

# Design and Evaluation of User-Centric Gestures for Locomotion in HMD-VR Interfaces for a Seated Position

*Thesis*

*Submitted in fulfillment of the requirements for the degree of*

**Doctor of Philosophy**

By

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## DECLARATION

I hereby declare that the work contained in this thesis entitled “Design and Evaluation of User-Centric Gestures for Locomotion in HMD-VR Interfaces for a Seated Position” is my work and done under the guidance of Dr. Keyur Sorathia, Associate Professor at the Department of Design , Indian Institute of Technology Guwahati (IITG), Assam, India. To the best of my knowledge it contains no materials previously published or written by another person or substantial proportion of the material which has been accepted for the award of any other degree or diploma at IITG or any other educational institution, except where the due acknowledgement is made in this thesis. Any contribution made to the research made by others, with whom I have worked at IITG or elsewhere, is explicitly acknowledged in this thesis. I also hereby declare that the intellectual content of this thesis is the product of my own work, and as per general norms of reporting research findings, due acknowledgements have been made wherever the research findings of other researchers have been cited in this thesis.

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## CERTIFICATE

This is to certify that the work contained in this thesis entitled “**Design and Evaluation of User-Centric Gestures for Locomotion in HMD-VR Interfaces for a Seated Position**” submitted by Mrs. Priya Vinod to the Indian Institute of Technology Guwahati, for the award of the degree of Doctor of Philosophy in Design is a record of bonafide research work carried out by her under my supervision and guidance. This work has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.

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## ABSTRACT

In recent times, Virtual Reality (VR) has gained widespread popularity and usage in diverse fields such as education, training, healthcare, industries, architectural overviews, entertainment, and others. VR technology combines hardware and software to provide users with a fully immersive experience in a 3D computer-generated world. This immersive experience allows users to interact with objects in the virtual environment (VE) and explore the virtual world, thereby enhancing their sense of presence in the VE and improving their user experience. With the advent of portable VR headsets and the availability of low-cost hardware, VR has transformed from being a laboratory technique to a widely accessible technology. This transformation has resulted in significant work being done on VR in various fields due to its low cost and potential to produce meaningful experiences. VR has found diverse applications in fields such as medicine, education, and data visualization. The emergence of new interaction metaphors, designs, and tools, such as training, learning, social interaction, creativity, etc., has been influenced by these new possibilities, leading to advancements in the field of Human-Computer Interaction (HCI) research.

Navigation is a crucial and frequently employed interaction task in VR, with bipedal walking being the most fundamental and natural mode of locomotion. This is primarily because bipedal walking involves various human senses during the interaction in comparison to other locomotion techniques. Walking facilitates the proprioceptive and vestibular senses in addition to vision and audio, while the user traverses through the VE. Conversely, when other locomotion techniques, such as joystick or controllers, are used in VR, the user experiences conflicting movement cues from proprioception, vestibular sense, and optical flow, which can negatively impact the sense of presence in the VE. Therefore, natural locomotion interfaces based on real walking in VEs have been shown to be advantageous for applications such as training, rehabilitation, or entertainment. However, this approach generates the issue that the application is restricted to the available tracking space in the physical environment, with recent commodity VR hardware such as the HTC Vive providing a tracking area of only approximately 4 × 4 meters. Moreover, real walking can cause physical fatigue when users navigate large VEs, necessitating the need for innovative locomotion techniques to overcome this limitation.

Studies suggest proxy gestures as a mode of interaction technique that can produce natural locomotion in a VE. Locomotion based on proxy gestures requires the user to perform gestures that serve as a proxy for actual steps. Gesture-based locomotion can produce proprioceptive feedback inherent to walking, generate a better feeling of presence and immersion, and perform better on different travel tasks.

However, several gesture-based techniques have been tested based on users performing single locomotion tasks. But, when scenarios are not purely exploratory, locomotion is often performed with other tasks that may require the users to interact with objects in the virtual world, e.g., to grab and manipulate them. In these cases, locomotion can be regarded as primary or secondary functionality, and aspects such as intuitiveness, comfort, and ease of use become essential factors for the outcome of the task. These calls for exploration and investigation of body gestures as a medium of interaction in a seated position for locomotion in a multitasking environment. We have explored seated-based gestural locomotion techniques as they can be adapted by different user groups, such as the disabled and the elderly, and also offer comfort to healthy users while traveling in large VEs. The research intends to identify and evaluate the natural and intuitive controller-less gesture for locomotion in VE in a seated position for three different multitasking scenarios

This research outlines the outcome of the five user studies in developing and evaluating three novel controller-less gesture-based locomotion techniques for multitasking environments that can be performed in a seated position. The first study investigated suitable body gestures for travel in different multitasking environments using the gesture elicitation method to generate three sets of user-centric gestures for locomotion. The second study evaluated these gestures based on appropriateness, ease of use, effort, and user preference. The gestures were further classified based on hand usage and geometric taxonomy. Three new gesture-based techniques, namely the *Calling gesture*, *Deictic Pointing gesture*, and *Mirror-Leaning gesture*, were designed and developed from the gesture set obtained for virtual locomotion. Three different comparative studies were conducted as a part of the research to compare these gestures with the techniques in the literature such as *tapping* and *teleportation*. The new gestures were evaluated for their task completion time, accuracy, intuitiveness, performance, comfort, ease of use, perceived workload, spatial knowledge, presence, simulation sickness, and user preference. The contribution of the thesis are (i) the proposal of new locomotion gestures for three different VEs, (ii) the evaluation of the gestures with the existing techniques to scientifically establish the results for the various objective and subjective measures, (iii) based on the results, we have designed the characteristic framework to help future designers select appropriate gestures for locomotion based on the application's requirements (iv) the research findings also suggested a set of design guidelines for gesture-based locomotion techniques that the application designers can use to build effective and efficient controller-less natural locomotion techniques for future VR applications.

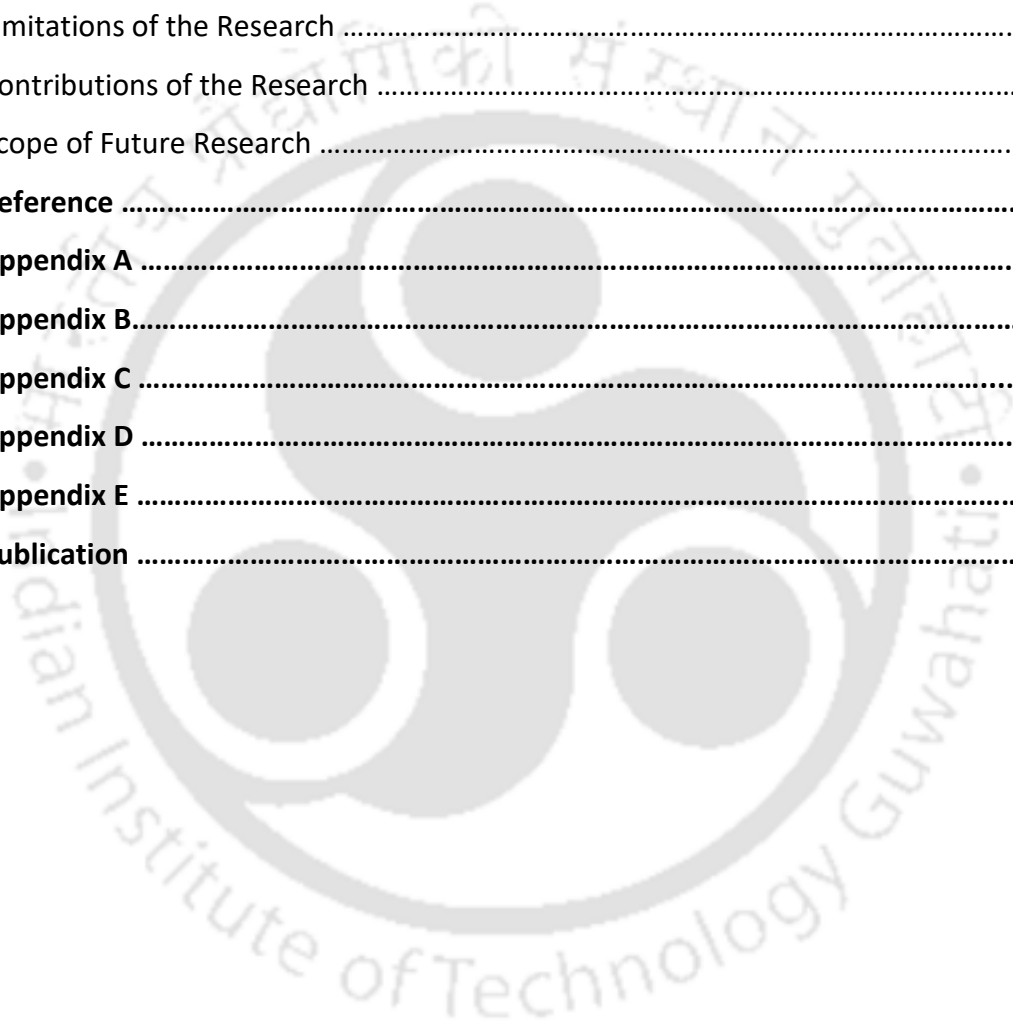
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## LIST OF ABBREVIATIONS

<b>VR</b>	Virtual Reality
<b>VE</b>	Virtual Environment
<b>HMD</b>	Head Mounted Display
<b>ALT</b>	Automatic Locomotion Technique
<b>HCI</b>	Human Computer Interaction
<b>VLTS</b>	Virtual Locomotion Techniques
<b>WIM</b>	World-In-Miniature
<b>RW</b>	Real Walking
<b>RDW</b>	Redirected Walking
<b>WIP</b>	Walk-In-Place
<b>AS</b>	Arm Swinging
<b>FOV</b>	Field of View
<b>UPD</b>	Unintentional Positional Drift
<b>AV</b>	Automated Vehicles
<b>AR</b>	Augmented Reality
<b>SDK</b>	Software Development Kit
<b>ANOVA</b>	Analysis of Variance
<b>SSQ</b>	Simulation Sickness Questionnaire
<b>SB</b>	Sense of being in the supermarket
<b>DR</b>	Extent to which VE becomes a dominant reality
<b>P</b>	Extent to which VE is remembered as a place
<b>CF</b>	Control Factors

<b>N</b>	Nausea
<b>TPS</b>	Total Presence Score
<b>MD</b>	Mental Demand
<b>PD</b>	Physical Demand
<b>TD</b>	Temporal Demand
<b>P</b>	Performance
<b>E</b>	Effort
<b>F</b>	Frustration
<b>MWWL</b>	Mean Weighted Workload
<b>O</b>	Oculomotor
<b>D</b>	Disorientation
<b>NASA-TLX</b>	NASA Task Load Index
<b>VE1</b>	Virtual environment with only travel task
<b>VE2</b>	Virtual environment with travel and one hand engaged in selection/manipulation of one virtual object
<b>VE3</b>	Virtual environment with travel and two hands engaged in the selection/manipulation of two virtual objects

# CHAPTER 1: INTRODUCTION

## 1.1. Introduction to this research

The market size of virtual reality (VR) HMDs in 2019 was \$5.5 billion, comprising a compound annual growth rate (CAGR) of 22.3%. This market size is projected to reach \$18.6 billion by 2026 (Valuates, 2020). It was estimated that the standalone VR HMD occupies the largest share of the AR/VR headset market in 2020 at 43.76%, the second largest being tethered VR HMDs (40.88%); third by the standalone AR HMD (5.82%), fourth by VR screenless viewer (5.55%), and the fifth by tethered AR HMD (3.49%) (IDC, 2020). Hence VR has gained immense popularity with the advent of low-cost and portable head-mounted displays (HMDs) that have brought the technology from the lab environment to the consumer end. The commercial drive of these HMDs has led to increased interest in the use of this immersive technology in different types of applications, such as medicine (McGrath et al., 2018), psychology (Peskin et al., 2019), and education (Freina et al., 2019) or training (Bozkir et al., 2019). VR is significant in driving innovation in spatial computing. Another rapidly growing area within the realm of VR is the metaverse. The concept has gained popularity in recent years, driven by advancements in virtual reality, augmented reality, blockchain technology, and online gaming. In the metaverse, users typically create digital avatars to represent themselves and can engage in various activities, such as socializing, working, gaming, attending events, and more. It creates a seamless, immersive, and interconnected digital universe that transcends individual platforms and applications. Major tech companies and developers are exploring and investing in metaverse-related projects, envisioning a future where people spend more of their online time in these shared, immersive spaces. The metaverse concept has implications for various industries, including gaming, social media, education, business, and entertainment. In contrast to conventional VR applications that function independently, the metaverse integrates all applications and services, delivering a seamless and continuous user experience.

There is a multitude of tasks that a user can potentially perform within a VE, and they are mostly application specific. Most interaction tasks fall under four categories: viewpoint motion control (locomotion), selection, manipulation, and system control (Bowman et al., 1998). Movement in VR is an essential interaction in VE applications apart from selection and manipulation. The user must move effectively in the environment to obtain different views of the scene. From the survey conducted by (Perkins Coie, 2020), it is estimated that in the education sector, about 42% of the new applications in

immersive technologies are expected to be related to virtual travel. Although VR shows a lot of optimism in emerging technologies, one of the main hindrances to its mass adoption is the user experience (Perkins Coie, 2020). User Experience is a user's perceptions and responses from using a product, system, or service (ISO 9241-11). For a good user experience, users should feel fully immersed and comfortable and perform natural interaction in a virtual environment (VE). The capability to perform multitasking activities such as interaction and movement within the VE in a similar way to the real world (natural interaction) may increase realism, improve the manipulability of virtual objects and enhance the sensation of presence (Slater et al., 1995).

Instead of physical devices such as controllers for inputs in a VE, the use of body gestures and motions creates interaction techniques that are much more immersive to the users. Locomotion based on gesture requires the user to perform actions that serve as a proxy for actual steps in VR. When used as a mode of interaction for virtual travel, the gestures are inexpensive and require very little physical space to move in a large VE. As a result, researchers have begun investigating gesture-based interaction with VR applications using contactless motion-sensing devices. The sensing devices, such as Microsoft's Kinect and Leap Motion (Buckwald & Holz, 2010), track the parts of the body in the physical space and enables the development of invisible interfaces. In this thesis, we design, develop and evaluate novel gesture-based techniques for locomotion that can be used for virtual travel and evaluate their efficiency and effectiveness. We also propose design guidelines that future designers and developers can use to design appropriate gestures for locomotion suitable for different scenarios.

## 1.2. Definitions used in this thesis

**(i) Virtual Reality:** According to Sherman and Craig (2003), "Virtual Reality (VR) is a channel for interactive computer simulations that allows the participants to sense their position and actions, providing multimodal feedback to one or more senses, and making them feel immersed in the simulation."

**(ii) Virtual Environments:** According to (Ellis, 1994), virtual environments can be defined as "interactive, virtual image displays enhanced by special processing and by non-visual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic space." It is also interchangeably called a virtual world, an application that lets users navigate and interact with a three-dimensional, computer-generated environment in real-time.

**(iii) Navigation:** Bowman et al., (1997) described navigation as the "movement of in and around a virtual environment." The navigation functionality of VR can be further divided into two components wayfinding and locomotion. a) Wayfinding—the cognitive component of navigation—involves higher-level processes, such as path planning and decision-making. Thus, wayfinding amounts to orienting oneself in the environment and determining the path to the desired location and may rely on natural and artificial aids such as landmarks, maps, and signs. b) Locomotion—this involves the lower-level actions which signify the motor component, such as controlling the position and orientation of the viewpoint and increasing or decreasing the movement velocity.

**(iv) Presence:** According to Sherman and Craig (2003), presence is the sensation of being within a virtual world. It can be viewed as purely a mental state, or it can be accomplished by physical means. Physical immersion is the synthetic stimulus provided to the body's senses using technology. Mental immersion is the state of being deeply engaged.

In the context of embodied cognition, it is suggested that the feeling of being present in a virtual environment (VE) arises from creating a mental model of the VE that combines spatial and functional aspects. This mental model is formed through two cognitive processes: representing bodily actions as potential actions in the VE and suppressing sensory input that doesn't align with the virtual experience. The conscious sense of presence is believed to reflect these two components as spatial presence and involvement. In defining presence psychologically, Slater and colleagues (Slater & Usoh, 1994) distinguished it from the concept of immersion. Immersion is objectively described as the extent to which computer displays can create an illusion of reality for the senses of a human participant. While immersion is objectively measurable, the sense of presence is a subjective experience and can only be measured by the user experiencing it.

