used the bootstrap comparison provided by the Quickpsy package. Shapiro-Wilk test was used to test the normal distribution of the data. When appropriate, we applied Greenhouse-Geisser adjustments to the degrees of freedom, to avoid any violation of the sphericity assumption. Post-hoc analyses were based on pairwise t-tests with Bonferonni corrections. Friedman test and post-hoc pairwise Wilcoxon tests with Bonferonni were used to analyze subjective data from questionnaires. All reported significant results had a p-value lower than 0.05.

8.2.5 Results

8.2.5.1 PSE and DTs

With the 1AFC question answers, we fit psychometric curves by turn direction, session, translation, and rotation type. We did not find any significant effect of the turn direction or the session on the PSE and DTs, thus we group the answers only considering the translation (nT, T) and rotation type (20° , 30° , 40°) (Figure 8.2). Table 8.2 reports the averaged PSEs and DTs per conditions. For the translational motion (10th and 11th lines of Table 8.2), bootstrap comparisons of PSE and DTs showed no effect between nT and T conditions, resulting in similar discrimination of rotation gains with or without virtual motion. For the rotational motion (7th, 8th and 9th lines of Table 8.2), bootstrap comparisons showed an effect where PSE were significantly lower for the 40° rotation (0.99) than the 30° (1.11) and 20° (1.12) ones as shown in Figure 8.3. 25% DTs were significantly higher for the 40° rotation (0.72) than the 30° (0.58) or 20° (0.64) ones, and 75% DTs were significantly lower for the 40° (1.19) than the 30° (1.36) or 20° (1.35) ones. These results mean that users tended to underestimate the rotation gains when the rotation speed was lower. Considering the interaction between translational and rotational speed (1st to

6th lines of Table 8.2), bootstrap comparisons showed a significant effect where the PSE for the nT20° condition had the highest values. This means that users underestimated most of the rotation gains at the lowest rotation speed without virtual translation motion.

8.2.5.2 Body segments behavior

Figure 8.4 shows the averaged normalized head amplitude depending on the rotational speed and gain. SPM analysis showed an effect of the gain on these time-series during the turn. Post-hoc tests demonstrated that the smaller the gain, the higher the delay with the baseline (movement of the sphere) during the turn. This observation can be seen by the rightwards shift with respect to the black line, where high gains are less shifted than the low ones. Thus, it is easier for users to align themselves with the sphere for smaller rotation speeds and a gain higher than one. However, no difference was observed between nT and T conditions that had similar profiles.

We can also observe on Figure 8.4 that, the higher the rotation speed, the higher the delay to face the sphere. Regarding the delays participants had with respect to the sphere at the end of the trial, a 3 way ANOVA (translation type x angular speed x gain) showed that the angular speed $F_{1.31,14.41} = 155.89$, $p < .001$, $\eta^2 = .94$ and the gain $F_{1.56,17.11} = 22.10$, $p < .001$, $\eta^2 = .67$ had an effect on the delays. There was an interaction effect between the angular speed and the gain $F_{2.63,28.97} = 21.25$, $p < .001$, $\eta^2 = .66$. Post-hoc analyses showed that the higher the angular speed the higher the delay ($p < .05$), the smaller the gain the higher the delay ($p < .05$).

Table 8.2 – The 25%, PSE, and 75% threshold gains computed from the psychometric curves. Deviance (D) and p-value (p) represent the goodness-of-fit. DTs and PSE are sorted by translation and rotation types.

		25%	PSE	75%	D	p
nT	20	0.72	1.16	1.42	17.30	1.00
	30	0.51	1.01	1.36	5.18	1.00
	40	0.71	0.94	1.17	3.36	0.91
T	20	0.49	0.98	1.30	6.55	1.00
	30	0.55	1.06	1.36	5.33	1.00
	40	0.75	1.03	1.26	1.65	1.00
	20	0.64	1.12	1.35	0.09	1.00
	30	0.58	1.11	1.36	1.98	0.97
	40	0.72	0.99	1.19	0.69	1.00
nT		0.66	1.08	1.33	21.64	1.00
T		0.64	1.07	1.32	8.89	1.00

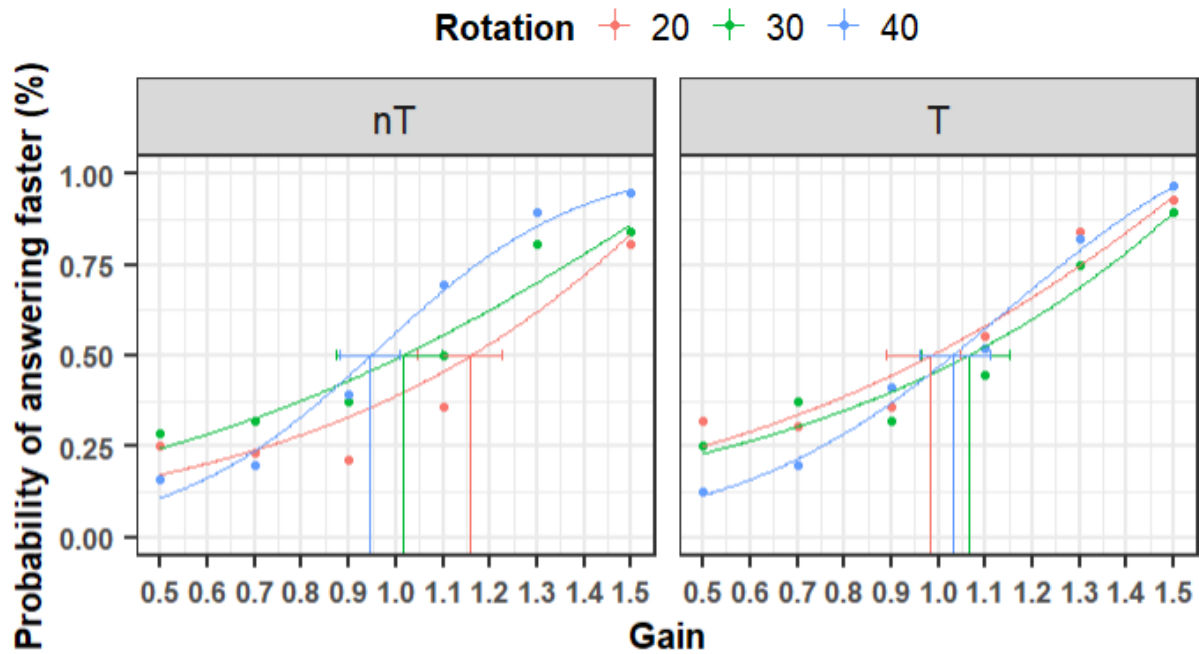


Figure 8.2 – Psychometric curves from the pooled results of the 1AFC question per translation (nT and T) and rotation type (20° in red, 30° in green and 40° blue). The PSE with a 95% confidence interval is indicated for each curve.

8.2.5.3 Gaze analysis

Figure 8.5 depicts the gaze distribution when grouping the data based on the direction and the translation conditions. Participants' gaze had an asymmetry for the left and right conditions (i.e., a shift with respect to the center of the sphere at (0,0) coordinate), suggesting a gaze behind the target, while an increased dispersion for the conditions in which there was no translational motion. For the statistical analysis, we only discuss the horizontal indicators (width and x-offset of the ellipse), as the object to follow did not exhibit any vertical motion.

For the ellipse width, a full factorial ANOVA analysis of direction \times gain \times translation \times rotation showed a main effect of gain $F_{1.76,17.63} = 14.47$, $p < 0.001$, $\eta_p^2 = 0.59$, and an interaction effect between translation and rotation $F_{1.98,19.77} = 17.74$, $p < 0.001$, $\eta_p^2 = 0.64$ (see Figure 8.6). Post-hoc tests showed that the width of the ellipse was significantly higher for the 1.5 gain condition ($M=4.34$; $SD=1.35$) than for the others $M=[3.30..3.62]$; $SD=[1.07..1.24]$, which suggests that gaze activity was more spread on the horizontal axis at the highest gain than the others. For the interaction effect, post-hoc tests (only significant comparisons are reported $p < 0.05$) revealed that the increase of the rotation speed had a higher increase of the width

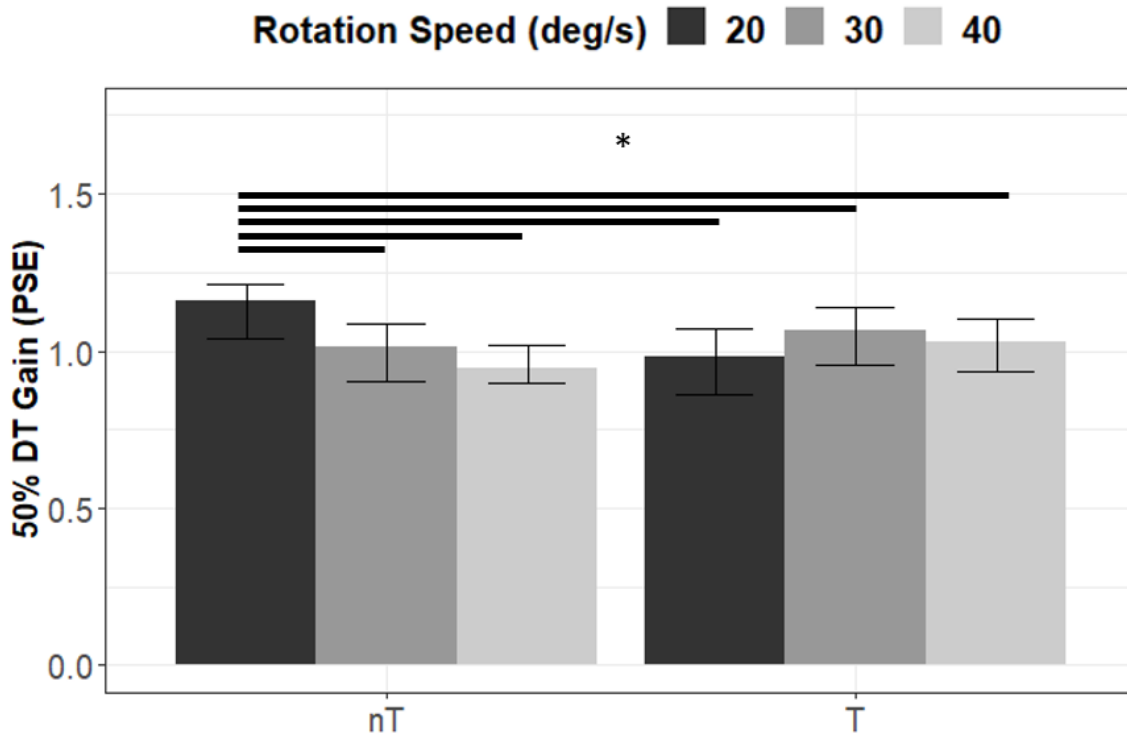


Figure 8.3 – PSE (middle) gain thresholds per translation type and angular speed. Significant pairwise comparisons are indicated by the black lines ($p < 0.05$).

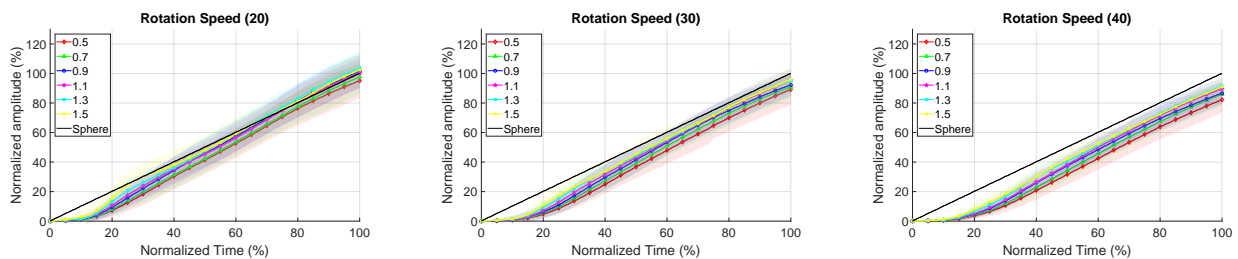


Figure 8.4 – This figure shows typical temporal evolution of mean and standard deviation of normalized head amplitude for each Rotation Speed (20° left, 30° center and 40° right), and gains (from 0.5 to 1.5 and the theoretical baseline). There is an effect of the gain during the whole turn duration (the F value for the factor gain is higher than the F^* computed).

of the ellipse for the nT condition ($20^\circ < 30^\circ < 40^\circ$) compared to the T condition ($20^\circ < 30^\circ$, $20^\circ < 40^\circ$). Moreover, the effect of the translation motion was significant at the 40° condition but not for the 20° and 30° conditions.