**(v) Gestures:** According to Sherman and Craig (2003), "Gestures are a body motion which expresses meaningful information through the movement of body parts such as fingers, arms, hands, legs, torso, head, and face for interacting with the outer environment." The gestures can be further classified as static and dynamic. A static gesture is observed at the spurt of time, for example, a stop sign with a hand. A dynamic gesture changes over time, for instance, waving a hand or nodding the head.

### 1.3. Research Motivation

The objective of VR systems is to immerse the users within a computer-generated VE and produce a natural experience while interacting with the virtual world. VR locomotion is one of the primary methods of VR interaction. Although locomotion is one of the most common and universal forms of interaction in VR (Bowman et al., 1998), it is often combined with other tasks such as object selection and manipulation, virtual exploration, and searching within the VE (Griffin et al., 2018). Many VR applications, such as gaming, architectural and museum walkthroughs, tourism, and training applications, require performing these tasks concurrently (e.g., picking up one or more virtual objects and moving them to a different location, traveling while manipulating objects, and so on) in the VE. However, natural locomotion (Nilsson et al., 2018) remains one of the most difficult challenges for researchers and developers aspiring to provide users with the ability to move and interact with virtual objects simultaneously. Present real-time complex VR applications such as shooting games, virtual shopping, industrial training, tourism interfaces, and geoscientific applications require the user to perform locomotion as a primary interaction and selection or manipulation as a secondary task. Such multitasking environments require the user to move naturally and relatively easily without assigning much explicit attention to the locomotion task. As a result, the research aims to design natural locomotion techniques that allow users to perform multiple activities while moving in a virtual space naturally and effortlessly.

Natural walking-based interaction with positional tracking on major consumer VR platforms such as HTC Vive, Oculus Rift, and Sony VR provides a high presence devoid of VR sickness (Usuh et al., 1999). However, it requires significant unobstructed physical space when the virtual space can be of exceptionally different size and scale compared to the real-world tracked volume (Nordahl et al., 2011). While real walking is the most natural and presence-inducing method, it requires a larger physical space to experience a large VE. Consequently, many locomotion techniques were designed that need smaller physical space while enabling the user to explore large VEs. One such classic locomotion solution is Artificial Locomotion Technique (ALT) or controller-based locomotion technique, typically activated using a handheld controller. While using ALTs in VEs reduces physical strain by enabling the users to sit and travel in virtual space, it does not provide vestibular or proprioceptive feedback. As a result, it confuses the senses, resulting in VR sickness (Bhandari et al., 2018). The controller-based locomotion is unnatural, and the users must carry the controllers throughout the virtual experience. Another form of locomotion using controllers is the teleportation technique. This type of locomotion reduces motion

sickness because it does not involve any apparent translational motion. However, it obstructs path integration, resulting in spatial disorientation (Bakker et al., 2003).

Existing research identifies controller-less techniques, primarily gestures, as one of the most promising approaches to locomotion in a VE. Studies show that gesture-based movement elicits a stronger sense of presence than ALTs (Bhandari et al., 2017) and helps provide better spatial orientation (Harris et al., 2014). The proxy gestures are natural as they mimic some part of the walking gait cycle. They are very simple, easy to learn, and inexpensive (Feasel et al., 2008), and some controllerless gestures provide proprioceptive feedback similar to natural walking (Slater et al., 1994). Furthermore, recognizing gestures does not require large mechanical setups. It allows them to be used as a locomotion technique in a home environment, requiring only less space and enabling the user to travel large VEs. They also increase the applicability in multiple platforms and cater to numerous technology devices. However, very few studies are reported in the literature where controller-less gestural interfaces have been investigated for virtual locomotion in multitasking scenarios.

We have also chosen to explore seated-based locomotion techniques, as experiencing VR in a seated position not only provides comfort but also causes less physical strain (Neumann et al., 2001) and is less likely to induce motion sickness (Merhi et al., 2007). Furthermore, studying gestures for seated positions is essential because they can be tailored to different user groups, such as the elderly and physically disabled, to explore the VE. We have adopted a user-generated gesture study methodology to identify natural and intuitive locomotion gestures for multitasking VEs.

These calls for exploration and investigation of body gestures as a medium of interaction in a seated position for locomotion in a multitasking environment. The research intends to identify and evaluate the natural and intuitive controller-less gesture for locomotion in VE in a seated position for three different multitasking scenarios where virtual travel is performed with (i) both hands-free, (ii) one hand engaged in the selection and manipulation of a virtual object and (iii) both hands engaged in object selection and manipulation of two virtual objects.

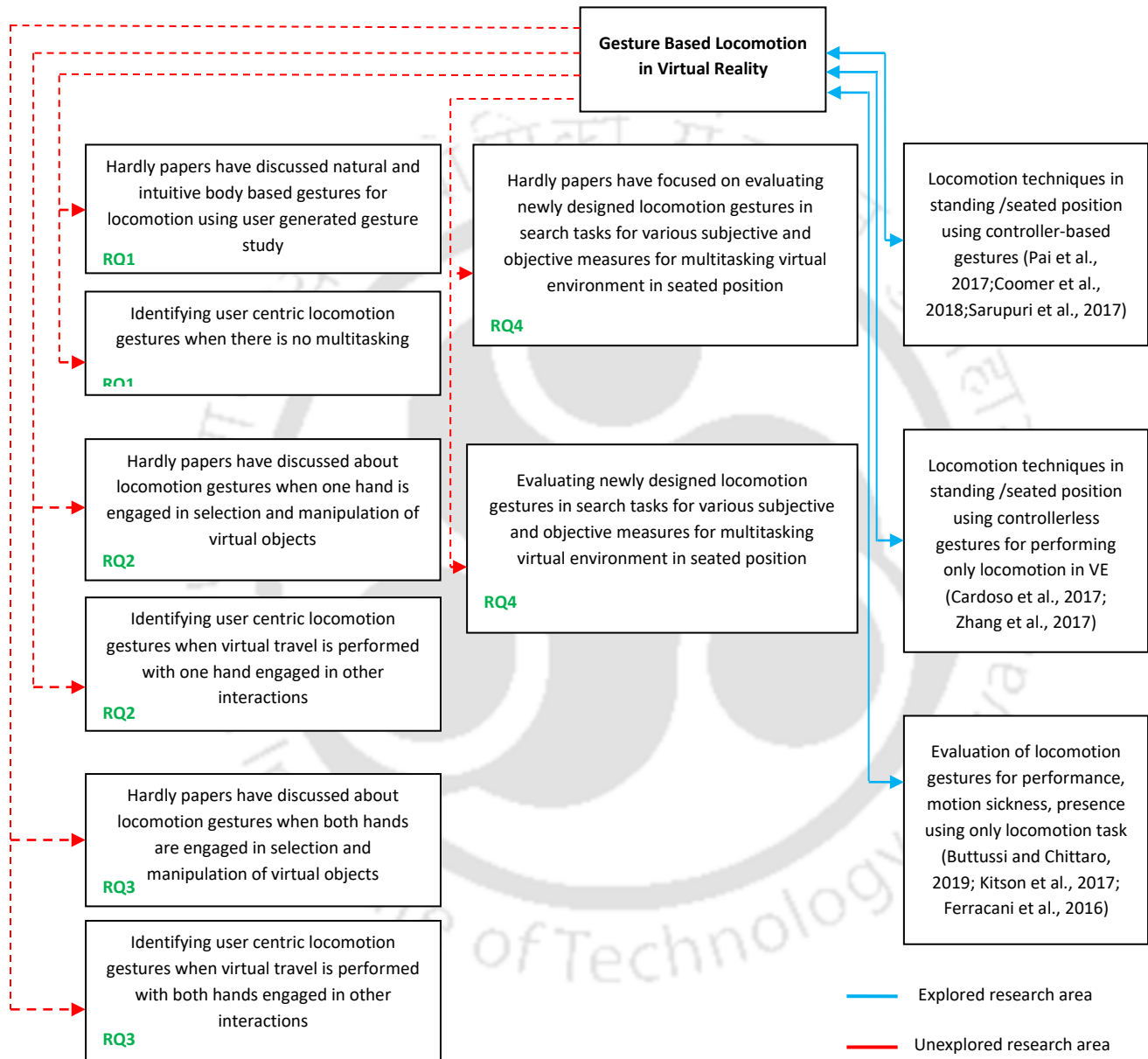
#### **1.4. Research Gap**

Research gap has been identified from three perspectives a) Identifying natural and intuitive body-based gestures for locomotion using user-generated gesture elicitation method, b) Identifying gestures for multitasking VEs that include locomotion and object selection and manipulation, c) Identifying gestures for locomotion in a VE specifically to be performed in a seated position.

An exhaustive literature review highlighted several controller-based gestures in standing and seated positions for locomotion (Pai et al., 2017; Coomer et al., 2018). There are also controller-less gestures (Cardoso et al., 2017; Zhang et al., 2017) for locomotion in standing and seated positions. Although using body gestures to interact within VE increases naturalness, it can be tiring if the body gestures are intense and used for an extended period. Furthermore, in addition to physical exhaustion, the user must exert cognitive effort while using the gesture in a multitasking VE. This mental effort can be significantly reduced if the design process also includes users in developing gestures. User-defined gestures are easier to learn and remember than the pre-defined gestures by system developers (Nacenta et al., 2013). To the best of our knowledge, none of the locomotion gestures discussed in the studies was created through a user-generated study. These lead to the research gap RQ1.

Furthermore, simultaneous object manipulation and locomotion are a requirement in many VR applications. Most methods discussed support locomotion and did not support gestures for other VR functions. As a result, there is a clear need to identify locomotion gestures for real-time scenarios, which includes locomotion with other interactions like selection and manipulation. These lead to the research gap RQ2 and RQ3.

The empirical studies in the literature (Buttussi and Chittaro, 2019; Kitson et al., 2017) evaluated the locomotion gestures for their performance, presence, and motion sickness by allowing the user to perform only locomotion tasks. But as discussed above, real-time applications such as games, training, VR shopping, tourism, etc., people frequently perform various tasks along with locomotion. Hence investigating newly designed locomotion gestures during multitasking scenarios is also required to evaluate their performance, presence, motion sickness, user preference, spatial knowledge and perceived workload when they are used along with selection or manipulation. These lead to the research gap RQ4. Figure 1.1 illustrates the research gaps identified from the literature review.



**Figure 1.1 Research Gaps that have been identified from the literature review**

## 1.5. Research Questions

In this thesis, we investigate the following research questions

**RQ1-** What are the user-centric gestures that are natural for locomotion in a VE when both hands are free in a seated position?

**RQ2** - What are the user-centric gestures that are natural for locomotion in a multitasking VE when one hand is engaged in another interaction, such as selecting or manipulating a virtual object in a seated position?

**RQ3** – What are the user-centric gestures that are natural for locomotion in a multitasking VE when both hands are engaged in other interactions, such as selecting or manipulating two virtual objects in a seated position?

**RQ4** – How do the newly designed gesture-based locomotion techniques impact the task completion time, collisions, intuitiveness, comfort, ease of use, perceived workload, motion sickness, spatial knowledge, and presence compared to existing locomotion techniques in a seated position?

## 1.6. Research Aim and Objective

### 1.6.1. Research Aim

This research aims to design and perform a sequence of user experiments through a gesture elicitation study for identifying user-centric gestures for locomotion in a multitasking environment in a seated position (i) when both hands are free, (ii) when one hand is engaged in the selection of a virtual object (iii) when both hands are engaged in the selection of virtual objects. It also aims to design new gesture-based locomotion techniques and evaluate them with the other gesture-based methods in the literature for their task completion time, collision, intuitiveness, performance, comfort, ease of use, perceived workload, presence, spatial knowledge, simulation sickness, and user preference. We can achieve the aim of the research through the following research objectives.

### 1.6.2. Research Objectives

- i. To identify user-centric gestures in a seated position for natural locomotion in VEs when (i) both hands are free, (ii) one hand is engaged in another interaction, such as selecting or manipulating a

virtual object, (iii) both hands are engaged in other interactions, such as selecting or manipulating two virtual objects.

- ii. To evaluate the gesture sets obtained based on appropriateness, ease of use, effort, and user preference.
- iii. To analyze the gestures based on their geometric features, such as hand usage and gesture forms.
- iv. To design and implement the gestures for a context-appropriate scenario that gives the user the most natural locomotion experience while in a seated position.
- v. To investigate the objective and subjective measures such as task completion time, collisions, intuitiveness, effort, ease of use, spatial knowledge, and simulation sickness of the newly designed locomotion gestures compared with the gestures in the literature.
- vi. To investigate the experiments' results and propose characteristic framework and design guidelines for efficient and effective gesture-based locomotion techniques to travel in a seated position for multitasking VEs.



## 1.8. Structure of the thesis

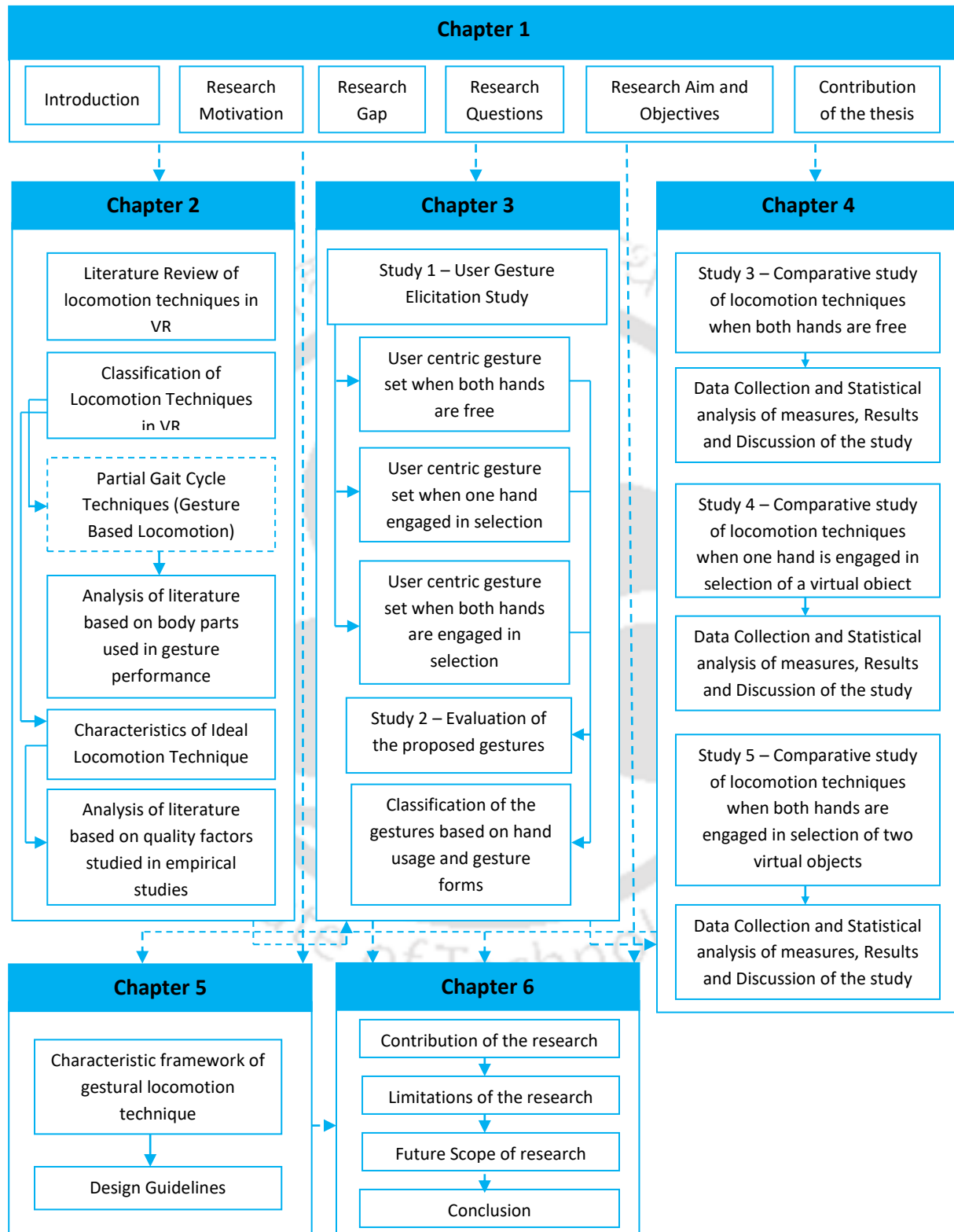


Figure 1.2 Flow Diagram of this thesis

## **1.9. Thesis Summary**

### **Chapter 1: Introduction**

This chapter introduces the theme and context of the thesis report. It starts with describing the growing trends of VR and its application in different fields. This is followed by detailing the importance of locomotion as an interaction in VEs. The chapter presents the research motivation behind this thesis. Further, it presents the research gap and the research aim and objective of the thesis. The chapter also presents the contribution of the research in terms of compilation and classification of a set of body-based gestures in a seated position for locomotion in different multitasking VEs, the addition of new gestures and their evaluation with the locomotion techniques in literature, and a set of design guidelines that can be used by designers while designing suitable techniques for their applications. Finally, the structure of the thesis is presented in the form of a schematic diagram.

### **Chapter 2: State of Art Literature Review**

In this chapter, we introduce the concept of VR locomotion, the classification of the locomotion techniques, and existing literature on the different methods. We discuss the gesture-based input interactions used in the literature. We present the analysis of the different controller-less gesture-based locomotion techniques based on the body part used to perform the gesture. Further, the chapter presents the characteristics of an ideal locomotion technique. The different characteristics studied in the empirical studies in the literature are presented in the form of a concept matrix. We discuss the need for design intervention for locomotion gestures in a seated position in a multitasking environment. We finally present the summary of different studies performed as a part of this research to answer the different research questions.

### **Chapter 3: Methodology and User Studies**

In this chapter, the methodology to investigate the research questions is discussed. An overview of the two user studies that were performed for gesture extraction is presented. This chapter discusses Study1, which investigates suitable body gestures for virtual travel in three different VEs. This section starts with a detailed review of existing elicitation studies used for designing gestures and elaborates upon the chosen approach of user-generated gesture design for this study. This is followed by conceptualizing different VEs for the studies. The details of the participants, experimental setup, study procedure, data collection method, method of gesture extraction, and the results are presented. The final gesture set for the three different VEs is tabulated. The chapter further presents Study 2, which evaluates the top three

preferred gestures from the first study on the basis of appropriateness, ease of use, effort, and preference. It further presents the classification of the gestures obtained from Study 1 based on hand usage and gesture form. This helped in finding the user behavior and gesture pattern for the virtual travel in three different VEs.

#### **Chapter 4: Design and Evaluation of proposed locomotion gestures**

This chapter presents the design of the VE (virtual supermarket) that was used for the three comparative studies. Further, it also gives an overview of the control flow model used in this research. The experimental task, procedure, and data collection method for the three studies are explained in detail. We present Study 3, which compares a newly designed gesture (*Calling* gesture), with the gesture in literature (*tapping* and *teleportation* gestures) for a VE where both hands are free for the user. Following this, the statistical analysis and the results of the study are discussed. This chapter further presents Study 4, which compares a newly designed gesture (*Deictic Pointing* gesture) with the gesture in literature (*tapping* and *teleportation* gestures) for a VE when one hand of the user is engaged in the selection and manipulation of a virtual object. Following this, the statistical analysis and the results of the study are discussed. This chapter further presents Study 5, which compares a newly designed gesture (*Mirror Leaning* gesture) with the gesture in literature (*tapping* and *teleportation* gestures) for a VE when both hands of the user are engaged in the selection and manipulation of a virtual object. The statistical analysis and the study's results are further discussed.

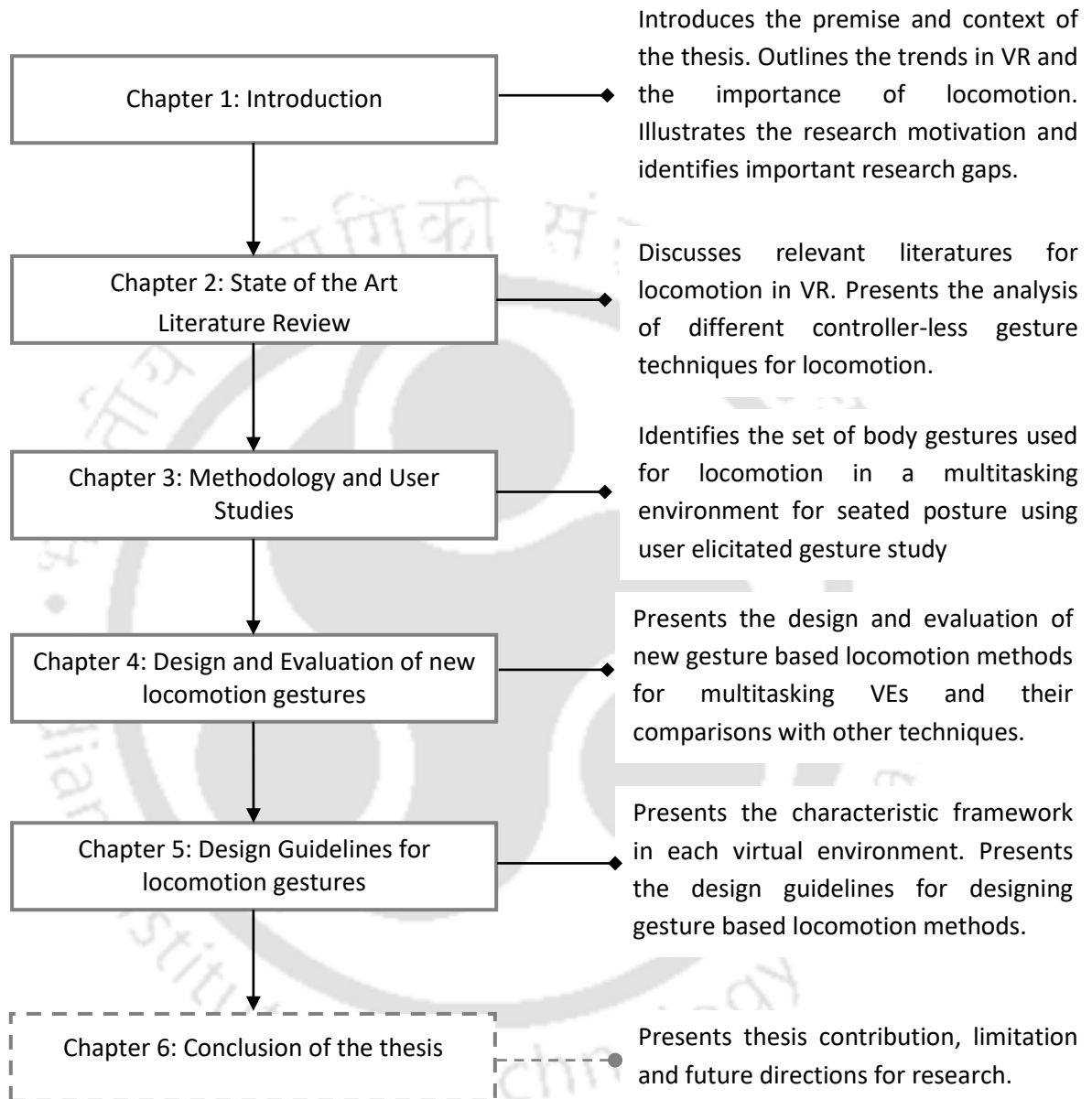
#### **Chapter 5: Design Guidelines for locomotion gestures**

This chapter discusses the characteristic framework detailing the benefits and drawbacks of various locomotion techniques from the results obtained from Study 3, Study 4, and Study 5 based on the functional and non-functional requirements. It also discusses the different design guidelines formulated from the results of our five studies. These design guidelines would be helpful for researchers and interaction designers to design locomotion techniques to travel in a seated position.

#### **Chapter 6: Conclusion**

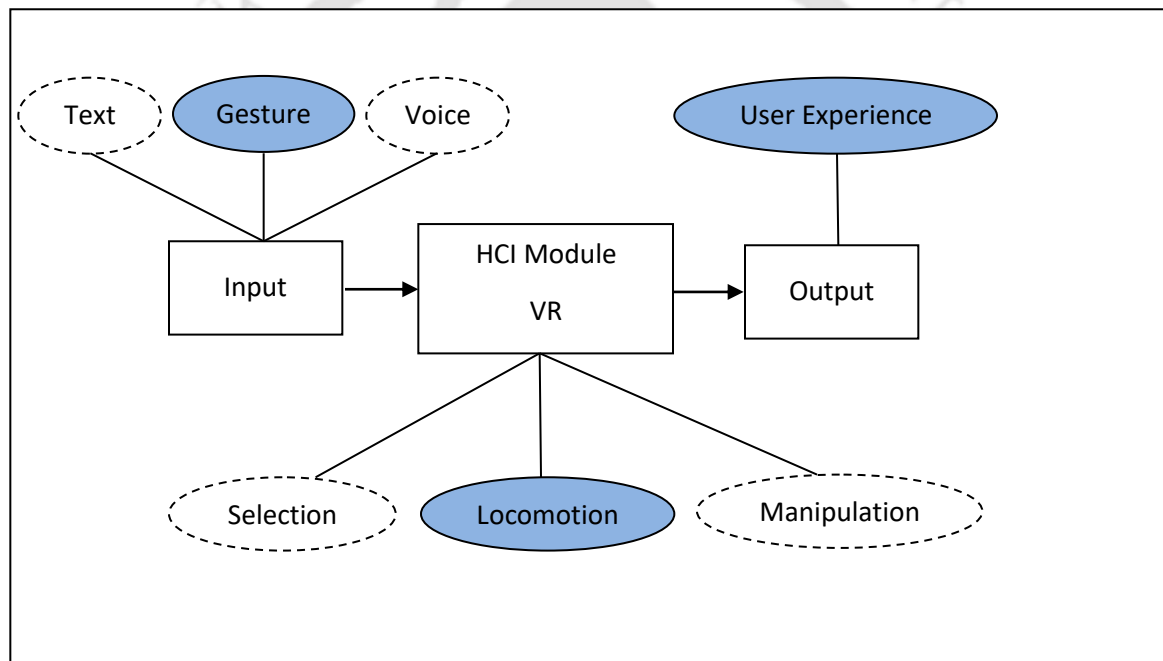
The conclusion is the last chapter of the thesis. It comprehensively discusses the thesis's overall summary and key findings in the form of a thesis contribution. Further, it discusses the limitations of the studies performed as part of the research. In the last section, the thesis examines future research directions for gesture-based locomotion techniques.

The chapter flow diagram is presented as follows:



## CHAPTER 2: STATE OF ART LITERATURE REVIEW

In this chapter, we introduce the topic of locomotion in VR, including its various techniques and classifications, as well as existing literature on different approaches. We also discuss the role of gesture-based input interaction techniques in locomotion and relevant human factors related to movement in VR. A block diagram is presented in Figure 2.1, which depicts the key components of the HCI system, with a particular focus on the input interactions in the form of gestures, the VR locomotion functionality, and the output related to the user experience of moving in the VE.



**Figure 2.1: A figure demonstrating the HCI module of VR locomotion and the focus area for the literature review**

In this chapter we present the classification of the locomotion techniques in VR based on their naturalness. We did an extensive literature review of different techniques and highlighted their advantages and disadvantages. We present a detailed analysis of the gesture-based locomotion techniques based on the different body parts used for performing the locomotion task. We further discuss the characteristics of an ideal locomotion technique from the literature. We present the concept matrix based on the quality factors studied in the empirical studies of all the reviewed techniques. From the detailed literature, we highlight the research gap and the research questions. Later in this chapter,

the need for design intervention in gesture-based locomotion technique is elaborated. The last section gives an overview of the different experimental studies performed as a part of this research.

## 2.1 Locomotion in VR

VR enables users to experience a simulated world. According to Bowman et al., (1998), the three fundamental interactions that constitute the building blocks in VR are locomotion, selection, and manipulation. Locomotion is considered one of the most basic and essential interactions to experience VEs. Locomotion refers to moving from one place to another in a VE using a change in the location of viewpoint motion control. One of the main challenges in VR locomotion is that the virtual world might be larger than the real-tracked world. Hence one of the requirements of the travel technique is that it should be able to map the infinite virtual space onto the finite tracked space without affecting the user's sense of presence.

Further, the travel technique should provide appropriate multisensory stimuli while the user interacts with the virtual world (e.g., sound accompanying each step, touch, and sight). The different feedbacks generated while the user walks in the physical environment are visual feedback, auditory feedback, haptic feedback, and various internal and efferent information. The visual feedback, called the optic flow, provides the user with information about the translational and rotational movement. This feedback dominates the spatial perception of the users in the environment. The auditory feedback gives the users information about the surrounding environment. When sounds are emitted in the real environment, it gives the user information about the size of the environment, the position of the different objects, and the various events in the environment (Waller and Hodgson, 2013). The haptic feedback gives the user information about the environment through cutaneous sensations felt via touch sensation (Marchal et al., 2013). The proprioceptive and vestibular systems produce internal sensory information. The efferent information helps to predict the consequence of performed actions before they have occurred (Harris et al., 2002). Hence, any locomotion technique that produces a natural walking experience in VR has the challenge of providing appropriate multisensory stimuli as in the real world. We are yet to see a commercially viable solution capable of offering high multisensory feedback and experience of real walking. In this section, we discuss different types of locomotion techniques: vehicular, natural, semi-natural, and non-natural locomotion techniques.

## 2.2 Classification of Virtual Locomotion Techniques (VLTs)

Mine (1995) classified the users' movement through the virtual world according to two essential parameters: direction of motion and speed. Direction control was categorized into Hand Directed Steering, Gaze Directed Steering, Physical Control, Virtual Control, Object-Driven, and Goal-Driven. On the other hand, speed control was decomposed to constant speed, constant acceleration, and hand-controlled, physically controlled, and virtually controlled speed. Bowman et al., (1997) proposed a taxonomy in which input conditions were also considered along with the direction and speed controls. The input condition represented how input was supplied to start and stop the virtual travel. Arns (2002) proposed a classification that categorizes VLTs based on direction and speed control and also incorporated additional components such as the type of VR display and interaction device. Bowman et al., (1997) proposed a taxonomy in which the VLTs were classified by the amount of control that the user has over starting/stopping travel along with factors related to controlling position and orientation.

Nilsson et al., (2016) organized VLTs into three orthogonal classifications: virtual movement source, metaphor plausibility, and user mobility. In virtual movement sources, the VLTs are distinguished into body-centric travel and vehicular technique. In body-centric travel, the virtual movement is exerted by users performing movements similar to physical walking, running, swimming, etc. (Fels et al., 2005). The vehicular technique involves the use of virtual vehicles or interfaces (Fiore et al., 2013; Wang et al., 2012) for movement in a VE. Metaphor plausibility distinguishes the VLTs into "magical" and "mundane." A magical technique involves virtual travel based on a metaphor that is not feasible in the real world, e.g., Teleportation (Bozgeyikli et al., 2016), world-in-miniature technique (Stoakley et al., 1995), or using hand-based manipulations in the virtual world (Stoev et al., 2001). In contrast, mundane techniques rely on metaphors adopted from real-world travel and can be either vehicle- or body-centric. Finally, based on user mobility VLTs are distinguished as mobile or stationary. The mobile technique involves the user's physical movement to travel in a VE, for example, real walking or Redirected Walking. Stationary techniques are methods in which the user remains stationary in the real world while moving in the VE, for example, the Walk in Place technique (WIP) or omnidirectional treadmills.