For the ellipse x-offset analysis (i.e., offset from the center of the sphere to track), as we did not observe any effect of the direction when mirroring left trials data, for the sake of

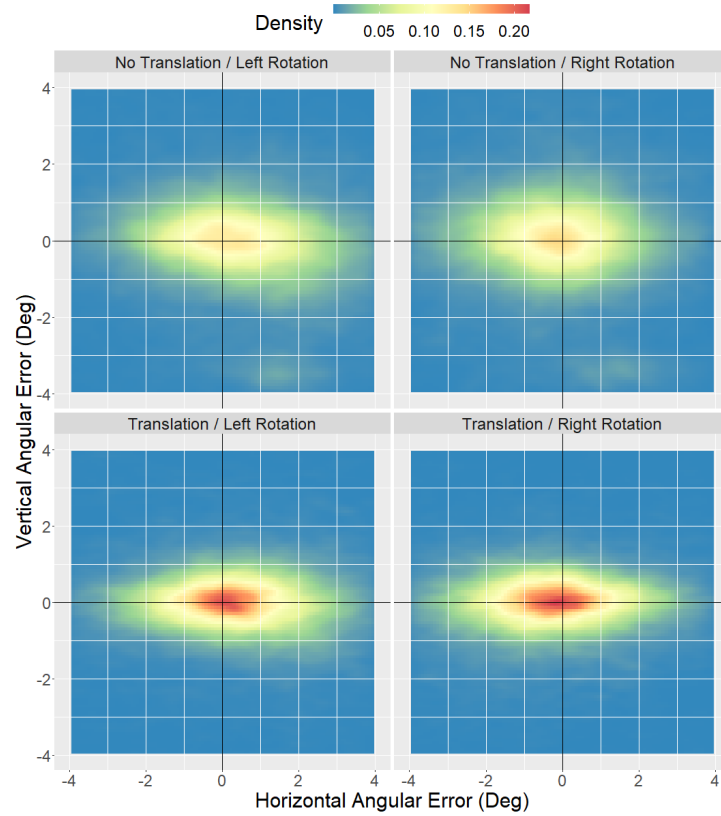


Figure 8.5 – Gaze error density plots when the sphere was rotating. The (0,0) represents the center of the sphere to track.

simplicity, we aggregated repeated samples by considering the mirrored values. The ANOVA analysis showed a main effect for gain $F_{1.90,18.99} = 9.13$, $p < 0.01$, $\eta_p^2 = 0.48$ and rotation speed $F_{1.15,11.46} = 8.74$, $p < 0.05$, $\eta_p^2 = 0.47$ (see Figure 8.7). Post-hoc tests suggest that the x-offset increases as the gain increases, although not all pairwise comparisons are significant. The strongest effects are found between the lowest and the highest gains, 0.5 ($M=0.09$; $SD=0.93$) and 0.7 ($M=0.22$; $SD=1.27$) conditions have a significant x-offset smaller than conditions 1.3 ($M=0.51$; $SD=1.06$) and 1.5 ($M=0.60$; $SD=0.95$). Regarding rotation speed, data also suggests that as the rotation speed increases the x-offset decreases. Post-hoc tests showed that the 40° condition ($M=0.21$; $SD=0.89$) was significantly smaller than the 20° ($M=0.49$; $SD=0.72$) and 30° ($M=0.41$; $SD=0.81$) conditions. Finally, we also observed two interactions effects between the translation and rotational speeds $F_{1.41,14.08} = 5.45$, $p < 0.05$, $\eta_p^2 = 0.353$ and between the gain and the translation speed $F_{3.10,31.05} = 7.53$, $p < 0.001$, $\eta_p^2 = 0.43$. Regarding the first interaction (see Figure 8.7 right), post-hoc tests showed that the $T40^\circ$ condition was the one exhibiting significantly less offset compared to the other combinations (no other significant

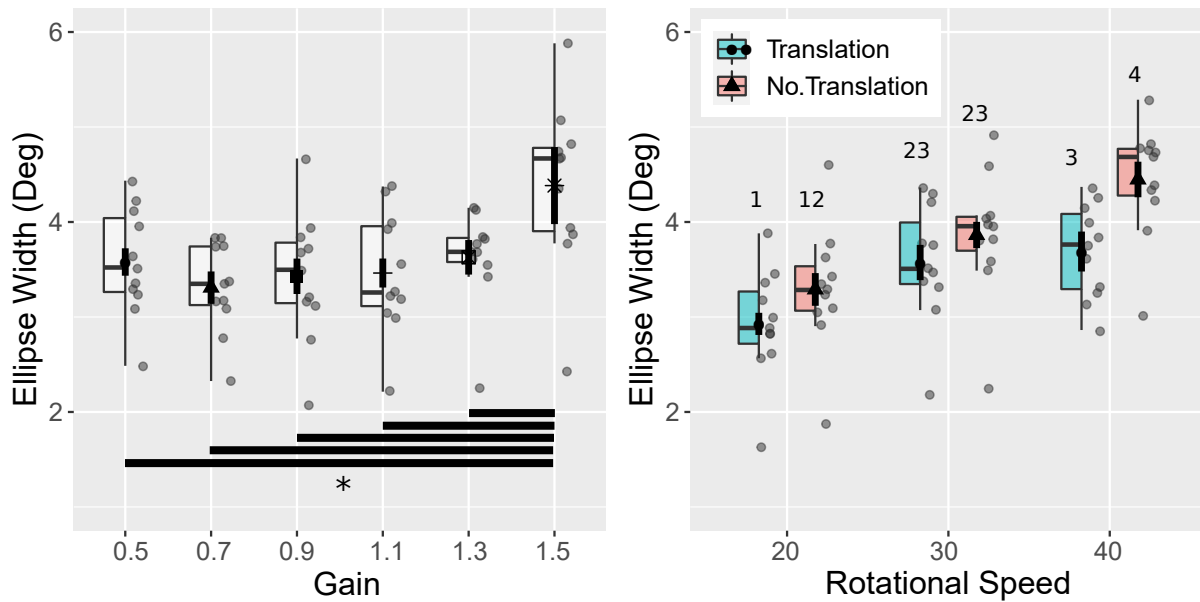


Figure 8.6 – Left - Ellipse width for the gain factor, significant pairwise comparisons are indicated by the black lines ($p < 0.05$). Right - Ellipse width for the translation and rotational factors. Post-hoc tests are reported using superscripts. Two levels sharing the same superscript are not significantly different.

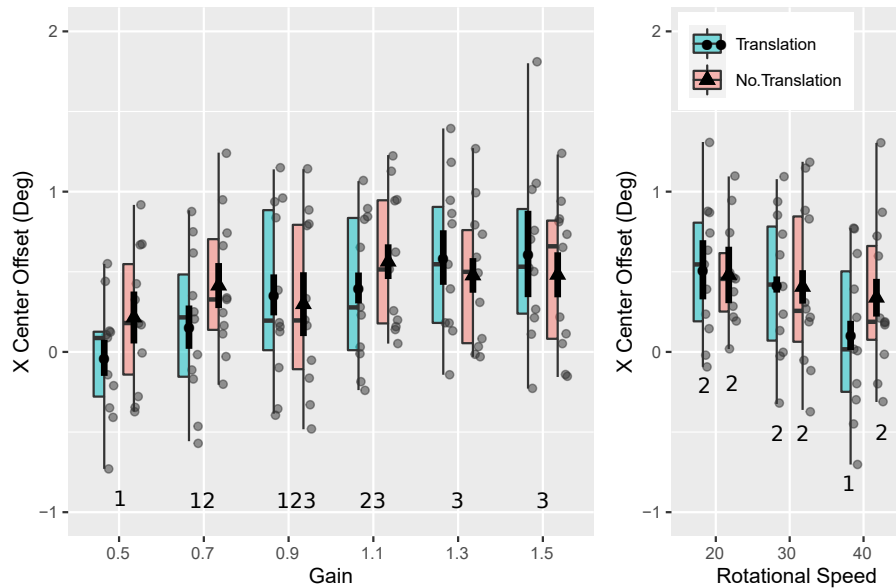


Figure 8.7 – x-offset for the interaction effects between translation condition on gain (left) and rotation speed (right). Post-hoc tests are reported using superscripts. Two levels sharing the same superscript are not significantly different.

pairwise comparison). Regarding the second interaction (see Figure 8.7 left), although the visual inspection suggests that having translational motion decreases the offset as the gain decreases, post-hoc tests showed inconclusive results.

8.2.5.4 Questionnaires

Table 8.3 reports the average and the standard deviation of pre, post, and delta SSQ scores for each scale (nausea, oculomotor, disorientation) and overall, grouped by the session order (first, second). Besides, we also noticed that there was no significant effect of session or translation type on every scale of pre SSQ scores, meaning that the users' state was equivalent at the beginning of both sessions and conditions. Thus, we focused on the statistical analysis of delta scores as they measure the increase after one session.

There was no significant effect of the translation type on SSQ delta score for the nausea $F_{1,13}=0.53$, $p=0.48$, oculomotor $F_{1,13}=2.43$, $p=0.14$, disorientation $F_{1,13}=0.08$, $p=0.77$ and total $F_{1,13}=0.20$, $p=0.65$. However, there was a significant effect of the session order on SSQ delta scores for the nausea $F_{1,13}=8.86$, $p<0.05$, $\eta_p^2=0.40$, disorientation $F_{1,13}=7.41$, $p<0.05$, $\eta_p^2=0.17$ and total $F_{1,13}=8.19$, $p<0.05$, $\eta_p^2=0.13$ scales. Post-hoc analyses showed that the delta scores were significantly lower after the second session than the first one.

Table 8.3 – Pre, post and delta scores computed per session for each scale (nausea, disorientation, oculomotor and total).

Session		Nausea		
		pre	post	delta
1		19.08±20.83	37.47±15.63	18.39±22.90
2		18.39±21.64	21.19±13.62	2.79±25.02
		Disorientation		
		pre	post	delta
1		12.80±12.76	61.64±42.19	48.83±41.19
2		13.73±16.39	25.85±24.32	12.11±27.14
		Oculomotor		
		pre	post	delta
1		25.98±21.79	36.81±16.24	10.82±21.58
2		20.03±25.85	23.82±14.82	3.79±25.18
		Total		
		pre	post	delta
1		18.96±17.93	37.66±16.94	18.70±19.62
2		16.56±20	20.57±12.51	4.00±23.35

Figure 8.8 reports the scores of the fast-SSQ answers after each block and for each session. Mean and standard deviation scores after a block of 18 trials performed were respectively 0.96 ± 1.78 , 1.96 ± 1.90 , 0.78 ± 1.72 , 1.60 ± 1.93 for the first, second, third and fourth blocks. We found no effect of session ($F_{1,13} = 0.88$, $p = 0.27$) nor block number ($F_{1,13} = 2.58$, $p = 0.09$) on the fast-SSQ scores.

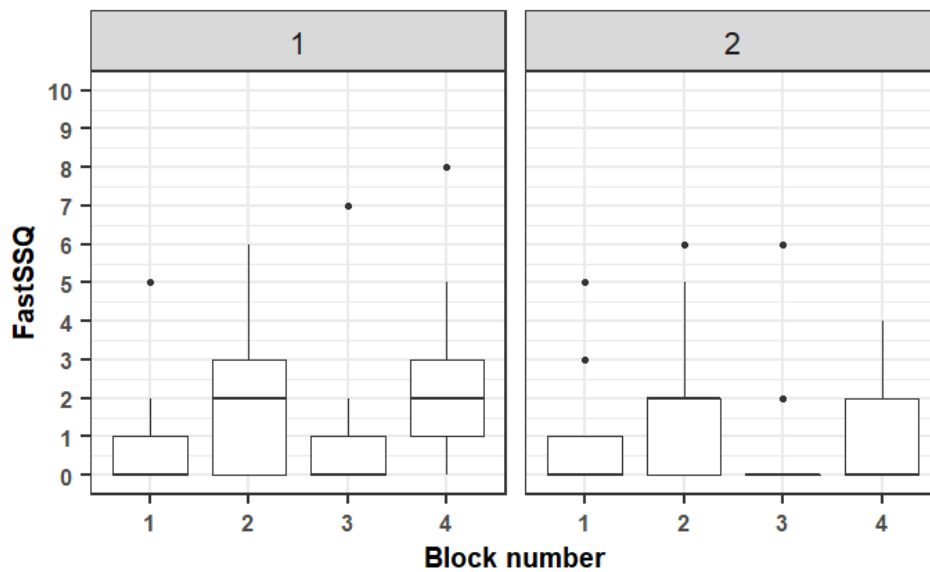


Figure 8.8 – Boxplot of the fast-SSQ answers after performing a block (grouped by session 1 and 2).