In this thesis, we classify the locomotion techniques based on their degree of naturalness into broad categories: Natural, Artificial locomotion Techniques, and Vehicular Based Techniques. We show the classification in Figure 2.2

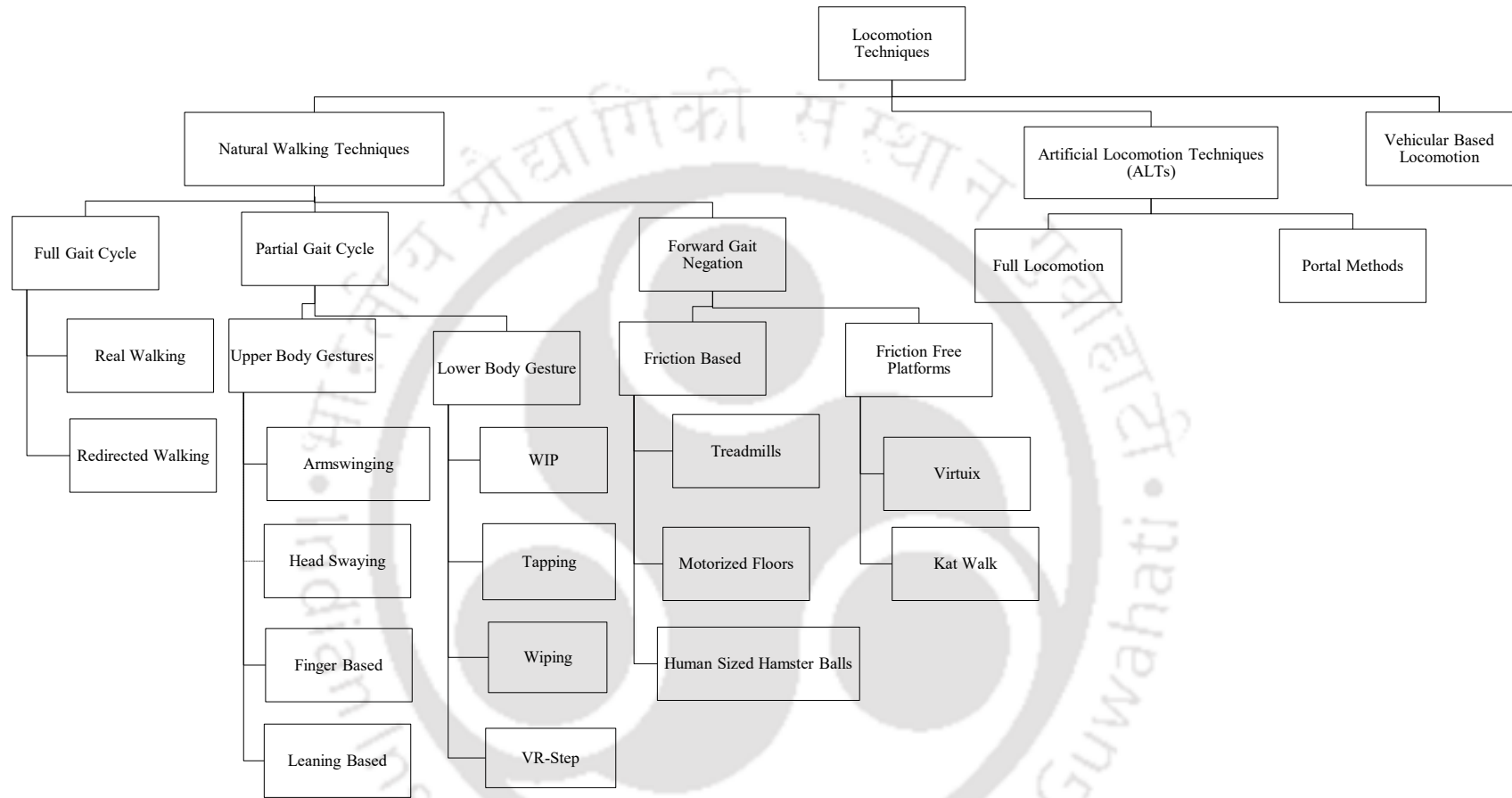


Figure 2.2: Classification of VR Locomotion Technique in the literature based on naturalness

### 2.2.1 Vehicular Locomotion Techniques

This technique simulates travel using a virtual vehicle and produces movement by interacting with the system interface. The user remains stationary relative to the vehicle and indirectly produces movement in the virtual world by manipulating the system's controls. Therefore, vehicular travel techniques do not require ample tracking space. Though the user is physically stationary, the movement of the virtual viewpoint can produce compelling self-motion illusions (Hettinger et al., 2002). However, due to the compelling self-motion illusions, it produces cyber-sickness or VR sickness. As the user remains stationary but visually perceives motion, the user experiences conflict between the external sensory information and vestibular sensation, which leads to cyber-sickness (Davis et al., 2014). Such a conflict can make the performance of the vehicular technique worse than both artificial and natural locomotion techniques, which would significantly reduce the interaction performance (McMahan et al., 2016).

One of the applications of this technique is VR flight simulation which is extensively used for training and evaluating pilots (Trinon et al., 2019; Koonce et al., 1998; Bell et al., 1998). Other power-driven vehicles include cars (Brooks 1999), ships, trucks, and buses (Ijspeert 2002), which are also used to experience navigation in immersive VR. They use physical steering techniques, which help the users to steer with a physical prop that often corresponds to the steering experience of a real-world vehicle. In many applications, the user is passively moved in the virtual world by giving control of the vehicle to the user, or the vehicle can be moved automatically. While the locomotion is done automatically, the users can focus on different interactions in the virtual world. This technique produces multisensory feedback, such as auditory (Väljamäe 2009) and vibrotactile (Whitton et al., 2008), which makes the simulation compelling and realistic. The vehicular techniques provide a sense of presence which comes from the fact that the user can reach out and touch the simulator, which is similar to the real vehicle; hence it provides the near field haptics. Another important factor that enhances the user experience is the sound effects produced during vehicular locomotion, similar to real-time travel.

Some of the advantages of having vehicular locomotion techniques in simulation applications are that they are cost-effective. Numerous emergency situations and scenarios can be experienced by the users of the system with minimal or no risks. The different scenarios in the training module can be customized according to the different difficulty levels, thereby enabling more significant experience and training per session. These scenarios can be run multiple times until the user gets trained for real-time situations.

### 2.2.2 Artificial Locomotion Techniques

As the name indicates, the locomotion techniques independent of any natural locomotion cues are artificial or non-natural locomotion techniques. They include locomotion based on controllers and portal methods. Many VR applications use joysticks or controllers to navigate the virtual world, as shown in Figure 2.3. This mitigates the need for tracking devices and hence allows the user to navigate large VEs in small physical spaces. Another advantage of such a technique is its continuous motion by pressing a controller button or joystick. This helps the user to enjoy continuous movement in the VE. Though they solve the problem of indefinite space, these techniques induce disorientation and simulation sickness due to sensory conflicts (LaViola 2000).

Another type of artificial locomotion technique is the teleportation technique. This uses magical metaphors for interactions, such as portal points, which can be an exciting and easy way of the movement in VE. Teleportation lets users navigate large VEs without the confines of limited available positional tracking space. Teleportation discontinuously translates the viewpoint in the VE. Since the travel is not continuous, teleportation does not generate any optical flow. Due to the absence of self-motion illusion, the teleportation method has reduced VR sickness. Although the lack of optical flow minimizes simulation sickness, it also affects path integration. Since the user is unable to estimate the total distance traveled, this leads to spatial disorientation. However, it has been observed that teleportation breaks presence (Bowman et al., 1997) since it allows users to navigate in a way that does not exist in real life. Its usage can also interrupt the intended gameplay (Martindale 2016). Bhandari et al., (2018) used the dash teleportation technique, a modified teleportation method that uses a quick but continuous viewpoint translation to retain some optical flow instead of discontinuous translation. A user study was performed to compare Dash to regular teleportation and found that it significantly improved the path integration while there was no difference in VR sickness. Thus, the teleportation techniques are suitable for applications requiring the user to traverse great distances inside the VE with less time and effort.

The magic wand technique illustrates the use of a wand to navigate through VE (Ciger et al., 2003). The World-in-Miniature gives the user a miniature version of the space they are in, as well as the user's location in the space. The world-in-miniature (WIM) navigation metaphor allows users to travel in large-scale VEs using a high-level overview of the VE. It depends on a handheld, scaled-down duplicate version of the entire VE, where the user's current position is displayed along with an interface to introduce the

user's subsequent movements (Bowman et al., 2006). Users can save the landmarks or areas of interest in the virtual world and navigate: The user can change the position of the miniature version to move in the virtual world using the scrolling and scaling functionalities (Stoakley et al., 1995).



a) Gamepad

b) Speed Pad

c) Oculus Rift Controllers

d) HTC Vive Controllers

**Figure 2.3: Device used in Artificial Locomotion Techniques**

### 2.2.3 Natural Locomotion Techniques

Physical walking is the most natural way of moving in a VE (Whitton et al., 2005). In the real world, humans move in their environment with their legs without designating explicit attention to the movement performed or the multisensory feedback produced during walking (Nilsson et al., 2018). According to Nordahl et al., (2011), the main challenge lies in creating a locomotion technique that would mimic the experience of real walking without the constraint of space and provide the necessary multisensory stimuli during user interaction with the VE. Most of the techniques in this category resemble the human gait cycle that consists of repeated stance and swing phases. The stance phase begins when the foot hits the ground and completes when the toe is lifted off. On the other hand, the swing phase begins after the stance phase and ends when the foot hits the ground again after a swing. Based on this, the VLTs in this category are classified as full gait, partial gait, and gait negation techniques.

**2.2.3.1 Full Gait Cycle Techniques:** This technique includes both the stance and the swing phase. This category consists of real walking and the redirection technique.

**a) Real Walking:** Real Walking (RW) is the most natural way to move in a VE because of the repeated gait cycles and the high biomechanical symmetry. The change in walking velocity depends on the time period of the stance and the swing phases (Multon et al., 2013). The walking velocity ( $|v|$ ) is given by equation 2.1

$$|v| = f \times l \quad (2.1)$$

where  $f$  is the step frequency, and  $l$  is the step length. In other walking models, Dean (1965) proposed that the walking speed depends on the step frequency and the user's height. Equation 2.2 is given as

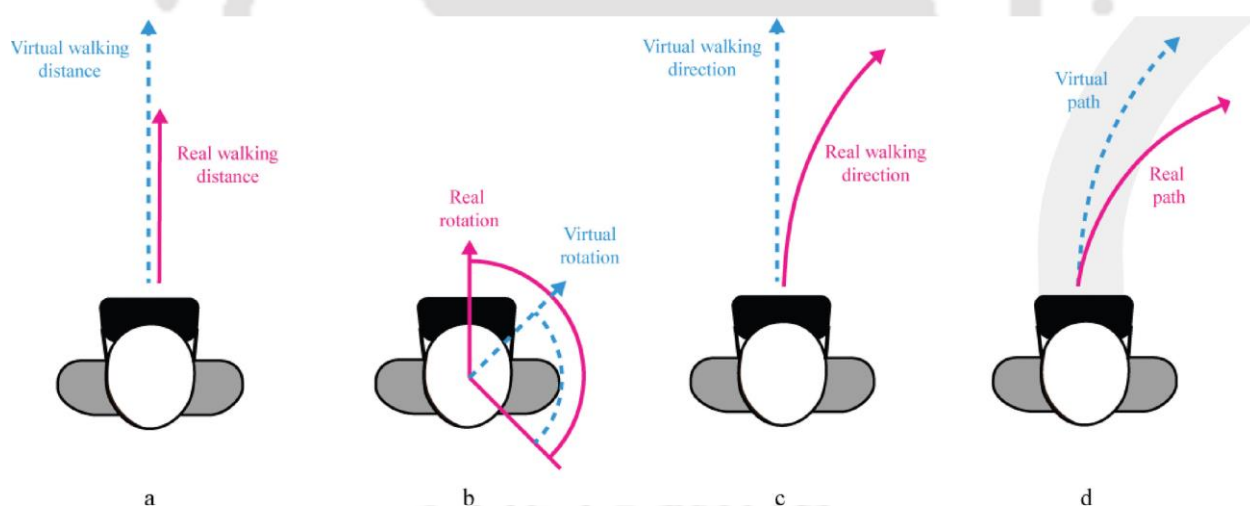
$$|v| = (f/0.157 \times h/1.72) \quad (2.2)$$

Chance et al., (1998) performed a study to observe the spatial orientation using a path integration task. Joystick control, RW, and gaze-directed steering (GDS) were compared, and it was observed that RW had significantly greater spatial orientation than joystick control. Usoh et al., (1999) compared locomotion techniques RW, walking-in-place (WIP), and flying for moving between two locations. It was found that RW was significantly easier to use than both WIP and flying. It was also found that real walking reported greater significance in the presence when compared to the other techniques.

Nabiyouni et al., (2015) compared the usability of three locomotion techniques that were different in their interaction fidelity: RW (natural interface), the Virtusphere (Medina et al., 2008) (semi-natural interface), and gamepad control (non-natural interface). The task consisted of following straight-line paths and right-angled paths. The completion time and the amount of deviation were measured in the study. The usability of each technique was measured subjectively. It was observed that real walking and gamepad techniques were found to be significantly faster, more accurate, easier to learn, and less fatiguing than the Virtusphere. The RW technique was found to be more natural than the virtusphere. With the advent of consumer VR platforms such as the Oculus Rift and the HTC Vive, real walking in a VE has been empowered at a relatively high quality and low cost, enabling VR locomotion to be more natural. However, the problem of scalability of tracking solutions remains unsolved when using this locomotion technique.

**Redirected Walking Techniques:** Redirected Walking (RDW) is one of the most popular and efficient travel techniques which can map the infinite virtual space to limited tracked space (Razzaque, 2005). Although real walking produces high naturalness and a subjective amount of presence, it limits the VEs to the size of the tracked space. Redirected Walking involves physical walking and addresses the above limitation by interactively rotating the virtual scene about the user without being detected by them (Razzaque, 2005). Redirected walking refers to a set of methods that enables the control of the user's path in the physical environment by steering the stimuli used to represent the VE (Suma et al. 2012). The redirected walking is based on either perspective manipulation or environmental manipulation. Perspective Manipulation is performed by applying changes to the user's virtual viewpoint. The ways of redirecting the users to stay within the confines of the physical boundary are through applying a set of

gains such as curvature, translation, rotational, and bending gains to the movement of the virtual camera, as shown in Figure 2.4. The redirected walking using translational gains helped to improve spatial awareness and accurate distance estimation in a VE (Langbehn et al., 2017). Razzaque (2005) suggested a set of generalized steering algorithms, steer-to-center, and steer-onto-orbit. These algorithms direct the user towards the center or towards the given targets by mainly applying imperceptible curvature gains. Another redirection strategy is by using visual distracters that force the user to make excess head rotations (Chen et al., 2017; Peck et al., 2010) by applying rotation gains. Environmental manipulation depends on a redirection by manipulating the properties of the VE. Suma et al., (2011) devised a method using the change blindness illusion, which is the inability of the users to detect changes in the environment to redirect them through subtle manipulation of the virtual architecture. Moreover, Suma et al., (2012) also proposed a technique called Impossible Spaces that compresses the virtual interior environments into comparatively smaller physical spaces with the help of self-overlapping architecture. Vasylevska and Kaufmann (2017) devised a flexible space method, which allows unrestricted walking within a dynamically generated interior VE.