Regarding the results of the multiple-choice question we asked at the end of the session, a chi-square test showed that both distributions of the answers for the static and moving conditions were dependent ($\chi^2(6) = 8.50$, $p = 0.20$). The numbers of answers per item were (number selected after nT / number selected after T): Body orientation (7/6); The ability to gaze the sphere (2/7); Motion of the sphere (7/10); My rotation speed (9/12); Rotation of the virtual environment (6/8); Salient elements of the virtual environment (2/0); Steps done during the task (10/4). Note that we can note that the most selected item for the nT condition was "Steps done during the trial" and "The ability to gaze the sphere" for the T condition.

8.2.5.5 Proprioception Task Results

Table 8.4 reports the relative angle error from the 90 degrees turns for each condition. A three way ANOVA (direction of turn x vision mode x body segments) showed that the direction of turn $F_{1,13} = 15.80$, $p < 0.01$, $\eta^2 = 0.55$, and the body segment $F_{1,13} = 20.88$, $p < 0.001$,

$\eta^2=0.616$ had an effect on the estimation of 90 degrees turn. We also found an interaction effect of the direction x body segment $F_{1,13}=10.98$, $p<0.01$, $\eta^2=0.45$, the body segment as well as direction x body segment x vision $F_{1,13}=6.91$, $p<0.05$, $\eta^2=0.34$. Post-hoc analyses showed that head error was higher than the pelvis one ($p<.05$), the error was higher for rightwards turns than leftwards turns ($p<.05$), and the highest error was the head during rightwards turns with vision ($p<.05$).

Table 8.4 – Average turning error of head and pelvis from the proprioception task.

Turn direction	Vision	Head error	Pelvis error
Left	Without	-0.21(22.42)	2.32(11.93)
	With	2.58(17.48)	0.33(16.99)
Right	Without	9.89(11.00)	4.47(9.78)
	With	13.90(11.25)	8.91(11.97)

8.3 Discussion

Our main objective was to assess whether translation and rotational speeds alter the perception of rotation gains in VEs. With the proposed study, we observed an effect of rotational speed, in which the lower the rotation, the less sensitive to the gains participants were, but also an interaction effect where condition nT20° was the configuration for which participants were the least sensitive. The experimental conditions also affected gaze and body segments behavior. We discuss in the following section these results.

8.3.1 Motion and Perception of Rotation Gain

While most of the studies related to the perception of rotation gains in VR excluded the translational component, it is important to consider it as it could bias the perception of rotation in the horizontal plane as demonstrated in both REs and VEs (Sarre et al. 2008). We hypothesized that translational motion could improve the perception of heading and thus could make the detection of gain more easier because motion parallax contributes to the perception of heading during rotation (Li and Warren Jr 2000). We did not find a global effect of the virtual translational motion on the perception of rotation gains, meaning that the addition of a virtual motion did not help users to discriminate the gains. One explanation might be that users could not rely on extra-retinal information to disambiguate the motion perception since they had to look at the

sphere. However, we found an interaction effect between the translational motion and the 20° rotational motion which suggests that it might be easier to apply gain during small rotations performed by the user while virtually translating in the VE. Thus, our results do not support [H1], since we did not find a global effect of translational speed. In particular, the interaction effect between low rotational speed combined with translation made the detection of gains harder, which contradicts our initial hypothesis. The influence of translation on the perception of rotation gain is still unclear and further work is required (e.g. assessing a wider range of speed, or comparing continuous and discontinuous motions) to investigate whether it could alter users' perception or not.

Regarding the impact of rotational component, results showed that users underestimated more rotation gains at lower speeds (i.e., it is easier to detect rotation gains as the rotation speed increases). Even though visual perception research supports that the faster the head is turned the less visual awareness of the environment, we suggest that staring at the sphere would have mitigated these effects. In contrast, [Neth et al. 2012](#) investigated the influence of walking speed on the detection of curvature gain. They demonstrated that people are significantly less sensitive toward walking on a curved path when walking slower. These results found for curvature gains are in line with the ones we observed: users were significantly less sensitive to rotation gains when turning at a slower pace. It is worth noticing that it has been shown that angular velocity profiles can differ depending on the turn to perform and the gain applied ([Dumontheil et al. 2006](#)). We also want to point out that, even though we found an effect of rotational speed, we are aware that there may be an interaction between the rotational speed and the amount of physical rotation to perform. Table 8.1 shows that both gain and rotation speed influenced the amount of physical rotation to perform. Thus, in some configurations, additional proprioceptive feedback was provided to users that may have helped users to better discriminate the rotation gains at higher rotational speeds, as it was already demonstrated in a previous experiment that showed that participants were better at discriminating rotations when the virtual turning angle is rather large ([Bruder et al. 2009](#)). This might also explain why we noticed in the subjective data that users rather relied on proprioception since they reported using more the information of their number of steps performed during the task in the nT condition, showing that the amount of rotation performed might be a metric used by participants to discriminate the gains. Last, when looking at Table 8.2 and Figure 8.3, we can notice that the 30° breaks the values pattern for the T condition where its PSE is higher than the 20° or 40°. This is an unexpected but real effect as we expected to have either increasing or decreasing DTs as the rotational speed changes. We suggest that users may have more difficulty to distinguish rotations gains at an « average »

rotational speed than the lowest and highest in our experiment. Thus, our results confirmed [H2], but additional work is required to understand users' ability to detect rotation gains in VEs with experiments focusing on manipulation of optic flow. Especially, the interaction between the gain and the rotation speed of the sphere may have impacted the performance, since users perception may have been filtered in order to rely mostly on the rotational speed (a more salient cue than a translation), thus leading to an inconsistency between virtual and real rotations.

8.3.2 Body Segments and Rotation Gain

Figure 8.4 shows the temporal evolution of head orientation over time by rotation speed and gains. The higher the rotational speed, the higher the delay is between the baseline (black line) and the average users' amplitude during the rotation. Since participants had no prior knowledge about the trial they should perform, they tended to be late in the rotation compared to the sphere rotation at high rotational speeds. This could explain also why participants tended to better discriminate at high rotational speed since they had to turn faster to catch up with the sphere. Thus, we suggest that the way users turn in studies investigating the perception of rotation gains should not be neglected as this delay could have been a bias to users to determine whether the rotation speed was faster or slower. For instance, in chapter 4, we investigated the impact of body segment coordination with different navigation techniques. Then, analyzing these coordination movements could lead to the design of new adaptive gains based on users movements, knowing that head anticipation is an invariant of human locomotion that is also preserved while navigating in VEs.

In addition, we observed differences in gaze behavior across the different experimental conditions, in particular an effect of translation and rotational speeds on gaze patterns. Figure 8.5 showed that there was more eye dispersion on the horizontal axis when no virtual translations were applied. We suggest that the virtual translation then provided more visual information and helped users to better focus on the sphere. By combining this information with the DTs found, we could suggest that the gaze error could provide some additional information to detect whether a user might notice a gain applied or not.

The analyses revealed that the higher the gain and the rotational speed, the higher the dispersion of the gaze (Figure 8.6 left). We believe that gaze activity could be an interesting metric to understand how participants differentiate gains. As the movements of the sphere and the were different, the ability to gaze at the sphere could have been more difficult for the highest and lowest gains. It is interesting to see that we did not find symmetry in the ellipse width dispersion as the dispersion only increased significantly for the highest gains. Moreover, we

found that the highest ellipse width was with the nT40 condition (Figure 8.6 right), but also that the higher the rotation speed, the easier users detected the gain. Thus, we could imagine detecting on the fly whether users can discriminate a gain or not based on their gaze activity to adapt or take advantage of gaze activity to modulate gains as it has been already done in some research work ([Langbehn et al. 2018b](#); [Sun et al. 2018b](#)).

These results support [H3], the experimental conditions having modified the gaze and body segments behavior, but future work should considering further analyses of gaze such as fixations and saccades.

8.3.3 Towards User-Centered Gain

Previous research work on the perception of rotation gains showed the impact of different experimental conditions such as the Field of View, the amount of rotation to perform, or the addition of distractors. In our experiment, we showed the impact of additional experimental conditions: translational and rotational speeds. This information could be important in the implementation of rotation gains. For instance, instead of applying the gain constantly during the whole rotation, we could consider different implementations. Congdon and Steed showed that the implementation of the gain (constant vs linear vs delayed) can influence the perception of rotation gains ([Congdon and Steed 2019](#)). It could be possible to consider different rotation gains transfer functions, considering as well the translational and rotational speeds. The use of virtual translation and real rotations could be considered in 360° video-based presence system ([Zhang et al. 2018](#)). One example of a consistent implementation based on our results could be to increase the rotation gain when users are turning slowly and decrease it when they turn fast. In addition, we could imagine increasing slightly more the rotation gain when virtual motion is performed by the mobile platform. Having the ability to adapt the gain during navigation would eventually improve redirection controllers.

The use of virtual translation in our study was inspired by redirection techniques. In particular, redirected walking uses rotation gains while users are walking in the workspace. We could imagine that those paradigms could be used for other types of techniques that require the use of virtual translation such as steering techniques. In chapter 6, we showed that users tend to drift in the workspace while using steering techniques, reaching the boundaries of the workspace even though those techniques do not require physical translational movements. Thus, the use of rotation gains during virtual translation could be interesting to manipulate users' movements and try to maintain them at the center of the workspace while navigating in the VE. In addition, rotation gains are used in 360° video-based telepresence systems ([Zhang et al. 2018](#); [Matsumoto](#)

[et al. 2020](#)). They are based on combining virtual translation of the mobile platform and user rotation in the workspace. Thus our results provide additional insights into how gains should be applied in such scenarios.

Regarding cybersickness, we found no effect of the translation type (nT or T) or the session on the fast-SSQ scores (Figure 8.8), meaning that adding additional virtual translation in T condition was not inducing more cybersickness than in the nT condition. We can also notice that the lowest fast-SSQ scores are after the first and third block, which can be easily explained by the fact users should feel more comfortable at the beginning of the session and after the 5 to 10 minutes break occurring after the second block. However, we found an effect of the session on the delta and post SSQ scores, where cybersickness was significantly lower after the second session performed 24 hours later than the first one (Table 8.3). We can suggest that users had some adaptation to rotation gains, leading to lower post SSQ scores on the second session, similarly to users that can adapt to increased curvature gains through separated sessions ([Bölling et al. 2019](#)).

In addition to cybersickness data, adding supplementary metrics such as gaze, proprioceptive or body-segment behavioral or movement data in the design of rotation gains may be promising as they could be adapted to user behavior. Indeed, taking advantage of gaze movements in redirection techniques has been already explored. Saccadic suppression of images has been already used to subtly reorient participants in the VE. They are based on the inability to detect changes, during or shortly after a saccade, in the location of a target when the change occurs immediately before ([Bridgeman et al. 1975](#)). Some perceptual studies and redirection controllers have been published ([Bolte and Lappe 2015](#); [Sun et al. 2018b](#); [Langbehn et al. 2018b](#)), showing the potential of using gaze information for implementing rotation gains. Gaze activity could be then considered when designing the implementation of rotation gains while navigating in VR.

Even though the analyses of gaze and body segment in a perceptual study of rotation gains are quite unusual, our results are encouraging and we suggest that considering these metrics could be interesting in the study and implementation of rotations gains for two reasons: (1) they may provide a better understanding on users perception when rotation gains are applied and (2) these objective metrics can be gathered and analyzed on the fly during VR navigation so that we could imagine adaptive rotation gains based on these metrics.

8.4 Conclusion

The study of the perception of rotation gains remains an active research topic in VR navigation. Understanding how users perceive those gains is necessary in order to implement subtle redirection techniques. Yet, it is important to consider the differences between the way the perceptual studies are performed, and the use of redirection techniques during navigation in virtual environments where gains are applied. In this contribution, we proposed to study and assess the impact of combined translational and rotational motions on the rotation gains perception. The results of our experiment revealed that participants are less sensitive to rotation gains when the rotational motion decreases. Regarding the impact of translation, even though our results suggest that the combination of virtual motion with a low rotational speed tends to make the rotation gains more subtle. In addition, the body segments and gaze analyses showed that the translational and rotational motions but also gains can alter users' behavior. These results open new perspectives and metrics about how users can detect rotation gains. To conclude, this contribution provides new results on how users perceive rotation gains in VR that could be used to improve the implementation of rotation gains in VR setups. We believe that considering both rotation and translation motions of users as well as their body and ocular movements while navigating could be an interesting approach to improve the redirection techniques, using a user-centered approach to make those controllers more adapted to the users.

Conclusion

In this part, we focused on the perception of rotation gain, defined as a modification of the virtual rotation with respect to the real rotation, that is widely applied to redirected navigation techniques

In chapter 7 we studied Field of View (FoV) restrictions, one solution that has been explored in VR as a mitigation strategy for motion sickness. Since they can alter user's perception and navigation performance in virtual environments, we conducted a study to estimate and compare perceptual thresholds of rotation gains while varying the vignetting type (no vignetting, horizontal and global vignetting) and the vignetting effect (luminance or blur). Results showed that the point of subjective equality was different across the vignetting types, but not across the vignetting effect or the turns. Subjective questionnaires indicated that vignetting seems less comfortable than the baseline condition to perform the task.

In chapter 8, we consider rotational motion because we noticed that in most studies that assessed rotation gains, participants could rotate at the pace they desire without having control over it. Also, no one investigated the influence of translational motion. We then estimated the influence of these motions and compared the perceptual thresholds of rotations gains. We varied the translational optical flow (static or forward motion), the rotational speed (20, 30, or 40 deg/s), and the rotational gain (from 0.5 to 1.5). The main results were that the rotation gains are less perceivable at lower rotation speeds and that translational motion makes detection more difficult at lower rotation speeds. Furthermore, the contribution provided insights into the user's gaze and body motions behavior when exposed to rotation gains.

All together, these results contribute to the understanding of the perception of rotation gains in VEs and how VR designers could improve rotations gains and redirection techniques.

PART IV

Conclusion and Perspectives

*« Quand l'écran s'allume je tape sur mon clavier
Tous les mots sans voix qu'on s'dit avec les doigts
Et j'envoie dans la nuit un message pour celle qui
M'a répondu OK pour un rendez-vous »*

Michel Polnareff, Goodbye Marilou

9

Conclusion

In this thesis, we aimed at investigating the impact of locomotion techniques on users' perception and action. The objective was to improve VR locomotion techniques by enhancing the understanding of how these techniques can alter users' movements during a given navigation task. Following a multidisciplinary approach combining knowledge from Computer Science, Human Movement Science, and Perception, we identified features characterizing human locomotion in RE and assessed them during locomotion in VEs. More precisely, we focused on two axes as presented in Figure 3:

1. How can steering techniques impact users' movements during a goal-directed task?
2. How can we alter the perception of rotation gains in VR?

In order to answer these questions, we first presented in Part I elements of the state of the art. In chapter 1, we introduced fundamental concepts involved during human locomotion in RE, including the role of human sensory systems, properties of human walking, and how motion is perceived. In chapter 2, we reviewed the literature regarding locomotion techniques for navigating in VEs. We presented how users' body can achieve locomotion in VEs based on the movements performed. We reviewed works on how sensory systems can be stimulated to improve the sensation of locomotion in VR and we presented some taxonomies. In chapter 3, we

detailed how VR locomotion techniques are assessed. In particular, we explained how evaluations of VR locomotion techniques are designed as well as the metrics used in user studies. We also reviewed some elemental results from popular experiments for walking, redirected walking, and steering techniques.

The review of the state of the art revealed that it could be interesting to understand the way users perceive the VE as well as the way they perform movements. However, we noticed that these two parts are closely linked when interacting in VR. In addition, most of the studies focus on either the perception or the action of users, but the whole loop was not always entirely considered. That is the reason why our two research axes, in which the first focused on users' movements, and the second on users' perception, were connected through a transversal axis that consisted in proposing new evaluations metrics to assess locomotion techniques in user studies. As locomotion in VR involves movements of body segment to produce motion in the VE, we paid attention to body segment behavior in most of the contributions presented. Moreover, vision is fundamental for navigating in environments, we then consider gaze data analysis to provide new insights in the understanding of the perception-action loop in VR as well as guidelines regarding the design of locomotions techniques. Our objective was to embed new analyzes in users studies to provide additional results regarding research questions that have been raised in VR literature.

Regarding the first research axis that investigated the interaction between users' movements and the locomotion techniques, we presented three contributions in Part II. In chapter 4, we aimed at understanding the differences in body coordination between physical and virtual navigation during a goal-directed task. While gaze anticipation has been demonstrated in REs, there was less information regarding VEs. In particular, we compared five different techniques including walking, three body-based steering, and one passive steering. We demonstrated that the top-down reorientation mechanism (i.e., gaze anticipates the future trajectory before the head and shoulders) is preserved for every technique tested during a lemniscate trajectory. Thus, we confirmed that the anticipatory behavior related to the perception of information in the environment in the future direction is preserved. However, the anticipation differs (i.e. more or less pronounced) according to the technique used, where we noticed quantitative differences in these delays. In particular, torso steering was the technique that had the most similarities to walking concerning delays. In chapter 5, we paid attention to the interaction between the control law and the curvature of the trajectory. We noted that VR literature lacks studies regarding how the control law can alter users' navigation in VR, thus, we wanted to assess how these two factors could influence users' movements during a goal-directed task. We focused on the speed update used in steering

techniques and we compared three speed transfer functions (constant, linear, and adaptive) and three types of slaloms in which we varied the curvature (low, medium, and high). The results showed that both the control law and the curvature's trajectory modified users turning behavior and in particular the angular speed profiles. Another unexpected result from this study was that we detected that the displacement of users' body center of gravity in the workspace was higher as the curvature of the slalom increased. This means that, even though the use of steering techniques should enable locomotion in VR without requiring physical displacements in the workspace, users were somehow shifting from their starting position while crossing the slalom's gates. We suggested that these movements were unintentional and we tackled the issue of UPD (Unintended Positional Drift) while using a steering technique in chapter 6. One major shortcoming of UPD is that users may unconsciously reach the boundaries of the workspace while using a steering technique, decreasing users' safety. We performed an analysis of the dataset gathered through the user study performed in chapter 5 in order to understand why and how users may have UPD in the workspace while virtually steering in the VE. We noticed that UPD occurred during the turns and that UPD direction was at the opposite of the turn direction (i.e. moving leftwards in the workspace during a virtual right turn and vice versa). We proposed two UPD models to encode this behavior, one based on linear regression and a second one based on Gaussian Mixture Models. We assessed these models through a simulation-based evaluation, reproducing the experimental protocol done in chapter 5. The simulation's results showed the feasibility of using simulations to study UPD. This contribution provides insights regarding the understanding of UPD during repetitive steering navigation tasks in VR.

While we focused on users' movements in the first research axis, we were rather interested in Part III on how users perceive their motion in VR, where we reported two experiments that aimed at studying the influence of visual and motion cues on the perception of rotation gains in VEs. In chapter 7, we focused on how dynamic modification of users FoV could impact the perception of amplified rotation gains. We tested two visual restrictor shapes (circular, typically used in vignetting, and horizontal, an uncommon approach to restricting users FoV) as well as two restriction effects (blurring the peripheral vision or reducing the contrast). While we did not notice any significant differences across the visual restriction effect conditions, we noticed an effect of the restriction shape on the perception of rotation where users were slightly less sensitive to rotation gains with the circular restriction. Based on these results, we wanted to study additional factors in order to understand users' perception of rotation. We then conducted a second experiment presented in chapter 8 that investigated the influence of motion on the perception of rotation gains. We tested for the first time whether the addition of virtual translation

and/or the rotational speed at which users rotate would alter the perception of rotation gains. Our results revealed that users are less sensitive to rotation gains when turning slowly and in particular with the addition of virtual translational motion. These findings provide new information on how rotation gains could be applied in VR.

The research objectives we addressed in this thesis addressed current but also new challenges that VR researchers may have to consider in the following years. While we investigated for the first time body segment coordination during curvilinear trajectories using different locomotion techniques, we still have not enough information about this mechanism. Gait and users movements are not considered enough in the evaluation of steering techniques and additional work should be done as for redirected walking ([Rothacher et al. 2018](#); [Tirado Cortes et al. 2019](#)) or WIP ([Reed-Jones et al. 2009](#); [Mun et al. 2018](#); [Wendt et al. 2010](#)). Regarding the control law, a recent user study also pointed out the effect of the speed update on task performance during straight steering navigation in VR [Gao et al. 2021](#). UPD has been first investigated for WIP ([Nilsson et al. 2013d](#); [Nilsson et al. 2014a](#); [Nilsson et al. 2013b](#)) but we noticed that it may happen for steering as well. UPD during steering may become a promising topic in VR navigation: for instance, a recent user study investigated UPD for other techniques including WIP, steering, and teleportation ([Kim et al. 2021](#)) where they demonstrated that UPD may occur more frequently during curvilinear trajectories than straight ones. Vignetting is more and more used in VR videogames as it tends to mitigate cybersickness but the results from user studies vary a lot depending on the experimental conditions. Manipulation of FoV seems an interesting method to improve users' comfort and more and more research work is addressing its potential use in VR systems, including its impact on spatial performance ([Al Zayer et al. 2019](#)), presence ([Teixeira and Palmisano 2020](#)), cybersickness ([Nie et al. 2019](#)). Furthermore, new restriction models could be considered, where most of the vignetting is based on users' rotational motion, [Adhanom et al. 2020](#) used gaze activity to adjust the vignetting according to users eye movements. Last, rotation gains are one key component of redirection techniques but most of the implementation is based on applying a constant gain. [Congdon and Steed 2019](#) pointed out that the rotational control law can alter the perception of rotation gains (i.e. a gain applied linearly is harder to detect than a gain applied constantly).

All together, the research work presented in this manuscript contributes to the understanding of how some factors alter users' perception-action loop while navigating in VR. Figure 9.1 sums up the factors and metrics we analyzed in the five contributions, where the red color refers to the first axis (influence of locomotion techniques on users movements) and the green one refers to the second axis (altering perception of rotation gains in VEs). This shows that the

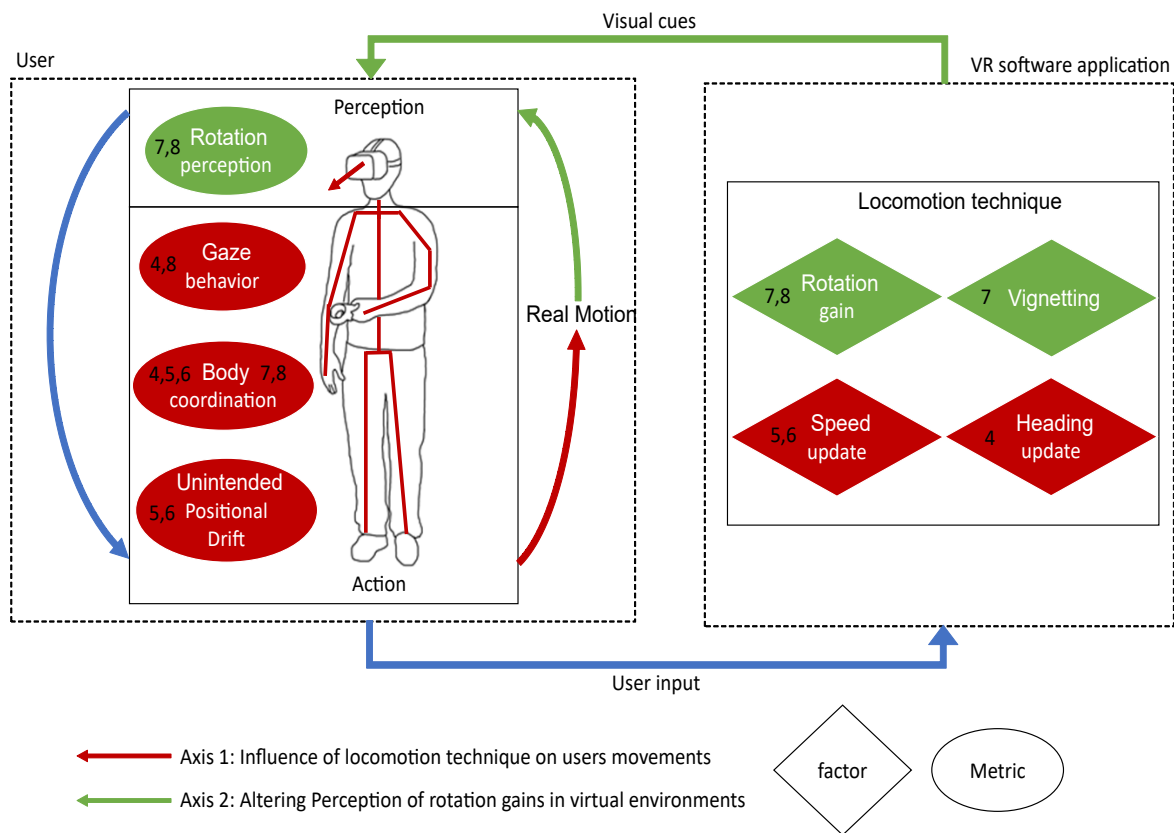


Figure 9.1 – Summary of contributions done during the thesis. Users were interacting with the VR system through a perception-action loop and we investigated how the locomotion technique and the navigation task could influence it. The numbers correspond to the chapter where we investigated the factors and metrics.

locomotion technique (e.g. the control law, the body segment used to steer in the VE or the use of rotation gains) and the navigation task (e.g. the curvature of a path, the rotational speed to perform a turn, or the amount of rotation to perform) used in VR software applications can modify the way users perform movements (e.g. body anticipation, gaze behavior, UPD), as well as the way users perceive these movements (e.g. perception of rotation gains). Yet, the study of the interactions between the implementation of the locomotion technique's control law, users movements, and perception should be more considered and deepened so that we would have a better understanding of the impact of both translational and rotational motion update on users behavior during navigation in VR. We present in the following chapter the perspectives of this thesis.