**Figure 2.4: Depiction of different Perspective Manipulation Gains a. Translation Gain, b. Rotation Gain, c. Curvature Gain, and d. Bending Gain. Source: (Nilsson et al., 2018)**

William et al., (2007) presented a set of resetting methods for users when they reach the physical limits of the HMD tracking system. It is a set of strategies that resets users when they walk and reach the boundary of physical space. Thus, resetting the users' location in physical space is manipulated to move them out of the physical obstruction while the users maintain their spatial updating of the VE. In the Freeze Backup method, the system indicates to the user that they have reached the end of the physical

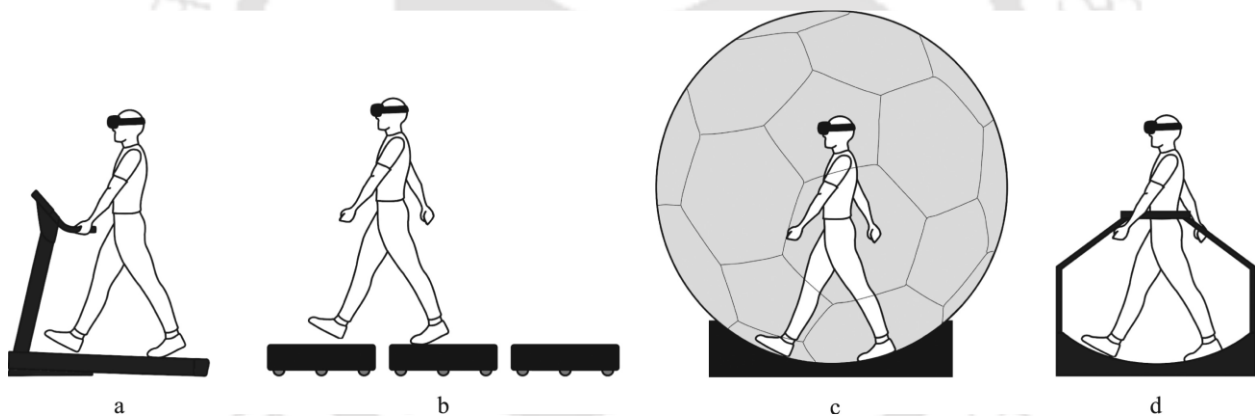
space and instructs them to take steps backward while the user's position in the virtual space is frozen. The virtual display gets unfrozen when the user has moved considerably inside the physical space. In freeze turn, when the user reaches the boundary, the display of the HMDs is frozen. When the user turns 180 degrees, the tracking is updated, and the user can continue to move in the VE. In 2:1 Turn, the user is instructed to turn 180 degrees in the physical space, but the yaw angle of the virtual camera is scaled twice and rotates 360 degrees. One of the redirection walking techniques that uses a magical metaphor is the seven-league boots. In this method, the user's physical translations are scaled by seven in the direction of their walking. This method allowed the users to travel large VEs and was designed such that the users could enable or disable the translation gains by pressing a button on the handheld device. Table 2.1 below presents the summary of redirection techniques in literature and the corresponding gains used.

**Table 2.1: Summary of Redirection Techniques**

Articles	Continuity			Gains		
	Cont.	Disc.	Rotation	Translation	Curve	Bending
Razzaque et al., 2005	*		*		*	
LaViola et al., 2001	*		*			
Razzaque et al., 2002	*		*			
Nitzsche et al., 2004	*				*	
Williams et al., 2007		*	*			
Interrante et al., 2007	*			*		
Engel et al., 2008	*		*			
Bruder et al., 2009	*	*	*			*
Steinicke et al., 2009	*			*		*
Suma et al., 2011		*				
Peck et al., 2012	*		*			*
Vasylevska et al., 2017	*		*	*		
Strauss et al., 2020	*		*	*		*
Lee et al., 2020	*		*	*		*

Nilsson et al., (2018) illustrated the overview of research that has been performed on redirected walking in immersive VE for the past fifteen years and described the different approaches and challenges while using the technique. Redirected walking requires a space larger than 30mx30m to perform well. For smaller tracked spaces, the redirected walking produces visual, proprioceptive conflict for the user. One of the other challenges with this technique is that the user has to physically carry the equipment for a longer period of time which induces fatigue while traversing large VEs.

**2.2.3.2 Gait Negation Techniques:** Gait Negation techniques are also called repositioning systems. They essentially negate the forward movement of the user in the real world, thereby ensuring the user remains relatively stationary in the physical world but moves forward in the VE. These techniques provide a full gait cycle and overcome the space constraint issues while traversing large VEs. However, these methods depend on heavy mechanical devices such as linear treadmills, step-based devices, low friction surfaces, etc., as shown in Figure 2.5. Usually, when the users walk on the treadmill in the real world, the users are moved the same distance in the virtual space.



**Figure 2.5: Repositioning Systems example - a. Traditional linear treadmill, b. motorized floor tiles, c. a human-sized hamster ball, and d. a friction-free platform. Image Source: (Nilsson et al., 2018)**

The repositioning systems are further classified into active and passive repositioning systems. Active repositioning systems require dedicated mechanical setups, such as linear treadmills, to negate the forward movement of the users (Feasel et al., 2011). One of the disadvantages of such a system is that the user can only walk forward in a VE. If the application requires a turn, then the user performs it indirectly using a joystick, or the entire treadmill platform is rotated as in ATLAS (Noma et al., 1998). Another disadvantage was that the linear treadmills did not allow movement uphill and downhill. Hence, Sarcos Treadport (Hollerbach et al., 2000) was designed to simulate this kind of walking, consisting of a

large tilting treadmill with a CAVE-like display. Omni-directional treadmills were designed later to address the issue of moving the user in different directions. One of the limitations of this technique is that the user could lose balance during turns and sidesteps while walking in these treadmills. Some other examples of active repositioning systems are motorized floor tiles and human-sized hamster balls. Passive repositioning systems are generally simpler and less expensive than active repositioning systems. They do not have any external actuation and are operated by the weight of the user's body or the force exerted by the user's feet. They rely on friction-free platforms.

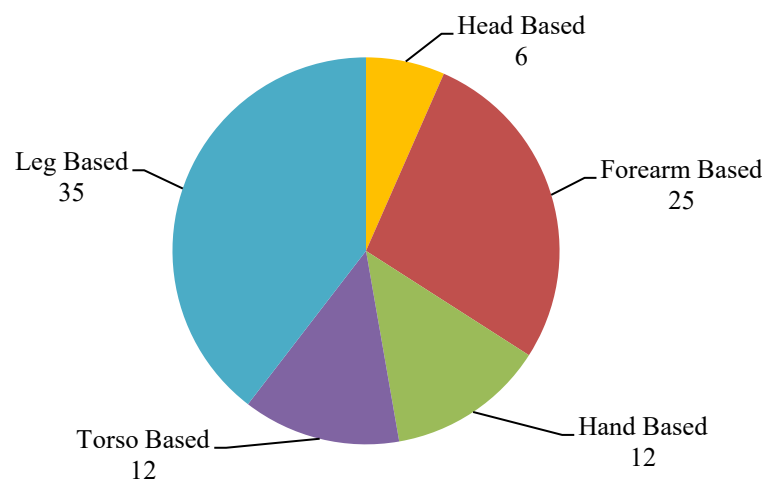
A more recent implementation of an omnidirectional treadmill is the CyberWalk (Souman et al., 2011) which can handle abrupt changes in the speed of walking and keeps the users close to the center of the treadmill. A user study was performed to compare Cyberwalk and real walking and measure the user's walking behavior and spatial updating performance in a task where the user followed a moving target in an arc. The results showed no difference between Cyberwalk and real walking for both measures. String Walker is another gait negation technique that ties the users' feet with strings attached to a turn table. A motor pulley is controlled by the pulling force of the strings, which enables the user to perform omnidirectional locomotion in a VE (Iwata et al., 2007). These interfaces had issues of bulkiness, complexity, and safety. Tracking the location of the user's feet was also difficult.

Step-based devices provide full gait navigation while the users are being stationary. Roston and Peurach (1997) proposed a virtual locomotion device in which the users navigate VEs by stepping over two motion platforms. To simulate travel in uneven terrains, Gait Master was designed (Iwata et al., 2001) that uses a step-based locomotion device. The Cybersphere (Fernandes et al., 2003) is a human-sized hamster ball that offers omnidirectional virtual travel as the user walks inside the spherical projection while being stationary, which is similar to the Virtosphere (Medina et al., 2008).

Some of the limitations of the repositioning systems are that they require sophisticated hardware and rely on elaborated mechanical setups, ease of use, and safety. However, some commercial low-frictional surfaces, such as Virtux Omni, KAT, and Cyberith Virtualizer, are affordable treadmills. Fig 5d shows an example of a friction-free platform. These systems ensure correct proprioceptive feedback.

**2.2.3.3 Partial Gait Cycle Techniques:** The partial gait techniques are also called the proxy gestures. Locomotion based on proxy gestures requires the user to perform gestures that serves as a proxy for actual steps. They use the advantage of the stance phase, where users step in place or perform different body-based gestures to move in a VE. Several gestural inputs have been developed based on the

biomechanical gait cycle of the human walking system. According to the body part used to perform the locomotion, the proxy gestures are distinguished into different subcategories. These gestures can be classified as upper-body gestures and lower-body gestures. The main aim of these techniques is to produce a walking experience that resembles actual walking; hence most of these techniques rely on lower body movements. Various body parts are involved while performing the gesture. The choice of gesture-based locomotion technique for VR applications depends on the body part used to perform the gesture and also the ability to track the parts for their natural movements. In this section, we classified gesture-based locomotion techniques based on the different body parts used to perform the gesture. Figure 2.6 depicts the number of instances of the technique classified according to the body parts used. We considered the point and teleport method to be a gesture-based interaction, similar to (Boletsis et al., 2022), because it uses gesture to point to a location where the user wants to reach, and the main motion is performed via Teleportation.



**Figure 2.6: Number of instances of locomotion technique classified based on the body part used**

**a) Leg-Based Locomotion:** The most common technique is the Walk-in-Place technique (WIP). Slater et al., (1995) proposed the first WIP technique with the virtual treadmill. When users walk in a place, their head oscillations are given as input to a neural network which translates the viewpoint of the user in the direction they are looking on the detection of a walking gesture. This implementation had several disadvantages, such as the virtual treadmill having to be calibrated for each user, the direction of travel being only forward, and the direction of travel being coupled with the head direction. Later several WIP techniques were developed to overcome these limitations. Some of the advantages of WIP techniques are: (1) They are very natural as they mimic real walking. (2) They are

very simple, easy to learn, and inexpensive (Feasel et al., 2008), (3) They provide some proprioceptive feedback similar to real walking (Slater et al., 1994), (4) WIP techniques provide better immersion in the VE compared to controller based techniques (Slater et al., 1995), and (5) WIP technique provided better spatial orientation for the users. (Williams et al., 2011).

Later, the Marching Gesture was introduced; in which users alternately lift each foot off the ground by lifting the thighs in front of the body. This gesture produced the same proprioceptive feedback as walking but required more energy. Nilsson et al. (2013) proposed Wiping and Tapping gestures for WIP. The wiping gesture is similar to an action in which the user alternately bends each knee, moving one lower leg backward. The tapping gesture is similar to an action in which the user lifts each heel without breaking contact with the ground. The gestures were graded on perceived naturalness, presence, and real-world positional drift. The tapping gesture felt more natural than the wiping gesture and was perceived as less strenuous than the other two techniques. Finally, the tapping gesture reduced positional drift significantly. Later, Nilsson et al. (2013) investigated the perceived naturalness of virtual locomotion methods that do not require explicit leg movements.

The run-in-place method (Kim et al., 2021) is also intended to overcome physical space constraints, allowing unlimited travel within a VE. In this technique, users are not required to move forward or backward, as in the WIP method, but must run on the spot to execute a virtual movement. Goose-stepping (Ke and Zhu, 2021) is a locomotion technique that uses leg movement similar to the ones used in formal parades and other ceremonies. The user swings their legs off the ground while keeping each leg straight in goose-stepping. Goose-stepping may require more leg muscle and a larger motion than the other two gestures considered (i.e., marching and tapping). Foot teleportation (Liu et al., 2021) allows users to teleport to a specific location by lifting their heels and then lowering them. The target distance is determined by the amount of force applied by the user to lift their heels. Longer distances are traversed with more force. VR-STEP (Tregillus et al., 2016) is a WIP implementation of virtual locomotion that employs real-time pedometry. VR-STEP requires no additional interface and allows the user to move around in a VE using the smartphone's inertial sensors. A user study compared VR-STEP to look down to move (LDTM), a popular auto-walk navigation method and found no significant difference in performance or reliability. VR-STEP was discovered to be a more immersive and intuitive way of traveling in a smartphone-based VR. The ankle platform (Otaran et al., 2021) is a seated, hands-free locomotion technique powered by an

electric motor and controlled by feedback. It creates a walking experience by using foot-tapping gestures to experience various types of walking terrains haptically.

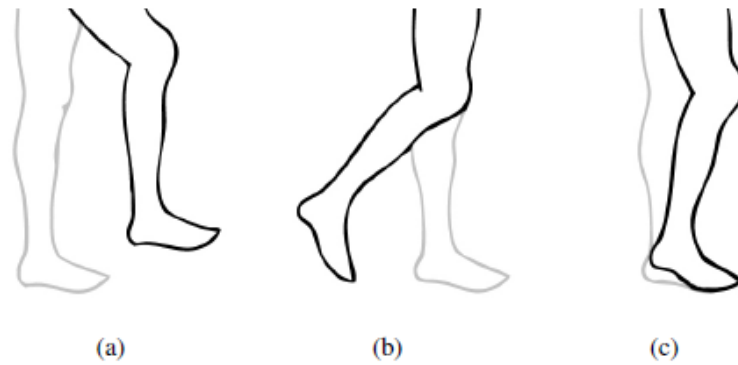


Figure 2.7: Leg-Based Gestures for WIP a. Marching b. Wiping c. Tapping. Image Source: (Nilsson et al., 2018)

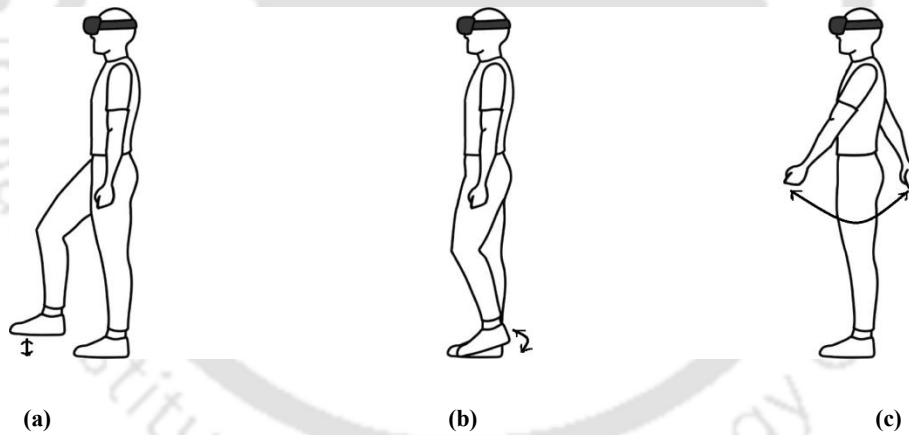


Figure 2.8: Gesture-Based Locomotion (a) WIP (b) Tapping in Place (c) Arm-swinging. Image Source: (Nilsson et al., 2018)

**b) Head-Based Locomotion Technique:** Tregillus et al., (2017) created an omnidirectional leaning locomotion technique for smartphone VR called "head tilt." The direction and degree of the user's head tilt are used to control the travel direction and speed. Griffin et al., (2018) carried out a user study to compare the performance, cognitive load demands, usability, presence, and VR sickness of two hands-busy (full locomotion/teleportation) and two hands-free (tilt/walking-in-place). The task required bimanual shooting as well as VE navigation. It was found that, while hands-free methods

provided more presence, hands-busy locomotion methods performed better. Prithul et al., (2021) presented a novel third-person locomotion method by combining skeletal tracking with head-tilt based input to enable omnidirectional navigation. A user study was conducted to compare the performance; usability, VR sickness incidence, and avatar embodiment of a head tilt method and controller for a navigation task involving object interaction. The head tilt method was found to offer significantly higher avatar embodiment. In head-directed navigation (Kitson et al., 2017), the user's head or HMD orientation is tracked. The users tilt their heads forward/back and rotate their heads left/right to move in those corresponding directions. This kind of navigation was found to be too slow, and the user's complained that they were unable to move and look around at the same time. However, this technique was found to be the most intuitive, providing the least motion sickness and the highest usability compared to the controller, Muvman, Swivel Chair, and Navichair-based locomotion.

**c) Forearm-Based Locomotion Technique:** Arm swinging gesture (AS) is an upper body gesture that facilitates a natural walking experience for the user by rhythmic swinging movement of hands. A user study performed by (Nilsson et al., 2013) compared the user experience of WIP and the AS technique. The AS was found to be equally natural and less fatiguing than the WIP technique. The users felt that AS was natural similar to real walking since it involves the rhythmic movement of hands. One of the limitations of the AS is that while moving in a VE, the user cannot interact with the VE as the hands are occupied performing the movement gesture. The tracking can be done using body tracking devices such as Microsoft Kinect (Ferracani et al., 2016) or wearable devices (Wilson et al., 2016), or controllers (Pai et al., 2017) as shown in Fig 2.9. The Arm-Cycling technique (Coomer et al., 2018) involves tracking the changes in the distance of hand-controllers. Thus, users can move the controllers in any direction to move forward. Hence users move their arms to translate in the yaw direction that their head is facing. The point-tugging method (Coomer et al., 2018) allows the user to choose a target point in virtual space and pull them towards it. This method was inspired by the game "tug of war," and it can be imagined as users "pulling" themselves through an immersive VE with an imaginary rope. Users can move in any direction using this method. The hand-flapping gesture (Bozgeyikli et al., 2016) method requires the users to flap their hands to move the viewpoint controller in the VE. The flying technique (Bozgeyikli et al., 2016) uses a hand-raising gesture to trigger the automatic locomotion in the VE. In point and teleport implementation (Bozgeyikli et al., 2016), an optical motion tracking system tracks the user's dominant hand and shoulder. The vector

from the virtual shoulder position data to the virtual hand position data determines the pointing direction. The virtual hand position generates a ray. The collision detection is done between the ray and the VE's floor. After that, the user is teleported to the new location.