*« Isten, könyörülj meg nekünk
Ne szenvedjen tovább népünk
Megátkoztál, meg is vertél
Örök csavargóvá tettél »*

Ando Drom, Cigány Himnusz

10

Perspectives

The contributions presented in this thesis showed how users' actions can be modified with respect to the locomotion techniques and the perceptual cues provided by the VR system, highlighting that locomotion techniques can have some technical and perceptual limitations that still required to be solved in the future. In this chapter, we suggest some future work derived from the contributions of this thesis.

10.1 Short Term Perspectives

Short-term perspectives relate to the future work that could be done to follow up with the contributions of this manuscript. We identified five axes (i.e., one per contribution) that we will describe hereunder.

10.1.1 Body Segments Coordination during Locomotion in VEs

The influence of the VR locomotion technique on users' movement, and in particular body segments coordination, has not been extensively explored. In chapter 4, we aimed to contribute to

the understanding of human behavior in VE. We were interested in how users would reorganize their body segments orientation during a navigation task involving a curved trajectory (lemniscate) in a featureless VE (without salient objects in order to minimize the optical flow). Our experiment was performed in a simple environment to avoid any influence on the gaze behavior (i.e., some elements can attract the gaze) and to allow the comparison with real-world experiments ([Authié et al. 2015](#); [Bernardin et al. 2012](#)). However, such an environment is not common in most VR applications. Thus, future works will have to consider more ecological situations, such as an unconstrained trajectory in richer and more complex environments. This would allow us to evaluate whether this anticipation strategy still applies in more realistic VR conditions.

In addition, the presented experiment did not assess how users would perform the virtual task in a real environment. We decided not to include the real task, considering that the FoV could have a potential impact on reorientation behaviour ([Authié et al. 2017](#)). It would have required to restrict the users' FoV in the real condition in order to match the FoV of the HMD. Additional studies should be conducted to better establish the role of the FoV in VE and RE, and determine up to which degree the FoV could have influenced the results.

Finally, it would be interesting to evaluate and compare the anticipation behavior with other techniques widely used in VR applications such as WIP or redirection techniques.

10.1.2 Impact of Locomotion Control Laws on Users' Motion

We investigated in chapter 5 how users would perform virtual turns with different control laws. While the description and evaluation of control laws were often overlooked in the literature, we wanted to investigate the influence of linear speed on users' motion. We designed a simple VE to avoid any influence of the external environment on the trajectories produced. Nevertheless, this type of environment is not common in most VR applications. Future studies could consider other VEs that better represent ecological situations (richer and more complex ones) with less constrained tasks.

Regarding the characteristics of the control laws, we defined the maximum speed and acceleration based on studies of human walking in REs ([Bohannon 1997](#); [Jian et al. 1993](#)). While most of the steering control laws implementations consider a speed ranging from $1m/s$ to roughly $1.4m/s$, there have not been any thorough evaluations on the impact of this setting. Then, the implications of minimum and maximum speed remain unclear and future work could consider whether they have an impact on performance and preferences or not. In addition, further work is required to determine the threshold values of the spatial steering control law parameters such as speed, acceleration, orientation, and position update, as it was already done with translation

and rotation gains for redirected walking techniques ([Steinicke et al. 2010](#); [Schmitz et al. 2018](#); [Langbehn et al. 2017](#)).

Regardless of the control law or the curvature type, our results showed some interindividual variability for linear speed, acceleration, and angular speed profiles (Figure 5.3). It should then be interesting to evaluate the control law at the individual level, but also considering the design of novel control laws could be in future work where we could assess them in the same manner as we did.

10.1.3 UPD as a Future Challenge to Consider and Solve

The analysis of UPD in chapter 6 provided new insights into how users drift while using virtual steering techniques, with practical implications for different applications and potential vistas for future work to compensate for UPD. However, there are also a few limitations of our current work, which may lead to additional research ideas in future work. To improve knowledge about UPD, further analyses should be performed using different navigation tasks. For instance, it could be interesting to study the eventual link between UPD and other factors such as the sense of presence or cognitive load ([Bruder et al. 2015](#)) as they might influence UPD. UPD was also assessed for WIP techniques ([Nilsson et al. 2013b](#)) but we do not have information for other techniques. Further analyses of data including navigation with other techniques should be considered (e.g., teleportation-based systems).

In addition, other approaches (e.g. machine-learning-based, using other metrics) for modeling UPD should be considered to improve the existing models. Meanwhile, these models could be also assessed through simulation-based analysis that would enable to have insights about UPD by performing fewer user studies. We intend to improve the simulation framework, by including a more flexible architecture that can be extended by VR practitioners, so that it could become in the future a testbed for studying UPD in VEs. One potential approach to reduce the UPD could be the use of gains but future work is required to study the effects of gains on UPD so that they can be used with steering techniques. We believe that gains could be a promising solution to minimize UPD because altering subtly users' movements could help to mitigate unintended movements performed by the users while using a locomotion technique. One example could be the use of rotation gains to modulate users rotations as we noticed that the UPD increase as users amplitude increase.

10.1.4 Modulation of Perception of Rotation Gains

Rotation gains have several applications in VR locomotion. For instance, they are used in redirected walking to redirect users in the workspace while walking ([Razzaque et al. 2001](#)), but they can also be used to amplify users rotation in situations where turning is physically limited ([Langbehn et al. 2019b](#)). Various studies regarding the perception of rotation gains have been conducted in VR literature, and our contributions presented in Part III provided new insights regarding this topic. However, future work is required to have a better understanding of users' perception of rotations in VR.

In chapter 7, we only used gains above 1 because we wanted to assess whether we can increase rotation gains with vignetting. However, this choice could have led to an asymmetry that could have biased our results (and therefore having an overestimation of the PSEs and DTs) since a gain was applied in 80% of the trials (i.e. answering « yes » to the 2AFC question). Besides, participants had to discriminate between real and virtual rotations during a single turn. However, some studies showed that PSEs and DTs can differ according to the rotation task (e.g. discrimination between (1) virtual and physical rotation and (2) two successive rotations) ([Steinicke et al. 2010](#)). Thus, further experiments are required to assess gains below 1 and varying the rotation task. The absence of significant differences between the FoV Vignetting Types could be linked to the vignetting model itself. Indeed, its design was based on previous models of the literature, and we respected the maximum contraction used in most VR applications. Yet, further work is required to determine how we could improve the vignetting so that it will be adapted to the user and could potentially increase the DTs for redirection techniques in VR.

In chapter 8, we assessed for the first time the impact of combined translational and rotational motions on the rotation gains perception. Our results provided insights into how users' perception can be altered while varying motions in VEs, with practical implications for future work to improve redirection techniques in VR. However, there are also a few limitations of our current work, which may lead to additional research ideas that may be investigated in future work. First, to improve knowledge about perception of rotation gains with virtual translations, further studies can be envisioned by varying the experimental factors. Additional levels of the linear speed can be considered (e.g. lower or higher speeds) and real translations (i.e. walking) could also be tested in which additional proprioception cues might play a role. Second, other design choices can also be considered, such as the rotation gain implementation and the virtual environment. Apart from a constant gain, other rotation gain control laws could be considered as they could alter users' perception ([Congdon and Steed 2019](#); [Langbehn et al. 2019b](#)). Furthermore, the environment could also play an important role in the gain detection as more « structured » environments (e.g.,

interior spaces like buildings) could make the detection easier. Third, in this paper, we proposed the analysis of gaze activity and body segments movements to assess the impact of the rotation gain in the user's behavior. However, additional data and further analysis are required to have a better understanding of how rotation gains can alter users' behavior during navigation in VR.

We selected factors related to the vision and motion that we assessed into two different experiments. However, no user study has assessed yet the potential interaction between the restriction of FoV and users motion on the perception of rotation gains. Considering more factors involved in the perception of human motion (e.g. multi-modal sensory information by stimulating both vestibular and visual system) seems an interesting option and future work should assess new untested factors to provide a better understanding of the perception of rotation gains. Another approach could be to modulate the implementation of rotation gains (as studied by [Congdon and Steed 2019](#)) and study the interaction with the factors we assessed with constant gains. For instance, we could imagine a new implementation of vignetting based on the amount of rotation gains applied and users' motion. Even though we have a clear understanding of the perception of constant rotation gains without modulating users' perception, a lot of work is required to determine whether the perception of gains differs across factors modulating users' perception.

10.2 Long Term Perspectives

Long term perspectives refer to ideas and problematics related to the thesis topic that we did not have time to explore. subsection 10.2.1 describes ideas regarding the evaluation of locomotion techniques in VR and subsection 10.2.2 discusses a new concept of locomotion technique that aims at minimizing UPD.

10.2.1 25 Years of Evaluation of Locomotion Techniques in VR: What are the Next Fundamental Steps?

To assess the advantages and drawbacks of locomotion techniques in VR, evaluations are required. While testbeds are considered so far as the gold standard, their main limitations are the infinite number of experimental conditions to test. In addition, the first evaluations started around 25 years ago ([Bowman et al. 1997](#)), and since that time the VR systems have been considerably evolving in terms of HMD with higher resolution and FoV, more powerful computer that can generate wider and more detailed VEs. This means that results discovered through user studies over years might change due to technology improvements. Then, the quest to

assess every condition seems infeasible and some heuristics are required to gather knowledge about VR evaluations. We consider four main long term research axes regarding the evaluation of locomotion techniques (meta-analysis and systematic review of VR evaluations, exploring new metrics, reconsidering the evaluations framework used in VR evaluations, and assessing techniques at the individual level) that we will describe in the following paragraphs

Towards a Meta-Analysis and Systematic Review of VR Evaluations

Hundreds of evaluations of locomotion techniques have been performed, all providing knowledge regarding navigation in VR. Most researchers having interests in VR locomotion know what are the main advantages and disadvantages of using some techniques under particular experimental conditions. However, little is known about meta-analyses and systematic reviews of VR evaluations. Most of the surveys done in VR navigation list implementations of techniques in VR systems, but there is not a global overview of the interactions between techniques and the factors assessed. Such analyses could help to determine which factors have been more studies and also the percentage of each technique assessed (e.g. we may suggest there are more studies on teleportation than treadmills) to identify what would be the future challenges in the evaluations of VR locomotion techniques.

Exploring New Metrics and Factors

Metrics are used to objectively evaluate locomotion techniques. We reviewed in section 3.2 the main metrics used by authors to understand the impact of locomotion techniques under experimental conditions. Most of these evaluations and metrics are not related to users' body segments motion or trajectory performed in both VE and RE. However, the purpose of locomotion techniques is to update the user's viewpoint in the VE, requiring users to move. Then, metrics based on users' motion should be more explored. For instance, they could provide significant new insights about this unknown phenomenon (e.g. UPD is mostly an unconscious concept where users do not notice their movements) and could help to improve users' navigation by understanding better users' gait and posture during navigation in VEs. In addition, more and more HMD provides eye-tracking capabilities, that enable to record easily gaze activity during VR navigation. Considering this data in VR studies could be interesting since little is known about the potential of gaze data to improve locomotion techniques. Maybe in the future, we could be able to automatically determine whether users are aware or able to detect a rotation gain based on their posture and gaze activity. Last, VR became an experimental tool to study human behavior. Then it is important to reproduce experimental conditions in VEs close to the ones experienced in REs. Such new metrics could give additional information about the differences between human behavior in VEs and REs.

Evaluating Locomotion Techniques at the Individual Level

More and more locomotion techniques are designed by varying either the input devices, the control law to update users' viewpoints, or adding sensory feedback. When designing a locomotion technique, we suggest that the main priority should be to minimize its impact on users' perception and action. We are aware that human factors can impact users' experience during navigation in VR, yet, most of the techniques do not consider while designing techniques. The ideal locomotion techniques should suit every user regardless of the variability of human factors, resulting in user-adapted techniques. However, the inter-subject variability is mostly assessed in VR evaluations but rare are the intrasubject variabilities explored. In our studies, we noticed high intrasubject variability but we were not able to have explanations of this variability. Therefore, if we wish to design new techniques that can improve users experiences in VR, future work must consider the intrasubject variability.

Improving or Creating New Evaluation Frameworks

Taxonomies of locomotion techniques enable us to understand the differences between several groups of locomotion techniques (e.g. walking versus steering versus teleportation). Most of VR evaluations compare techniques of different taxons to show which technique suits better to the given tested experimental conditions. Yet, fewer evaluations are performed to compare techniques from the same taxons. Intragroup variability between techniques is also important because minor changes in the implementation (e.g. the transfer function to update the speed in the VE) can alter user behavior. While we have already gathered a lot of results regarding evaluations of techniques from different taxons, we should rather pay more intention to more low-level features of the implementation of locomotion techniques (e.g., the control law).

So far, we know that each locomotion techniques have their own advantages and shortcomings and we mostly know the differences between a group of locomotion techniques for several experimental conditions. Our goal as designers and researchers is to use appropriate techniques that fit a given navigation task. To achieve this, we must consider the factors we want to maximize for a given VR application (e.g., find the trade-off between performance, accuracy, and presence). Yet, this mapping depends on extrinsic factors that can influence locomotion techniques and users' actions. Since a systematic evaluation of a locomotion technique cannot be considered, the following research questions could be arisen in the future to extend the literature of VR locomotion techniques: Which would be the new metrics to assess existing factors in VR locomotion? What are the external factors that can influence locomotion techniques? Which metrics are linked to assess navigation tasks? How the control law could be improved to be adapted to specific navigation tasks?

10.2.2 Redirected Steering: Concept of a New Locomotion Technique

As soon as we noticed in chapter 5 that performing a repetitive slalom with a steering technique could produce some UPD, we wondered if we could minimize UPD in order to prevent users from reaching the physical boundaries of the workspace. First, we needed to assess UPD based on the experimental observations we found (that we described in chapter 6). Then we could consider the design of a new technique that would reduce UPD during steering. Inspired by redirected walking techniques, we believed that we can design a technique sharing the same philosophy but for steering locomotion. We would call it *Redirected Steering* and its design would be based on a steering control law that maintains the users at the center of the tracking area while navigating. In this subsection, we present its concept and briefly discuss a proof-of-concept example.

We considered a first paradigm *reorient to center* (Figure 10.1) inspired from redirected walking controller (steer to center). The challenge would be then to cunningly update users heading to the center of the workspace with respect to the potential UPD that may occur during the navigation task. To achieve this, we considered several parameters that we will describe hereafter.

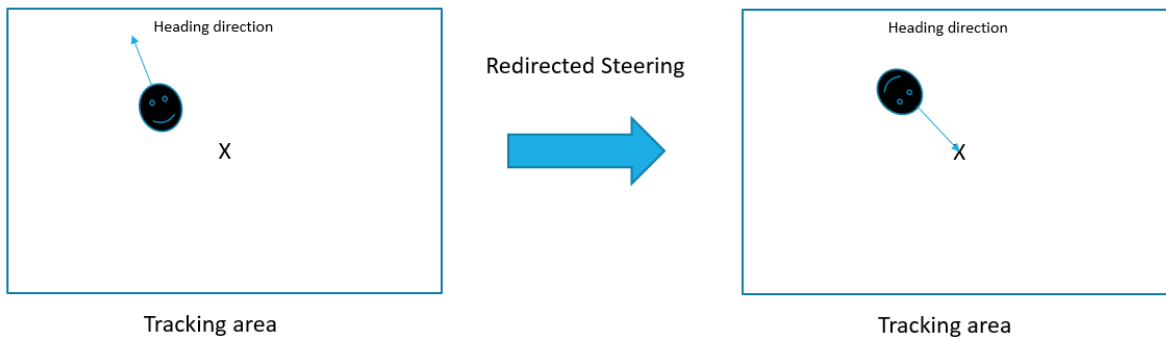


Figure 10.1 – Redirected Steering: Reorient to Center Paradigm

Regarding the input we could use in the control law, we considered that the user position and orientation in both VE and RE are needed to know in which direction we should reorient the users. In addition, based on the results observed in Part III, translational and rotational speeds should be considered as well. Recent preliminary work showed that considering the curvature of the path could be an interesting metric (Nie and Rosenberg 2021). Another heuristic we discussed was the intensity of the redirection based on where the users are in the RE. For instance, we could split the workspace into zones with a given geometry (e.g. squares, circles,

or even isocurves) that would provide how prior the redirection should be (i.e. the closer the users is to the center of the workspace, the less necessary the redirection should be). Then, we considered when the redirection should be applied based on users' actions during navigation. Indeed, results from chapter 8 suggested that it may be easier to apply a gain while users are performing a rotation with a virtual translation. It is easy to determine at each timestep whether users are performing a virtual translation or not while rotating. Even though we know where the users are located and what they are performing, we still do not know how we should apply the rotation gain. We imagined that we could compute a redirection angle α as the amount of rotation to perform so that users heading are aligned with the center of the workspace as shown in Figure 10.1. Since we do not control how the users will rotate, we had to define whether the rotation they are performing is either increasing or decreasing α . Some computation should be required to determine whether users are performing a rotation that minimizes α or not. Based on all these information, we could design a control law that update users virtual camera by applying a rotation gain based on α . One idea could be to rather increase or decrease the user's physical rotation based on the amount of rotation they had to perform to face the center of the workspace.

Since there are numerous factors to consider while designing such a technique, we imagined that the simulator presented in chapter 6 to assess UPD could be used to optimize the parameters of the *Redirected Steering* technique. For instance, we could test several implementations of *Redirected Steering* by varying its control law and determine through simulation-based evaluations which are the values that could minimize the UPD for a given navigation task. Then a user study could help to confirm the hypothesis we had thanks to the simulations.

While the concept of *Redirected Steering* is still hypothetical, we are enthusiastic regarding its potential benefits to minimize UPD while using steering techniques. The studies presented in this manuscript were motivated by this idea that came out during the thesis and early developments showed encouraging perspectives. However, we are aware that the design space of such technique is sparse and additional implementations then evaluations should determine the usability of such navigation paradigm for VR.

*« You start off as Mr. X, who happens to be an engineer, and
sooner or later you're just an engineer who happens to be called
Mr. X. »*

Antal Szerb, *Journey By Moonlight*

11

Epilogue

Human locomotion in VR is a large and recent research field. Understanding the way users perceive and interact with their REs has been studied for decades in the field of human movement science but now we must reconsider all the knowledge we have to determine whether it remains true or not in VEs. Humans will always seek for exploring REs, and would, even more, seek for exploring VEs as we can design and generate an infinite number of VEs. Yet, the means for exploring REs differ from the ones we have in VR. Evaluations enable to have guidelines about which technique or factors can improve locomotion in VEs, but there is still numerous combination of factors (e.g., the impact of both translational and rotational control law on users movement, the impact of rotation gains on users UPD) involved that have not to be explored which could influence the perception-action loop. In particular, the main objective to make locomotion comfortable in VR systems should be to make the user interface as transparent as possible to minimize its influence on the perception-action loop. In my opinion, minimizing the influence of the locomotion technique on users' perception-action loop could be achieved by following two guidelines. On one hand, we should consider improving the evaluations of locomotion techniques (e.g., using new evaluation methods and finding new metrics than the ones used in VR evaluations). On the other hand, we should also consider the type of task and

the VE that could make some techniques not affordable. That would imply VR practitioners to always consider the environment as a variable. Yet, most of the studies focus on the locomotion technique itself instead of varying the environment. The studies conducted during this thesis tried to be in line with these two guidelines. They showed that there are interactions between the users, the interface they used, and the navigation task. From the perception and sensation of locomotion to the action performed in a given task, there are infinite interactions that still need to be assessed. Maybe in the future, navigating in VR would be as natural as walking in RE but researchers still have to first better understand the human factors related to locomotion in VR to have a global overview, then to consider that the locomotion technique must be adapted to each user. While the first consideration seems affordable and has been studied a lot in VR literature, the second one seems much harder to reach. It is important to keep in mind that the perfect locomotion technique does not exist. Taking into account individual characteristics might be an interesting option to improve the locomotion interface for navigating in VEs. We could compound Sutherland's VR description in *The Ultimate Display* with the following words: « the perfect locomotion technique would be transparent enough to explore virtual environments without even realizing users are using it. »

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Résumé Long en Français

Cette thèse, intitulée « Vers des Techniques de Navigation Adaptées à l'Utilisateur dans les Environnements Virtuels : Étude des Facteurs Influençant la Navigation des Utilisateurs en Réalité Virtuelle » décrit les recherches contribuant à la littérature sur la navigation dans les environnements virtuels (EV). L'objectif est de fournir de nouvelles informations sur l'influence de certaines conditions expérimentales sur la navigation des utilisateurs en Réalité Virtuelle (RV) ainsi que de nouvelles méthodes d'analyse pour évaluer les techniques de navigation afin de mieux comprendre la perception et l'action des utilisateurs lorsqu'ils naviguent en RV.

Le Désir de Naviguer et d'Explorer des Environnements

Depuis mon 20^{ième} anniversaire, j'ai le désir d'explorer et de découvrir de nouveaux endroits. J'ai commencé à m'intéresser aux peuples nomades et à leur mode de vie qui est principalement basé sur le voyage. L'opinion des sédentaires sur les peuples nomades est controversée : certains semblent aussi bien fascinés que repoussés à leur égard. Libres de leurs mouvements et peu prévoyants, ils sont souvent considérés comme des hors-la-loi, des sauvages qui vivent dans la nature et qu'il faudrait civiliser. Pourtant, les humains ont toujours cherché à explorer les environnements qui les entourent pour diverses raisons (figure 11.1). À la préhistoire, le genre *Homo* devait explorer son environnement pour trouver de la nourriture, survivre et se reproduire ; les capitaines Phéniciens, l'une des civilisations les plus prolifiques au niveau de la navigation et du commerce durant l'Antiquité, utilisaient des carnets de voyage, des points de repère le jour et la lune et les étoiles la nuit, pour explorer en toute sécurité les mers non découvertes ; au Moyen Âge, des philosophes, des astronomes et des mathématiciens ont proposé de nouvelles interprétations du fonctionnement du monde et de l'univers ; entre le XV^{ième} et le XVIII^{ième}, à l'Âge des découvertes, les défis économiques entre les pays européens ont conduit à plusieurs explorations à travers le monde ; de nos jours, les problèmes liés au réchauffement climatique ou à la guerre rendent des régions invivables et obligent leurs habitants à migrer vers des régions plus sûres. La variable commune à ces exemples est que, lors de l'exploration et de la navigation, les humains ont toujours dû interagir avec leur environnement afin d'atteindre de nouvelles destinations. Qu'il s'agisse de marcher dans des plaines ou des montagnes, ou encore d'être en orbite dans une fusée spatiale, il existe de nombreuses façons de se déplacer et d'aller d'une destination à une autre. Quel que soit l'environnement, le moyen de navigation, la tâche à accomplir ou la destination à atteindre, les humains ont toujours trouvé des raisons d'explorer et d'interagir avec leur environnement pour repousser les limites de leur monde connu.

Si la locomotion dans un environnement est une tâche quotidienne essentielle qui s'effectue



FIGURE 11.1 – La navigation humaine dans les environnements à travers l’histoire (de gauche à droite) : chasseurs à l’ère préhistorique ; phoeniciens naviguant durant l’Antiquité ; l’astrolabe inventé au Moyen Âge pour effectuer la navigation céleste ; les expéditions européennes ont fourni de nouvelles ressources et informations sur les environnements qui les entouraient ; Mihály Munkácsy - Cigány család, une peinture du *XIX^{ième}* siècle représentant une famille nomade en Hongrie ; ; La fusée, permettant l’exploration spatiale, a fait l’objet d’une attention particulière ces dernières années

naturellement sans nécessiter une forte demande cognitive pour les personnes neurotypiques, son traitement neuronal n’en est pas moins complexe. Une navigation réussie vers un but implique un transport sûr du corps tout en évitant les obstacles dans l’environnement (WINTER 1991). Ensuite, l’homme doit percevoir un environnement donné et son état actuel afin d’identifier où il se trouve, où sont les objets, quelles sont les relations entre les objets et quelles sont les actions possibles à effectuer (MARSHALL et FINK 2001). Gibson, le fondateur de la théorie écologique de la perception, affirme qu’il existe un couplage fort entre l’homme et son environnement. Il mentionne notamment que « Nous devons percevoir pour nous déplacer, mais nous devons aussi nous déplacer pour percevoir » (GIBSON 1979). Cela signifie que les humains interagissent avec l’environnement par le biais d’une boucle de perception-action qui permet la perception d’informations sensorielles (par exemple, un indice de mouvement important, appelé le flux optique, perçu pendant la navigation est le modèle de mouvement relatif des objets entre le marcheur et l’environnement) de l’environnement afin qu’une action puisse être exécutée par des commandes motrices, mais aussi que le mouvement généré fournisse ensuite de nouvelles infor-

mations pour percevoir et exécuter de nouveaux mouvements. Ainsi, il est possible d'effectuer des interactions dans différents environnements tels que faire des courses dans un supermarché, courir dans un parc ou conduire un véhicule. Les progrès technologiques et scientifiques dans le domaine de l'informatique graphique ont permis la simulation d'environnements virtuels (EV) en 3 dimensions. Il est désormais possible de découvrir de nouveaux environnements qui n'ont jamais existé auparavant, et surtout de les explorer.