Figure 2.9: User performing arm swinging gesture. Image Source: (Pai et al., 2017)

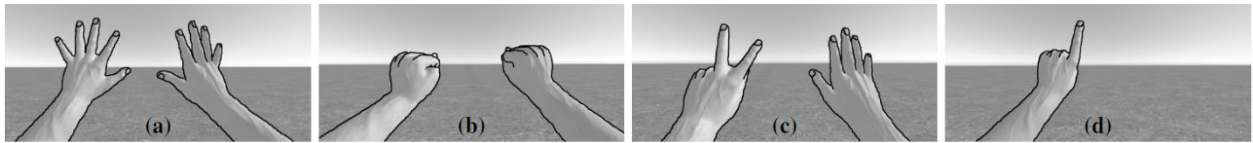
**d) Hand-Based Locomotion Technique:** Ferracani et al., (2016) performed an extensive user study to investigate the perceived naturalness and effectiveness of four locomotion methods, such as arm-swinging, WIP, tap, and push gestures as shown in Fig 2.10. The tap gesture is a metaphorical gesture that uses the index finger to tap and move in the desired direction. The push gesture is a metaphor for pushing a lever to control the locomotion machines. It entails closing and opening the hand while moving it forward in relation to the user's elbow. It was found that the tap and the push were the most preferred gestures by the users.



Figure 2.10: Four gestures for locomotion. Image Source: (Ferracani et al., 2016)

The LM-Travel (Cardoso et al., 2017) as shown in Fig 2.11, is based on hand gestures that allow the users to control the movement to start/ stop, movement speed, and rotation. This technique uses

the Leap motion 3D sensing device for detecting hand gestures. A user study compared the LMtravel technique with a gamepad and gaze-directed techniques. It was found that the gamepad technique outperformed in performance and felt more comfortable moving in a VE.



**Figure 2.11: Hand poses for LMTravel Technique. Image Source: (Cardoso et al., 2017)**

The double hand-gesture interaction (DHGI) implemented by Zhang et al., (2017) uses hand gestures to control the translation (walk/run) forward or backward by turning the user's left palm upward or downward and the direction of the avatar is changed to the left or right with the right thumb pointing toward either direction. This method was compared with the joystick input device and portal methods. It was found that the DHGI was very intuitive, easy to learn, easy to use, and provided less physical fatigue. The users felt immersed in the VE with a reduced sense of motion sickness. Triggerwalking (Sarupuri et al., 2017) is a finger-based locomotion technique that generates near-realistic virtual bipedal steps using the controller's triggers. The usability of triggerwalking was compared with the joystick, teleportation, and WIP methods. Triggerwalking was found to be less physically demanding than WIP and induced less motion sickness than a joystick. PinchMove technique by Pai et al., (2018) as shown in Fig 2.12 uses the pinch gesture to grab a position in 3D space and drag the user to the targeted point based on the change in the position of the hand. This method allowed the manipulation of the viewport for accurate near-field traversal using both unimanual and bimanual modes.



**Figure 2.12: Pinch move being used bimanually. Image Source: (Pai et al., 2017)**

The Palm steering technique by Caggianese et al., (2020) is a freehand steering technique that allows the user to specify the direction using their palm orientation. The locomotion is performed using a constant speed. The input condition to start and stop the traveling is by using a grab gesture. Hence both direction and input conditions are controlled together using the same hand, and the user has the ability to move in all directions. In the index steering technique, the direction is controlled by the

user placing their hand in the FOV of the sensor with only the index finger raised. The locomotion is performed using a constant speed. The input condition to start and stop the locomotion is by tracking the thumb poses of the same hand that controls the traveling direction. The TwoHandIndex and TwoHandPalm with active Teleportation and OneHandIndex and OneHandPalm with passive teleportation methods designed by Schäfer et al., (2021) use the hand and the palm body parts for the movement. A comprehensive study was performed to evaluate the effectiveness and efficiency of the four locomotion techniques. It was found that OneHandIndex and OneHandPalm method was more effective and comfortable for traveling in a virtual world.

**e) Torso-Based Locomotion Technique:** To produce virtual movement, the hip movement gesture (Nilsson et al., 2013) requires the user to alternately swing the hips right and left while keeping both feet grounded. This method provided proprioceptive feedback while reducing unintentional positional drift (UPD). The leaning technique is the most common torso-based locomotion technique. In this method, the user leans forward, backward, and sideways (strafing) in either a sitting or standing position. Harris et al., (2014) developed a method called the Wii-Leaning, which allows the users to physically lean using a Wii Fit Balance Board to explore a VE. This technique was compared with the joystick method, and the users felt that the spatial representation of VE was more accurate with the Wii-Leaning method. Kruijff et al., (2016) used a custom-designed foot haptics system combined with leaning in standing posture and illustrated that adding auditory, visual, and vibrotactile cues could enhance the vection and presence. Wang et al., (2018) designed three gestures to enable sidestepping while moving in a VE. The three gestures include hip movement, lean torso, and side step. The results of the user study suggested that the leaning yielded a significantly more natural walking experience and also produced less positional drift. Buttussi and Chittaro (2019) compared leaning with the joystick and teleportation technique and found that the performance of leaning was better than that joystick. The use of a chair-based method is another relevant technique. Users sit in a chair or stool, and their turning and tilting motions are mapped to VE's direction change and translation motions. Kitson et al., (2017) compared the non-motion cueing interface joystick with motion cueing interfaces such as NaviChair (stool with springs), MuvMan (sit/stand active stool), Swivel Chair (everyday office chair which allows leaning), and Head-Directed (Oculus-Rift DK2) as shown in Fig 2.13. The qualitative suggested that overall, participants preferred the motion cueing interfaces but felt that the leaning interfaces needed modifications before they would switch from

using a Joystick. Some of the chair-based techniques discussed in the literature are ChairIO and VRChairRacer (Willich et al., 2019).

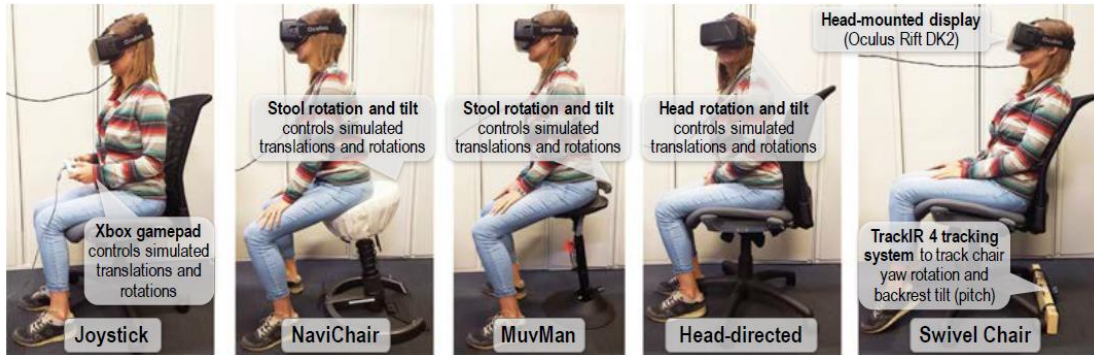


Figure 2.13: The five interfaces for leaning based locomotion. Image Source: (Kitson et al., 2017)

Below we present a summary of the gesture-based locomotion techniques based on the body part used to perform the gesture in the different user studies in the literature.

Table 2.2: Summary of Gesture-Based Locomotion Techniques

Article	Head Based	Fore-arm Based	Hand Based	Torso Based	Leg Based	Sitting/ Standing
Nilsson et al., 2013					Wiping Tapping	Standing
Nilsson et al., 2013		Arm swinging		Hip	WIP	Standing
Nilsson et al., 2014					WIP	Standing
Nilsson et al., 2014					WIP	Standing
Williams et al., 2013					WIP-Kinect	Standing
Harris et al., 2014				Wii-Lean		Standing
McCullough et al., 2015		Armswinging-Myo				Standing
Bozgeyikli et al., 2016		(i) Flying(ii) Hand Flapping(iii) Point and teleport			WIP	Standing
Tregillus and Folmer, 2016	LDTM				VR Step	Standing
Kruijff et al., 2016				Leaning		Sitting
Bozgeyikli et al., 2016		Point and Teleport			WIP	Standing

Article	Head Based	Fore-arm Based	Hand Based	Torso Based	Leg Based	Sitting/ Standing
Ferracani et al., 2016		Arm swinging	(i) Push (ii) Tap		WIP	Standing
Wilson et al., 2016		Myo Armswinging			Myo WIP	Standing
Cardoso, 2017			LM Travel			Sitting
Tregillus et al., 2017	Head tilt				WIP	Standing
Xu et al., 2017		Point and Teleport			WIP	Standing
Kitson et al., 2017	Head Directed			(i) Navi Chair(ii) Muvman (iii) Swivel Chair		Sitting
Sarupuri et al., 2017		Point and Teleport	Trigger walking		WIP	Standing/ Sitting
Bhandari et al., 2017					WIP	Standing
Zhang et al., 2017			DGHI			Sitting
Pai et al., 2017		Armswinging				Standing
Coomer et al., 2018		(i) Armcycling(ii) Point Tugging(iii) Point and Teleport				Standing
Griffin et al., 2018	Head Tilt	Point and Teleport			WIP	Standing
Wang et al., 2018				(i) Move Hip(ii) Lean torso	Sidestep	Standing
Pai et al., 2018			Pinch Move			Sitting
Boletsis et al., 2019		Point and teleport			WIP	Standing
Bozgeyikli et al., 2019		Point and teleport			WIP	Standing
Willich et al., 2019				VRChair Racer		Sitting

Article	Head Based	Fore-arm Based	Hand Based	Torso Based	Leg Based	Sitting/ Standing
Buttussi and Chittaro, 2019		Teleportation		Leaning		Sitting
Caggianese et al., 2020			(i) Palm Steering Technique(ii) Index Steering Technique			Standing
Awada et al., 2021					WIP	Standing
Khundam and Nöel., 2021		Armswinging		Squat		Standing
Prithul et al., 2021	Head Tilt					Standing
Kim and Xiong, 2022					(i) TIP(ii) JIP(iii) SIP	Standing
Otaran and Farkhatdinov, 2021					Ankle interface	Sitting
Khundam, 2021		(i) Point and Teleport(ii) Armswinging				Standing
Cannavò et al., 2020		Arm swinging			WIP	Standing
Gao et al., 2021	Head Leaning	Arm swinging		Leaning	Knee WIP	Standing/ Sitting
Ke and Zhu , 2021					(i)Marching (ii) Tapping(iii) Goose Stepping	Standing/ Sitting
Schäfer et al., 2021			(i) Two hand index (ii) Two hand palm(iii) One hand index(iv) One hand palm			Standing

Article	Head Based	Fore-arm Based	Hand Based	Torso Based	Leg Based	Sitting/ Standing
Mousas et al., 2021					WIP	Standing
Xing and Saunders, 2021			Pointing			Standing
Kim et al., 2021		Point and Teleport			(i) WIP(ii) RIP	Standing
Liu et al., 2021					(i) Foot fly(ii) Foot Step(iii)Foot teleport	Standing

#### 2.2.4 Discussion

Vehicular locomotion is effective when realistic experience is required as it mimics the steering experience of the real world. However, this method always requires additional props to make VR experience compelling. Artificial locomotion via joystick is a straightforward method of locomotion in VR, but it causes cyber-sickness. Magical metaphors like teleportation provide a simple way to travel in VR, but abrupt changes in viewpoint cause spatial disorientation. Real Walking is the most natural and efficient way to move around in VR. Previous user studies in the literature have illustrated that walking in VR performs better in search-related tasks, enhances presence, reduces cybersickness, and improves the spatial orientation of the users. However, the primary constraint is the tracking space when users want to traverse large VE.

To some extent, Redirected Walking addresses this constraint by redirecting users to use limited tracked space for larger VEs. Redirected Walking, like real walking, provides users with better spatial understanding (Zanbaka et al., 2004) and performs better in obstacle avoidance tasks. However, redirected walking still requires a minimum tracking space of (12m x 44m). It is unsuitable for VR applications that involve several turns and sudden increases in velocity as they may lead the users to cross the tracking boundary. The Gait Negation Technique requires omnidirectional treadmills to provide a natural walking experience in VE. They cannot be considered a viable alternative for using these techniques at home as they require huge expensive mechanical setups. Their prolonged use may cause the users physical fatigue.

In terms of simplicity, directness, and naturalness, partial gait techniques cannot compete with real walking in their current forms. However, research suggests that they may elicit a stronger sense of presence than techniques that require users to advance by pressing a button. Although proxy gestures do not provide much vestibular feedback, their inherent user safety, convenience, and cost-effectiveness have been highlighted as major factors in research on their naturalness while traveling in large VEs. Furthermore, the recognition of proxy gestures does not necessitate large mechanical setups. With the technological advancement of "inside-out tracking" present in current HMDs, there is no need for additional interfaces to be attached to the existing system, saving users money on purchasing additional hardware specifically to recognize gestures. This method, when compared to other methods discussed, also allows users to use it in the home environment in a standing or seated posture as it takes up less space and allows the users to travel a large VEs.

### **2.3 Characteristics of Ideal Locomotion Technique**

Bowman et al., (1998) proposed a set of quality factors that correspond to effective virtual travel. A few more characteristics are added to the ideal locomotion technique based on the human factors in the literature. We should also take into account that the characteristics of an ideal locomotion technique vary depending on the application. There is no requirement that an ideal locomotion technique for a specific VR application includes all of the characteristics listed below.

**Speed** – This factor corresponds to the task completion time. A good locomotion method should be efficient to complete the given task. Walking, for example, is not ideal if the VE is too large and requires the user to travel long distances. A steering metaphor, such as a joystick, or a magical metaphor, such as teleportation, can be used to traverse long distances.

**Accuracy** – It is defined as the proximity to the desired target. The completion time and accuracy together are used to measure the performance of the user. The degree of accuracy also depends upon the number of errors performed during the travel, such as collisions, deviation from the ideal path, and turning errors. An ideal locomotion technique should have high accuracy in completing the task, for example, avoiding collisions while traveling on a narrow path.

**Spatial Awareness** – Spatial Awareness is a characteristic that constitutes users' awareness of their position and orientation in relation to their surroundings during and after travel.

**Ease of Learning** - This specifies a novice user's ability to use the interface quickly and efficiently. A good locomotion method should be simple to learn.

**Ease of Use** –This factor denotes the complexity or cognitive load of the technique when used to travel in a VE by the user.

**Information Gathering** – This corresponds to the user's ability to actively acquire information during the movement in a VE.

**Presence** – This measure refers to the user's sense of immersion or "being within" the environment due to travel. A good locomotion technique should improve immersion in the VE.

**User Comfort** – An ideal technique should induce minimal simulator sickness, dizziness, or nausea even after prolonged use.

**Usability**-Defined by ISO 9241-11 as "the extent to which specified users can use a product to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use."

**Naturalness** – This emphasizes that the user should interact and explore the VE naturally, similar to the real world.

**Real-world transfer**– This is more relevant for virtual training simulations. It measures how well a user can perform a real-world task based on virtual-world training. This characteristic is particularly relevant to VR applications that train users for a specific skill that must be used in real life.

The quality factors allow for some uncertainty in mapping specific travel techniques to specific VE applications. Application developers can then specify the levels of each important quality factor for their application, and the technique that comes closest to that specification is chosen. High levels of spatial awareness ease of use, and presence, for example, may be required in an architectural walkthrough, whereas high speeds may be unimportant. In an action game, on the other hand, speed, accuracy, and ease of use may take precedence over information gathering. These characteristics are guidelines for developing or selecting the best locomotion technique based on the needs of the VR application; there is no requirement that a locomotion technique should have all of the characteristics. The reviewed techniques are classified into a concept matrix based on the quality factors studied in the empirical studies as below table 2.3.