Découvrir de Nouveaux Environnements en Réalité Virtuelle

Lorsque je mentionnais que je faisais un doctorat dans le domaine de la Réalité Virtuelle (RV), cela suscitait souvent des réactions intéressantes. L'existence de la RV suscite la curiosité des gens, où la RV semble faire référence à une réalité différente qui n'est pas la réalité actuelle, ou même une réalité qui ne parvient pas tout à fait à être réelle. D'autre part, la RV a reçu beaucoup d'attention depuis sa première caractérisation en 1965 par Ivan Sutherland. Dans son essai, *The Ultimate Display*, il décrit la RV comme « une pièce à l'intérieur de laquelle l'ordinateur peut contrôler l'existence de l'objet, dans laquelle l'ordinateur peut contrôler l'existence de la matière. Une chaise affichée dans une telle pièce serait être assez bonne pour s'y asseoir. Des menottes affichées dans une telle pièce seraient contraignantes, et une balle dans une telle pièce serait fatale. (SUTHERLAND 1965) » La RV est encore un sujet de recherche récent et ses concepts sous-jacents sont en constante évolution. Dans ce manuscrit, nous nous référons à la définition donnée par (ARNALDI et al. 2003) :

La réalité virtuelle est un domaine technique et scientifique qui utilise l'informatique et les interfaces comportementales afin de simuler le comportement d'entités 3D dans un monde virtuel qui interagissent en temps réel entre elles et avec l'utilisateur en immersion pseudo-naturelle par des canaux sensori-moteurs.

La RV permet de créer de nouveaux environnements en trois dimensions générés par ordinateur dans lesquels les utilisateurs peuvent percevoir et interagir (JERALD 2015). Pour offrir une expérience convaincante et naturelle, l'interaction dans les VE doit être aussi similaire que possible à l'interaction dans les environnements réels (ER). La RV doit alors fournir un rendu en temps réel des EV, un espace de travail physique dans lequel les utilisateurs peuvent utiliser le système de RV et des interactions.

L'être humain tente toujours de repousser les limites de l'exploration, mais il est confronté à de fortes contraintes qui l'empêchent parfois de découvrir de nouveaux territoires. Par exemple, sous nos pieds, il existe des zones inconnues qui constituent un vaste terrain de jeu pour les spéléologues. Concernant les fonds marins, seuls moins de 10% du relief au-delà de 200 mètres de profondeur sont connus. L'exploration de l'espace soulève des questions écologiques et éthiques pour ne pas reproduire les mêmes erreurs que par le passé. En revanche, la RV et la simulation d'EVs permettent de nouvelles possibilités concernant l'exploration humaine (figure 11.2). Par exemple, il est possible de reproduire des ERs existants en RV, comme dans l'application *Google Earth VR*. Nous pouvons créer de nouveaux EV comme des forêts ou des paysages virtuels, mais nous pouvons également défier les lois de la physique et de la géométrie en créant des environnements qui suivent des règles différentes de celles du monde réel (par exemple, des EV non euclidiens, des EV avec des fractales infinies...). Ainsi, le désir de naviguer dans les EVs reste l'un des éléments clés de la RV, mais la manière d'explorer les EVs à en RV diffère de celle de la vie réelle car des interfaces supplémentaires sont nécessaires.



FIGURE 11.2 – Des EVs réalistes aux EVs irréalistes (de gauche à droite) : Une vue du parc Yellowstone dans l'application *Google Earth VR* ; Une forêt virtuelle issue du jeu *Forest VR* ; Un EV 3D composé de fractales.

Dans la plupart des systèmes de RV, les utilisateurs sont immergés dans les EVs en portant des dispositifs d'affichages (par exemple, des écrans, des CAVE (CRUZ-NEIRA et al. 1992), un casque avec affichage à tête haute (HMD), des lunettes stéréoscopiques) qui permettent de visualiser l'EV et les technologies de suivi 3D permettent les mouvements dans l'EV. Au cours de la dernière décennie, les prix des HMD ont diminué et sont devenus abordables pour le grand public, ce qui a augmenté le nombre d'applications en RV basées sur les HMD dans lesquelles les utilisateurs sont immergés tout en ne voyant plus l'ER. Cette occultation peut influencer la perception de l'utilisateur, puisque les informations visuelles recueillies entre les ERs et les EVs diffèrent, et les actions de l'utilisateur, puisque l'interface utilisateur fournie par le système de RV implique différentes actions à effectuer.

En particulier, la façon dont les utilisateurs naviguent dans les EVs peut être différente de la

marche réelle dans les ERs. Pour que l'utilisateur ait un retour cohérent entre les actions qu'il effectue et la perception dans l'EV, des caméras virtuelles sont utilisées. Le principe consiste à contrôler une caméra virtuelle dans l'EV qui s'adapte aux mouvements et aux actions de l'utilisateur tout en respectant les règles définies par le système de RV. Ainsi, lors d'une tâche de navigation dans un EV, l'utilisateur devra contrôler la position et l'orientation ainsi que la vitesse et l'accélération de la caméra virtuelle. Pour cela, plusieurs métaphores de navigation ont été conçues pour interpréter les actions de l'utilisateur afin de mettre à jour les caractéristiques de la caméra virtuelle. Par exemple, il est possible d'utiliser soit la marche naturelle comme dans les ERs, soit un joystick pour diriger la caméra virtuelle. Des métaphores de navigation irréalistes existent également, comme le fait d'être téléporté d'un endroit à un autre instantanément ou de voler comme un super-héros. Ces interactions fournies par le système de RV peuvent plus ou moins stimuler les systèmes sensoriels, ce qui constitue le fil conducteur de cette thèse : les dispositifs d'interaction en RV, les techniques de navigation en RV et l'expérience des utilisateurs en RV peuvent affecter la boucle perception-action des utilisateurs et en particulier la façon dont les utilisateurs naviguent dans les EVs.

Les Contraintes de Navigation en Environnement Virtuel

Comme dans les ERs, les utilisateurs doivent se déplacer dans l'EV pour effectuer des actions. Ce mouvement peut être un simple mouvement de la tête pour observer des objets, mais aussi un mouvement pour visiter un monument ou pour se déplacer autre part. Les utilisateurs se déplaçant dans les EVs sont confrontés à plusieurs défis : ils doivent être capables de se localiser dans l'EV, de chercher les destinations où ils doivent se rendre et de savoir comment s'y rendre. Par conséquent, la navigation implique des actions pour se déplacer vers une nouvelle position et la recherche d'un itinéraire basé sur un processus cognitif pour définir un chemin dans l'environnement. Dans ce manuscrit, nous nous concentrerons uniquement sur les mouvements qui sont physiquement réalisables pour un être humain.

La locomotion est une tâche courante effectuée dans notre vie quotidienne et la marche humaine bipède reste la technique de locomotion la plus courante dans les ERs ([STEINICKE et al. 2013](#)). De même, la locomotion est une activité importante dans les EVs car elle permet aux utilisateurs d'explorer le monde virtuel. Bien que des techniques de locomotion virtuelle (par exemple, la téléportation ou les techniques basées conduites, dites *steering*) puissent être utilisées, la marche réelle dans les systèmes de RV pourrait être intéressante puisqu'elle est censée être la forme de locomotion la plus écologique ([USOH et al. 1999](#)). L'implémentation

de la marche réelle dans les systèmes de RV se fait généralement en faisant correspondre la position et l'orientation réelles de la tête de l'utilisateur à ses positions virtuelles. Ce mappage isomorphe permet de faire correspondre les mouvements réels aux mouvements virtuels (par exemple, marcher d'un mètre en avant dans l'ER correspond à marcher d'un mètre en avant dans l'EV). Cela fournit un retour sensoriel cohérent entre les mouvements réels et virtuels. Cependant, la marche nécessite un grand espace de travail physique pour explorer les EVs que les systèmes de VR typiques n'ont pas (un sondage réalisée sur Reddit il y a quatre ans a montré que 90% des utilisateurs de RV avaient un espace de travail inférieur à 3×3 mètres.¹). Ceci illustre un défi majeur de la navigation RV qui consiste à créer de nouvelles techniques de locomotion permettant une navigation libre et infinie dans un EV plus grand que l'espace de travail physique et basé sur la marche réelle. Par exemple, des solutions matérielles telles que des tapis roulants omnidirectionnels (SCHWAIGER et al. 2007a), ou des tuiles de robot de mouvement (IWATA et al. 2005) ont été conçus pour permettre de marcher dans des EVs. Cependant, ils sont encombrants, coûteux et difficiles à réutiliser dans les configurations de RV les plus courantes. Ainsi, dans ce manuscrit, nous nous concentrons plutôt sur les solutions logicielles qui sont plus utilisées par les utilisateurs de RV.

Parmi les solutions alternatives qui ont été proposées pour la navigation virtuelle en RV (LAVIOLA et al. 2017), certaines encouragent le mouvement physique des utilisateurs (par exemple, la marche redirigée ou la marche sur place), tandis que d'autres nécessitent un mouvement minimal de la part des utilisateurs, comme les techniques de *steering* ou la téléportation. Chaque technique a ses propres avantages et inconvénients, et la littérature sur le sujet de la RV s'est beaucoup concentrée sur l'évaluation et la comparaison des techniques de navigation entre elles. Un problème majeur des techniques virtuelles est qu'elles peuvent altérer la boucle perception-action. Par exemple, les utilisateurs peuvent porter un HMD et être assis dans leur canapé. Ils peuvent utiliser une manette de jeu pour se déplacer dans l'EV sans se déplacer dans le ER. Dans ce cas, le retour visuel dans le HMD fournit une sensation de mouvement aux utilisateurs, mais ils ne se déplacent pas dans l'ER, ce qui crée une divergence entre le retour sensoriel observé dans le HMD et l'absence de retour vestibulaire qui est fourni pendant la marche. Dans le cas de la navigation en RV, un décalage entre les mouvements attendus et les mouvements actuels pourrait induire un sensation similaire au mal des transports (REASON 1978) ou le mal des simulateurs (*cybersickness*) (LO et SO 2001).

Ainsi, la conception des techniques de navigation est confrontée à deux défis principaux.

1. https://www.reddit.com/r/Vive/comments/4fq4a/vr_roomscale_room_size_survey_answers_analysis/

Premièrement, les techniques de locomotion doivent permettre une locomotion illimitée et sans contraintes dans les EVs pendant les tâches de navigation. Pour cela, il faut soit disposer d'un espace de travail suffisamment grand pour permettre une marche naturelle (ce qui n'est pas le cas dans la plupart des cas), soit fournir des techniques qui ne nécessitent pas de mouvements complets de la part des utilisateurs. Deuxièmement, les techniques de navigation en RV ne reproduisent pas nécessairement la marche naturelle et peuvent donc fournir un retour perceptif et des sensations différentes.

Objectifs et Axes de Recherche

Bien que de nombreuses études aient été consacrées à la conception et à l'évaluation des techniques de navigation dans les EVs, il reste des défis importants à relever pour améliorer leur conception. Par exemple, les techniques *steering* peuvent encore être inconfortables car elles créent un décalage entre le mouvement virtuel et physique perçu par le système visuel ([LANGBEHN et al. 2018a](#)). Les techniques de redirections peuvent briser le sentiment de présence lors de la navigation ([WILLIAMS et al. 2007](#)). La marche redirigée, nécessite toujours un espace physique plus important que celui des utilisateurs moyens pour réaliser une marche infinie.

Puisque les dispositifs d'affichages de RV et les interfaces de navigation modifient la boucle perception-action des humains, il est crucial de prendre en compte les facteurs de perception humaine lors de la conception des techniques de navigation. Un défi scientifique de la navigation en RV consiste alors à trouver les facteurs qui peuvent influencer le plus le comportement des utilisateurs et quelles sont les limites perceptives des utilisateurs lorsqu'ils naviguent en RV. Une meilleure compréhension de la perception et du comportement des utilisateurs lors de la navigation en RV permettrait de comprendre comment améliorer et fournir une interface de locomotion capable de réaliser une navigation sans contrainte dans les EVs tout en maximisant le confort des utilisateurs. En outre, un autre défi consiste à créer des expériences de navigation en RV qui reproduisent au mieux les situations réelles. Puisque la RV peut être utilisée comme un outil expérimental pour étudier le comportement humain ([TARR et WARREN 2002](#)), il est important de se rapprocher des situations écologiques rencontrées dans les ERs pendant les expériences en RV.