**Table 2.3: The reviewed techniques are classified into a concept matrix based on the quality factors studied in the empirical studies.**

Article	Naturalness	Usability	Sickness	Presence	Time	Collision	Spatial Knowledge	User Experience	User Preference
Nilsson et al., 2013	x			x					
Nilsson et al., 2013	x			x					
Nilsson et al., 2014	x								
Nilsson et al., 2014	x								
Williams et al., 2013							x		
Harris et al., 2014							x		
McCullough et al., 2015							x		
Bozgeyikli et al., 2016	x	x			x	x		x	x
Tregillus and Folmer, 2016		x		x					x
Kruijff et al., 2016		x		x					
Bozgeyikli et al., 2016			x	x	x	x		x	x
Ferracani et al., 2016	x				x	x			x
Wilson et al., 2016						x	x		
Cardoso, 2017			x		x	x			x
Tregillus et al., 2017		x	x	x		x			
Xu et al., 2017						x	x		
Kitson et al., 2017	x	x	x	x			x	x	x
Sarupuri et al., 2017	x		x						x
Bhandari et al., 2017		x		x	x	x			
Zhang et al., 2017					x	x			x
Pai et al., 2017			x	x					
Coomer et al., 2018		x	x						
Griffin et al., 2018		x		x	x	x			

Article	Naturalness	Usability	Sickness	Presence	Time	Collision	Spatial Knowledge	User Experience	User Preference
Wang et al., 2018	x								
Pai et al., 2018			x			x			
Boletsis et al., 2019		x		x				x	
Bozgeyikli et al., 2019		x	x	x	x			x	x
Willich et al., 2019	x								
Buttussi and Chittaro, 2019		x	x	x	x				x
Caggianese et al., 2020		x	x		x	x		x	x
Awada et al., 2021				x				x	
Khundam and Nöel., 2021		x	x		x			x	x
Prithul et al., 2021		x	x		x	x			
Kim and Xiong, 2022								x	
Otaran and Farkhatdinov, 2021	x		x						
Khundam, 2021		x	x						
Cannavò et al., 2020	x	x	x	x	x	x		x	x
Gao et al., 2021					x	x			x
Ke and Zhu , 2021					x	x			x
Schäfer et al., 2021		x	x		x			x	x
Mousas et al., 2021		x	x					x	x
Xing and Saunders , 2021					x				
Kim et al., 2021					x	x			
Liu et al., 2021			x						x

## **2.4 Need for Design intervention for locomotion gesture for a VE in a seated position**

The preceding literature shows that both controller-based and controller-less body gestures are widely used for locomotion in VE. This includes finger-based gestures such as trigger walking, controller-based gestures such as the pinch move, head gestures such as shaking and tilting, and bare hand gestures such as the LMTravel and DHGI. Although using body gestures to interact within VE increases naturalness, it induces physical fatigue when used for a longer period. Moreover, when the user performs different gestures for different functionalities such as locomotion, selection, and manipulation, the user exerts cognitive effort while using the gesture in a multitasking VE. This mental effort can be significantly reduced if the design process also includes users in developing gestures. To the best of our knowledge, none of the above gestures were created through a user-generated gesture elicitation design process. Hence this raises our research question

***RQ1- What are the user-centric gestures that are natural for locomotion in a VE when both hands are free in a seated position?***

Most of the work discussed above was only intended to complete the locomotion task. People frequently carry out a variety of functions while adjusting the position and rotation of their viewport. Furthermore, the user simultaneously performs locomotion with other tasks in many VR applications such as shooting games, architectural walkthroughs, etc. Most of the tasks support only locomotion in the empirical studies discussed in the literature. As a result, there is a clear need to investigate those locomotion gestures that can be performed along with other gestures like selection and manipulation for real-time scenarios. This led to the next three research questions

***RQ2 - What are the user-centric gestures that are natural for locomotion in a multitasking VE when one hand is engaged in another interaction, such as selecting or manipulating a virtual object in a seated position?***

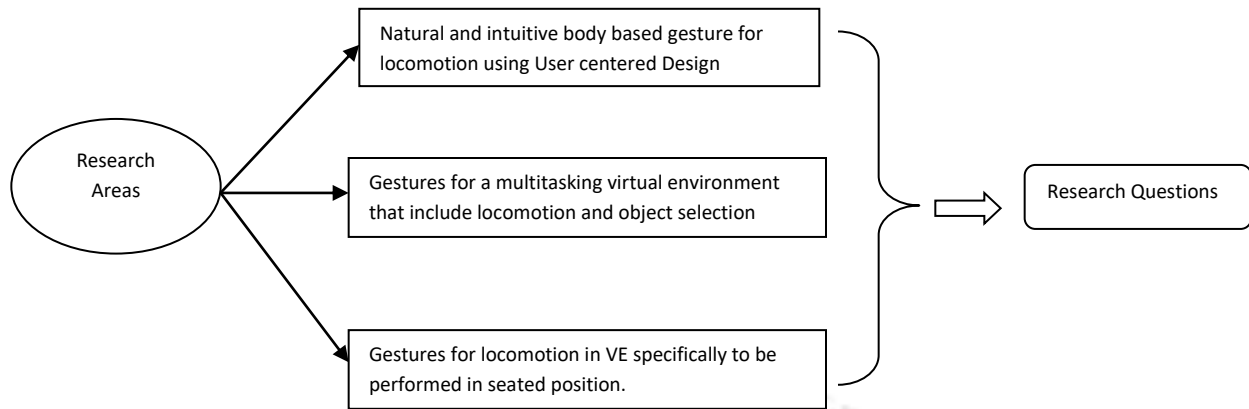
***RQ3 – What are the user-centric gestures that are natural for locomotion in a multitasking VE when both hands are engaged in other interactions, such as selecting or manipulating two virtual objects in a seated position?***

**RQ4** – *How do the newly designed gesture-based locomotion techniques impact the task completion time, collisions, motion sickness, spatial knowledge and presence compared to existing locomotion techniques in a seated position?*

The study also aimed to explore locomotion techniques that can be performed while seated, as many VR games and applications use simulated avatars performing physical activities in a standing position, but users often prefer to sit comfortably while playing with hand or finger-based controllers. Additionally, applications such as VR tourism require users to be seated while experiencing new places through a standing or walking avatar. Seated-based navigation can also benefit individuals with mobility issues who are unable to explore their surroundings in the physical world. VR technology can allow disabled individuals to experience activities such as climbing mountains, skateboarding, or swimming while in a seated position. Therefore, one of the primary goals of the study was to develop gesture-based techniques that support seated-based navigation.

Seated-based applications have several benefits, such as in the case of conditionally automated vehicles (AV), which allow drivers to perform secondary tasks while traveling. VR can serve as a useful tool for training drivers and familiarizing them with the equipment. Seated-based navigation is crucial for measuring the effectiveness of the training. Another application of seated-based VR is in exergames, which can offer safe and effective therapies for the elderly, who are at a higher risk of falling. These games are designed with clinical experts and therapists to provide fall-prevention exercises that can be done while seated. Elderly users with limited mobility can also benefit from virtual travel experiences that allow them to see the world from the comfort of their seats. These experiences are available on platforms such as Oculus Go and Gear VR and provide users with the opportunity to travel through time and explore different locations.

Hence this research aims to design and perform a sequence of user experiments through a gesture elicitation study for identifying user-centric gestures for locomotion in a multitasking environment in a seated position (i) when both hands are free, (ii) when one hand is engaged in the selection of a virtual object (iii) when both hands are engaged in the selection of virtual objects. It also aims to design new gesture-based locomotion techniques and evaluate them with the other gesture-based methods in the literature for their intuitiveness, performance, comfort, ease of use, perceived workload, presence, spatial knowledge, simulation sickness, and user preference.



**Figure 2.14: Need for design intervention for gesture-based locomotion techniques**

## 2.5 Experimental studies performed during this research

During the course of this research, we performed five user studies to answer our research questions. The first experimental study (Study 1) was a user-generated gesture elicitation study. Three different VEs were designed, and the users' elicited full body gestures for locomotion that consists of both walking and running tasks. In Study 2, we evaluated the three sets of user-centric gestures (one set for each VE) based on appropriateness, ease of use, effort, and user preference. We also performed the classification of the gestures based on hand usage and gesture forms. These two studies' results helped us answer the research questions RQ1, RQ2, and RQ3. We designed and implemented three new locomotion techniques for three different VEs. We compared the newly designed gestures with the gestures in literature in Study 3, Study 4, and Study 5. This answered our research question RQ4. From the results of the comparative studies, we developed the characteristic framework and formulated the design principles. The below schematic diagram gives a summary of our five experimental studies.

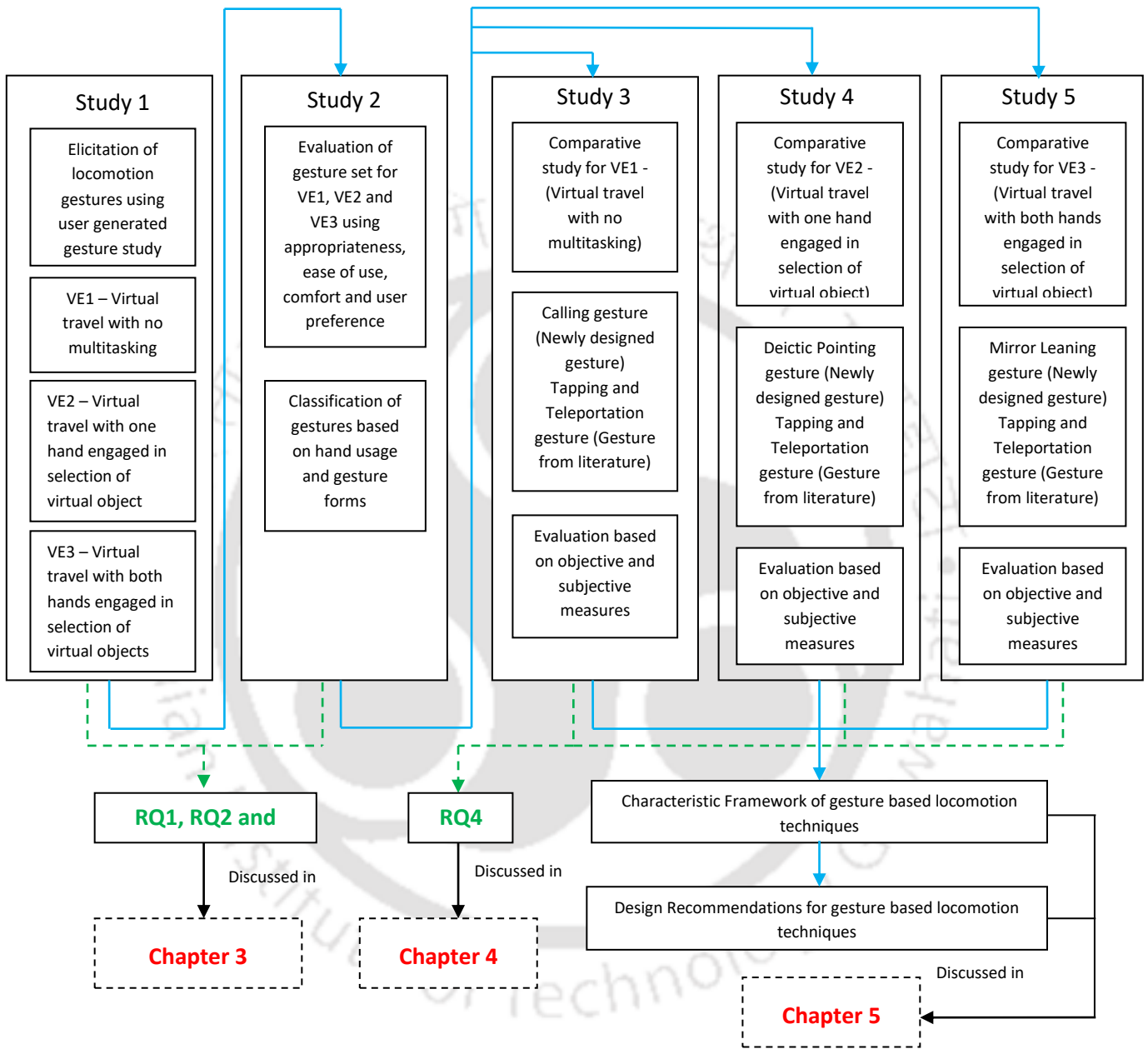


Figure 2.15: Schematic diagram representing the five experimental studies in the research

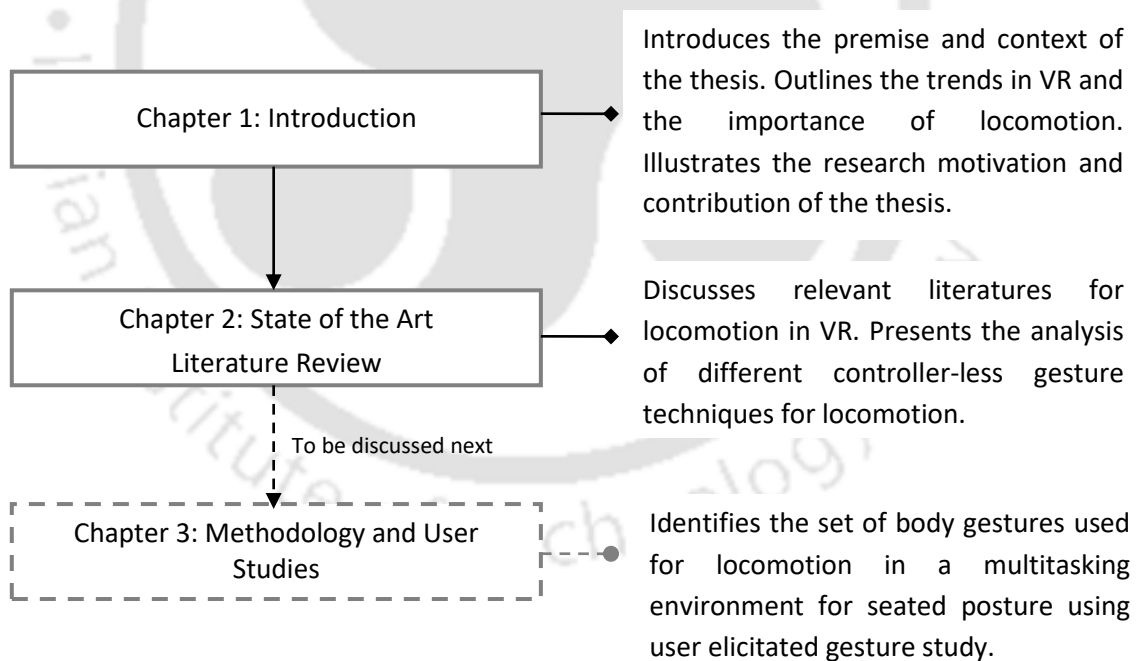
## 2.6 Summary

Overall, this chapter presents a literature review of different locomotion techniques classified based on their naturalness. We further present the characteristics that are needed for an ideal locomotion technique. We further discuss that every locomotion technique differs in its characteristics, and not a single locomotion technique can satisfy all the measures presented. Hence based on the application requirement, we can select the suitable virtual locomotion technique. Through the in-depth reporting and analysis of existing literature, we establish the need to intervene and design body gestures as a suitable interaction modality to be used at home in a seated position for a multitasking environment.

In the next chapter, we discuss two experimental studies based on a user-generated gesture elicitation approach to collect and extract a set of natural and intuitive virtual locomotion body-based gestures for different multitasking environments in a seated position.

### A quick recap of previous chapters:

The visual summary of the chapters covered so far is provided as follows:



## CHAPTER 3 - METHODOLOGY AND USER STUDIES

From the extensive literature review, we found that among the different locomotion techniques, proxy gestures have been proven to be an effective input modality for VR locomotion. However, certain limitations exist regarding the gestures' naturalness, intuitiveness, and physical fatigue associated with using the gesture for a longer duration. When used as a locomotion method, the proxy gestures must be natural, comfortable to perform, and able to cover large virtual distances without physical fatigue. This chapter discusses the two experimental studies executed to collect and extract a set of natural and intuitive virtual locomotion body-based gestures for the different multitasking environments in a seated position. The procedure followed and the results of the two main studies are illustrated in this chapter.