Une solution pour améliorer les techniques de navigation est alors de considérer les niveaux auxquels la boucle perception-action est altérée. La perception humaine implique des facteurs internes par l'intégration multi sensorielle, mais aussi des facteurs externes puisque la tâche et

le contexte de l'environnement influencent le comportement de navigation (par exemple, les marcheurs regardent une région de l'environnement afin de maximiser le degré d'information pour marcher en toute sécurité (MARIGOLD et PATLA 2007)). De plus, les techniques de navigation font intervenir plusieurs facteurs dont des facteurs liés à l'utilisateur (âge, sexe, pied dominant...), le contexte écologique dans lequel la navigation serait utilisée (tâche à réaliser, type d'EV...), mais aussi des paramètres concernant l'interface utilisateur elle-même (impact du HMD, vitesse de navigation, manipulation du champ de vision et du flux optique...). Le lien entre les utilisateurs et les interfaces d'interaction RV doit par conséquent être considéré dans les deux sens puisque les utilisateurs doivent apprendre à utiliser le système afin d'interagir avec lui, mais en même temps le système pourrait aussi s'adapter aux actions de l'utilisateur afin de réduire son impact sur la perception des utilisateurs. Ainsi, considérer les connaissances de la biomécanique de la marche humaine et de la perception en plus de la littérature sur la RV peut être une approche intéressante si nous voulons réduire l'impact de la RV sur la boucle perception-action des utilisateurs.

figure 11.3 décrit l'approche de recherche que nous avons utilisée au cours de la thèse pour étudier l'impact des techniques de locomotions in VR sur la boucle perception-action des utilisateurs. Les utilisateurs interagissent avec leur environnement avec une boucle de perception-action. Pourtant, dans les applications logicielles de RV, les techniques de locomotion sont utilisées pour mettre à jour le point de vue virtuel des utilisateurs dans l'EV. Les utilisateurs reçoivent ainsi un retour visuel (flèche rectangulaire verte) qu'ils peuvent percevoir afin d'effectuer de nouvelles actions (flèche courbée bleue). Les actions de l'utilisateur comprennent ses mouvements réels dans l'espace de travail (flèche courbée rouge), qui sont des indices de mouvement supplémentaires perçus par l'utilisateur lorsqu'il navigue dans l'environnement virtuel (flèche courbée verte), ainsi que le dispositif d'entrée qu'il utilise pour interagir avec l'environnement virtuel (flèche rectangulaire bleue). Dans ce manuscrit, nous avons étudié comment certains facteurs des techniques de locomotion en RV (représentés par des losanges) pouvaient influencer le mouvement réel des utilisateurs et nous avons mesuré cette influence avec des métriques (représentées par des ellipses). Nous présentons des contributions analysant l'impact de la technique de locomotion sur la boucle action-perception qui sont divisées en deux axes de recherche et un axe de recherche transversal.

Axe 1 : Influence de la technique de navigation et la tâche sur les mouvements des utilisateurs

De nombreuses techniques de navigation existent pour explorer les EVs et leurs caractéristiques sont connues pour influencer la navigation et les expériences des utilisateurs dans la RV

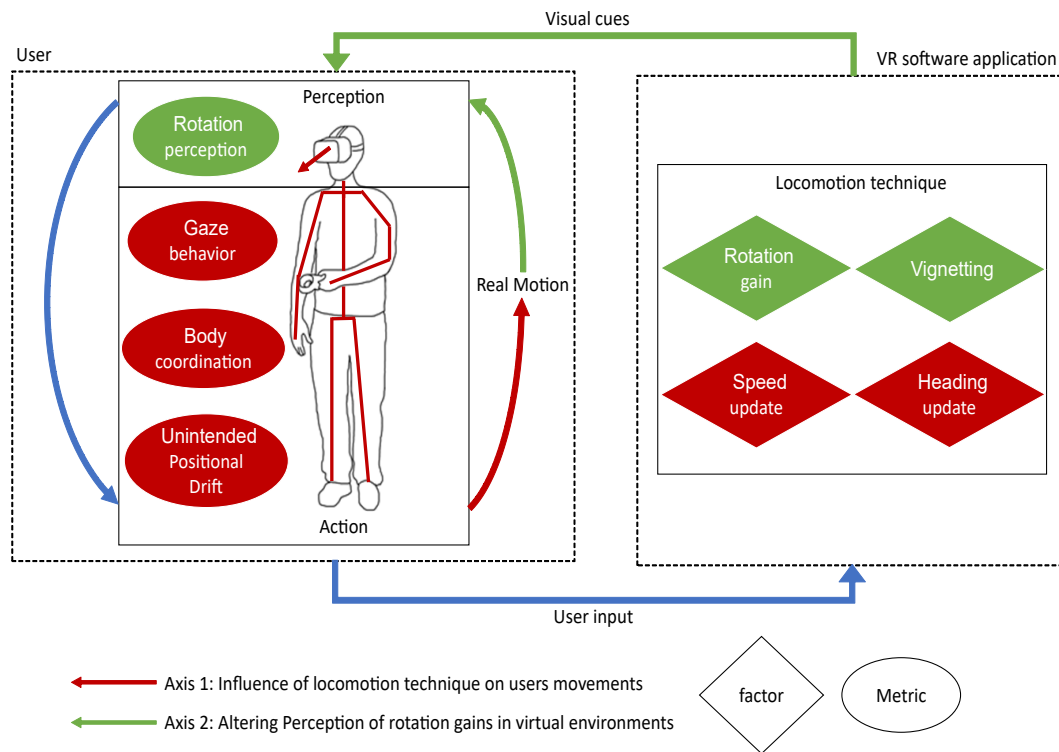


FIGURE 11.3 – Représentation de certains facteurs (représentés par des losanges) influençant la boucle perception-action des utilisateurs. Nous avons mesuré l'impact de ces facteurs à travers des métriques (représentées par des ellipses) mesurant le comportement des utilisateurs lors de la navigation en RV avec des techniques de locomotion. Les facteurs ont été séparés en deux axes de recherche, l'un se concentrant sur l'influence de la technique de locomotion sur les mouvements des utilisateurs (en rouge), l'autre sur la façon dont nous pouvons modifier la perception des gains de rotation (en vert).

(par exemple, le *cybersickness*, les préférences, le confort...). Le type de tâche à accomplir peut également influencer la façon dont les utilisateurs naviguent en RV. Pourtant, l'impact de ces techniques sur les mouvements des utilisateurs et les trajectoires effectuées a été moins étudié dans la littérature. Cet axe se concentre sur la façon dont l'interface utilisateur, en particulier la technique de navigation qui permet les mouvements dans l'EV, et le type de trajectoires à effectuer dans l'EV, peuvent modifier les comportements des utilisateurs. Notre objectif était de trouver des résultats concernant l'impact de l'interface de navigation sur la locomotion dans les EVs. Nous avons réalisé une première expérience pour explorer les différences entre la marche, le *steering* et le mouvement passif sur le regard des utilisateurs et le comportement des segments corporels pendant des trajectoires curvilignes. Nous avons montré que la technique de navigation peut influencer la coordination corporelle pendant la navigation en RV. Ensuite, nous avons étudié

l'impact de la loi de contrôle (et en particulier la mise à jour de la vitesse) pendant une tâche de slalom en utilisant une technique de *steering*. Nous avons montré que la cinématique des utilisateurs est modifiée par la loi de contrôle et que la façon dont la vitesse est mise à jour pour naviguer dans les EVs joue un rôle sur le comportement des utilisateurs. Enfin, nous avons analysé l'impact que les techniques de *steering* peuvent avoir sur les déplacements involontaires des utilisateurs dans l'espace de travail physique. Nous avons proposé une méthodologie complète pour caractériser, modéliser et simuler ce phénomène particulier.

Axe 2 : Influence des informations visuelles sur la perception des rotations

La perception en RV a été largement étudiée. En particulier, pour améliorer les techniques de navigation, la littérature s'est intéressée à la perception de la rotation physique et à la manière dont les utilisateurs peuvent différencier leur rotation physique des rotations virtuelles amplifiées (gain de rotation). Il est fondamental de comprendre comment les utilisateurs perçoivent ces rotations dans différentes conditions expérimentales afin d'améliorer les techniques de navigation. Cet axe se concentre sur la façon dont la manipulation du retour sensoriel fourni par le système de RV à l'utilisateur, et en particulier les indices visuels, pourrait influencer la façon dont les utilisateurs perçoivent les rotations dans les EVs. Dans une première étude, nous avons exploré comment la manipulation du champ de vision de l'utilisateur (restreindre la vision périphérique en ajoutant du flou ou en réduisant le contraste) peut être utilisée pour modifier la perception de la rotation en RV. Dans une seconde étude, nous avons exploré comment la vitesse de translation et de rotation dans l'EV pouvait modifier la perception des gains de rotation. Nos résultats ont montré que la manipulation des indices visuels ainsi que le flux optique modifient la perception des gains de rotation, mais qu'elle peut également modifier le comportement des utilisateurs, comme l'activité de leur regard et leur cinématique.

Axe transversal : Nouvelles métriques d'évaluations et analyses pour évaluer les techniques de navigation

Cet axe fournit des indications sur de nouvelles façons d'évaluer les techniques de navigation en considérant les interactions entre les différents facteurs de niveau (perception \times interface utilisateur \times tâche de navigation \times action). En particulier, nous avons démontré de nouveaux résultats concernant les modèles et le comportement du regard pendant la navigation, et proposé de nouvelles analyses statistiques qui pourraient améliorer la compréhension de la navigation des utilisateurs en EVs. L'objectif est de sensibiliser les chercheurs en RV à l'utilité de considérer de nouvelles métriques d'évaluation dans les évaluations des techniques de navigation en RV ainsi que de prendre en compte l'utilisateur au centre de la conception de ces techniques afin d'évaluer l'impact de chaque facteur sur la boucle perception-action des utilisateurs.

Titre : Vers des Techniques de Navigation Adaptées à l'Utilisateur dans les Environnements Virtuels : Étude des Facteurs Influençant le Navigation des Utilisateurs en Réalité Virtuelle

Mot clés : Réalité Virtuelle, Techniques de Locomotion, Perception, Locomotion

Résumé : La navigation est une interaction fondamentale en Réalité Virtuelle (RV) qui permet aux utilisateurs de modifier leur point de vue afin d'explorer l'Environnement Virtuel (EV). Des techniques de locomotion alternatives à la marche ont été explorées pour permettre aux utilisateurs de naviguer quelle que soit la taille de l'espace de travail physique. Cependant, l'utilisation de ces techniques peut influencer l'expérience des utilisateurs car l'interface de locomotion peut modifier la façon dont les utilisateurs perçoivent et exécutent leurs mouvements. Ce manuscrit vise à mettre en évidence les facteurs liés aux techniques de locomotion qui pourraient influencer la perception et l'action des utilisateurs lorsqu'ils naviguent en RV.

Pour ce faire, nous nous sommes concentrés sur deux axes : (1) l'influence des techniques de locomotion sur les mouvements des utilisateurs, en particulier comment la manière de mettre à jour le point de vue de l'utilisateur peut modifier leurs coordinations. (2) Comment modifier la perception des gains de rotation dans les EVs, où nous avons évalué d'une part, si la modification du champ de vision, et d'autre part, la vitesse de translation et de rotation, peuvent modifier la perception des gains de rotation dans les EVs. Ces résultats contribuent à la compréhension du comportement des utilisateurs lors de la navigation dans les EVs et sont discutés pour améliorer la conception des techniques de locomotion en RV.

Title: Towards User-Adapted Navigation Techniques in Virtual Environments: Study of Factors Influencing Users Behavior in Virtual Reality

Keywords: Virtual Reality, Locomotion techniques, Perception, Locomotion

Abstract: Navigation is a fundamental interaction in Virtual Reality (VR) that enables users to update their viewpoint in order to explore the Virtual Environment (VE). Alternative locomotion techniques to natural walking have been explored to enable users to navigate infinitely regardless of the size of the physical workspace. However, the use of such techniques can influence users' experience as the locomotion interface can modify the way users perceive and perform movements. This manuscript aims at highlighting factors related to the locomotion technique that could influence users' perception and action during a navigation task in VR. To achieve this, we focused

on two axes: (1) the influence of the locomotion techniques on users' movements, where we investigated how either the way to update heading or speed in the VE could modify users' movements and coordination. (2) How to alter the perception of rotation gains in VEs where we assessed on one hand, whether modification of the Field of View and on the other hand, translational and rotational speed, could alter the perception of rotation gains in VEs. Altogether, these results contribute to the understanding of users' behavior while navigating in VEs and are discussed to improve the design of locomotion techniques in VR.