In section 3.1, the overview of the two experimental studies is presented. Section 3.2 presents Study1 - Investigating suitable body gestures for virtual travel in three different VEs. This section starts with a detailed review of existing elicitation studies used for designing gestures and elaborates upon the chosen approach of user-generated gesture design for this study (Section 3.2.1 and Section 3.2.2). This is followed by conceptualizing the three different VEs (VE1, VE2 and VE3), in section 3.2.3. The details of the participants (section 3.2.4), experimental setup (section 3.2.5), study procedure (section 3.2.6), data collection method (section 3.2.7), method of gesture extraction (3.2.8) and the results (section 3.2.9) are elaborated. The final gesture set for the three different VEs is tabulated. Section 3.3 presents Study 2 - A user evaluation study for the top three preferred gestures from the first study. The gestures were evaluated based on appropriateness, ease of use, effort, and preference. Section 3.4 analyzed the gesture sets for VE1, VE2, and VE3 from Study 1 based on the geometric taxonomy of hand usage and gesture form. The tables 3.11, 3.12 and 3.13 presents the classification of gestures based on hand usage and gesture form for VE1, VE2 and VE3 respectively. In section 3.4.2, the findings and insights of the classification of the gesture set are discussed in detail for the different VEs. The analysis helped in gaining insight into the end-users' mental models while performing the gesture for virtual travel. This aided in determining user behavior and gesture patterns for virtual travel in three distinct VEs. The chapter is finally summarized in section 3.5.

### 3.1 User-Generated Gesture Study – An Introduction

We performed two studies to identify user-centric gesture sets for each environment. The first study was *Study 1- Investigating suitable body gestures for virtual travel in three different VEs*. This study uses a user gesture elicitation method to identify virtual travel gestures by requiring participants to perform gestures of their choice for locomotion for each of the multitasking environments. The second study was *Study 2 – Evaluation of the proposed virtual travel gestures*. This study included a new group of participants who evaluated the gesture set obtained in Study 1 on different factors such as appropriateness, ease of use, effort, and user preference for the three multitasking environments. Study 2 helped to design new gestures that were developed and compared for the different environments later discussed in Chapter 4.

We intend to answer three of our research questions from these two studies.

**RQ1** - *What are the user-centric gestures that are natural for locomotion in a VE when both hands are free in a seated position?*

**RQ2**-*What are the user-centric gestures that are natural for locomotion in a multitasking VE when one hand is engaged in another interaction, such as selecting or manipulating a virtual object in a seated position?*

**RQ3**- *What are the user-centric gestures that are natural for locomotion in a multitasking VE when both hands are engaged in other interactions, such as selecting or manipulating two virtual objects in a seated position?*

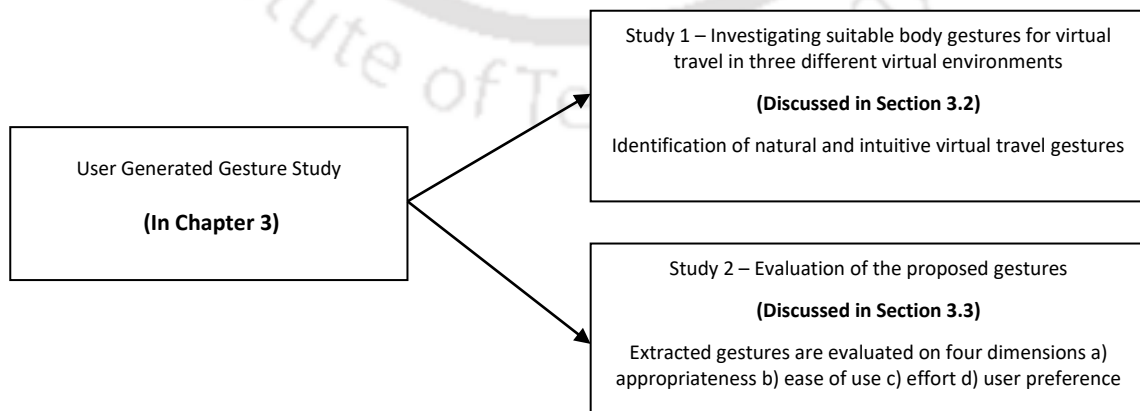


Figure 3.1: User Studies conducted as a part of user research

## 3.2 Study 1: Investigating suitable body gestures for virtual travel

A gesture elicitation study was conducted to identify the most natural and intuitive gestures for traveling a VE while in a seated position. The study collected user-generated gestures for both walking and running functions of locomotion. This section presents a detailed description of existing elicitation studies for designing gestures in the literature. We further describe the different VEs used in the experiment. It also discusses the participants in the study, the experimental setup, the study procedure, the method of gesture extraction, and the results and findings of the study. The study results in the form of user-centric gesture sets for VE1, VE2, and VE3 are presented later in this section

**3.2.1 Overview of existing gesture elicitation studies to design gestures:** Gesture elicitation studies are a popular and effective method in HCI for informing the design of intuitive gesture commands that reflect end-user behavior and can be used to control a wide range of interactive devices, applications, and systems. Nielsen et al., (2003) proposed a user-generated gesture approach for generating an intuitive and usable gesture set by collecting user-performed gestures. The proposed system's functions are conceptualized to be available to all users. Users' gestures are further extracted based on semantic representations of associated functions. Henze et al., (2010) defined free-hand gestures for a music playback system. In their method, the usage context of the interface is first defined. In the second step, the set of functionalities is validated, and multiple gesture sets are derived from participatory design techniques. Wobbrock et al., (2009) performed a gesture elicitation study to obtain gestures for manipulation and navigation tasks for the tabletop interface. Arora et al., (2019) explored the use of hand gestures for performing animation tasks in VR. They further analyzed the gestural interactions by classifying them along semantic and geometric dimensions to identify the common trends in how participants expressed various spatial and temporal operations. Piumsomboon et al., (2013) used a participatory design method to explore hand gestures in AR for 40 selected tasks. Ruiz et al., (2011) performed a study for user-defined motion gestures to invoke commands on a smartphone device. Akers, (2006) adopted the participatory and observation-based approach to finding a set of gestures for the 3D selection of neural pathways. A wizard of Oz prototype system was created to assist with the process of finding the gesture set. The prototype allowed the user to perform core selection operations. Vatavu et al., (2012) conducted an elicitation study to propose gestures for free-hand TV Control. The memorability of free-form gesture sets for invoking actions was investigated by Nacenta et al., (2013). Three types of gesture sets: user-defined gesture sets, gesture sets designed by the authors, and random gesture sets were compared by the users. The results illustrated that the user-defined

gestures were easier to learn and remember than the pre-defined gestures by system developers. Overall, the methods described above involve users in the design process and added gestures derived from user input.

The two main motivation factors for this study are (a) to the best of our knowledge, no studies have created a user-generated gesture set for the locomotion task in a VE while in the seated position. (b) Previous research has only evaluated virtual travel techniques in the context of a single navigation task; thus, the impact of travel gestures in a multitasking environment that also includes selection or manipulation has not been assessed. This effect is critical because it significantly impacts performance and overall user experience (Griffin et al., 2018). Hence we intend to generate the user-centric gesture set for locomotion when one hand is engaged in another task, such as selection /manipulation, and when both the hands of the user are engaged in selection/manipulation.

**3.2.2 User-Generated Gesture Design – methodology of gesture design study:** For this research, a user-generated gesture design methodology proposed by Nielsen et al., (2003) was used for the elicitation of user-generated gestures. The three steps followed in the study are

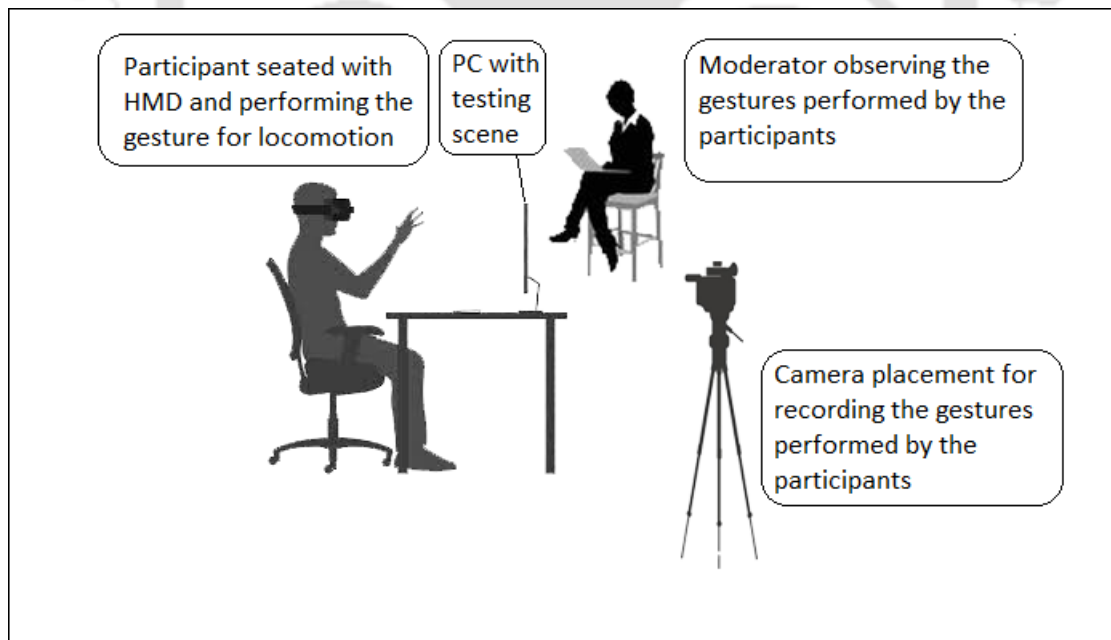
- a) Define the usage context and function – The usage context of the interface is defined, and the initial functionalities are found. The usage scenarios need to be concretized to design the interface for situations where it uses gestural input. The different multitasking VEs are defined and designed in this step. The functionalities include finding gestures for the forward movement in VE at walking and running speeds.
- b) Finding the logical gestures - Identification of the user-created gestures for the virtual travel functionality in different VEs.
- c) Gesture Extraction – Extract the gestures obtained for different VEs based on logical mapping to the intended functionality, frequency of gesture performance, shape and trajectory, and system limitations.

**3.2.3 Designing the Virtual Environments:** In this empirical study, 40 participants performed self-derived gestures to complete a virtual travel task in a VE. Three VEs with varying levels of multitasking were presented to participants. They were given the task of performing the gesture (s) of their choice that they thought would be the most natural for executing the virtual travel task. The VE, which consisted of a maze through which participants had to travel from point A to point B, was designed. The VEs made two turns, one right turn and one left turn, at distances of 50 m and 40 m, respectively. The



**3.2.4 Participants:** The study included 40 university students (27 male and 13 female) ranging in age from 21 to 35 years. An open email was used to invite participants to participate in the study. For their participation, they were given traditional sweets. They were all right-handed. There were no participants with a motor disability. All participants had prior experience with VR interfaces, particularly with Oculus Rift and HTC Vive VR games. Each participant spent 50-60 minutes on the experiment, which included the introduction, pre-questionnaire, warm-up, instructions, and gesture performance for the given tasks.

**3.2.5 Experiment Setup:** The experiment was carried out in a university lab. The lab provided enough space for full-body gestures. An HTC Vive VR platform connected to a laptop was used. The VIVE Hand tracking SDK was used to implement the pinching gesture for selection and manipulation tasks. The moderator acted as a wizard, translating the commands of the participants into VEs. Figure 3.3 depicts the view of the experimental setup room, where the participant wearing the HMD is seated in front of the computer to perform the gestures. The moderator is positioned on the computer's side. The camera is positioned in such a way that it records the gestures performed by the participants while performing the travel task for the different VEs.



**Figure 3.3: Setup of the experiment area for Study 1**

**3.2.6 Study Procedure:** This experiment was carried out in five steps. The procedure began with a pre-study questionnaire in which participants filled out their initial profile details, such as participant's age, gender, and VR usage experience. They were asked questions related to their vision, such as whether they wear glasses or contact lenses, and have had recent eye exams. It was ensured that participants can adequately see and read the content displayed in the VR environment. Second, the study objectives were explained to the participants so that they had a better understanding of the whole study. The participants then went through a training session. They were instructed to familiarize themselves with and practice the selection and manipulation task in all three VEs. The VEs presented during the training session were not the same as those used in the experiment. Fourth, the task was introduced to the participants. The three VEs were randomly distributed to the participants. The participant was asked to perform suitable gestures they would use while traveling in the given VE. The virtual travel from position A to position B was the task under consideration. The velocity of travel was divided into two levels. The walking speed was 1.2m/sec, and the running velocity was 3.2m/sec (Chou et al., 2009). The participant would first walk for 100 meters using a gesture before switching to a running gesture for another 100 meters. The wizard who acts as a moderator would move the user in the VE accordingly. Participants were asked to make the gesture they thought was most natural, intuitive, and best represented the virtual travel task. The participants were instructed to perform at least two gestures, but they were free to perform more. While performing each gesture, participants were encouraged to think aloud and explain the gesture they were performing. Finally, a post-study interview was conducted in which participants were asked to select their favorite gesture from those they performed for each VE. Following the study, the motivation behind each gesture and gesture preferences was also discussed. The participants were asked for permission ahead of time for the experiment to be videotaped. The video recordings of each participant were later used to classify and count the various gestures generated in each environment.



**Figure 3.4: Procedure followed for Study 1**

**3.2.7 Data Collection Method:** The gestures made by the participants for virtual locomotion in each VE were video recorded, and their preferences were also obtained. The feedback that was collected post-study to learn the motivation for performing the gestures was also discussed in an open discussion between the moderator and participants. They were also asked about their motion sickness and presence while traveling in the VE for each of the scenarios.



**Figure 3.5: Users performing the gestures during the study for the different VEs**

**3.2.8 Method of Gesture Extraction:** In order to categorize the user-defined gesture set, two steps were taken. Firstly, gestures with the same shape and/or trajectory were combined into a single gesture. Second, for gestures with similar shape and/or trajectory characteristics, the corresponding video files collected during the elicitation process of each participant were replayed and discussed whether and how to group them based on the verbal explanations (mental models) of experiment participants. The first and second most preferred gestures for each environment were considered, and the total frequencies were calculated and shown in tables 3.1, 3.2, and 3.3. The unique gestures with three or

more frequencies were presented in the tables. The top three most frequently occurring gestures were chosen as travel gestures for the second study.

**3.2.9 Results:** For VE 1, VE 2, and VE 3, 149, 136, and 109 gestures were performed, respectively. Tables 3.1, 3.2, and 3.3 show the gestures and frequencies for VE 1, VE 2, and VE 3. *Calling* Gesture, *Bike Riding* gesture, and *Leaning* Gesture were the final three gestures for VE1, as shown in figure 3.5. *Leaning*, *Calling* gestures, and *Deictic Pointing* were the final gestures for VE2, as shown in figure 3.6. *WIP*, *Tapping*, and *Leaning* gestures were chosen for VE3, as shown in figure 3.7.

**Table 3.1: A set of user-centric gestures identified for VE1 (virtual travel only)**

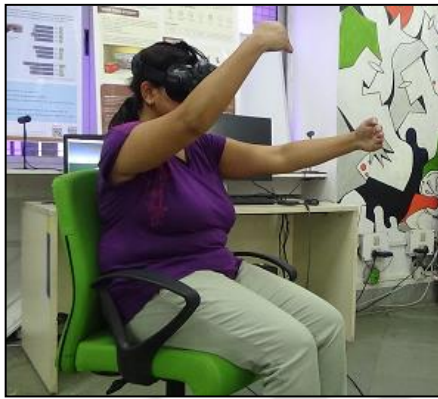
Sr. No.	User-performed gestures for virtual travel	Gesture for increasing the speed	Total frequency	Frequency of 1 <sup>st</sup> preference	Frequency of 2 <sup>nd</sup> preference
1	Cyclic movement of the right hand as calling someone	Increase the speed of the calling Gesture	21	10	11
2	Bike riding with both hands	Leaning to increase speed	16	6	10
3	Torso leaning	Increase the angle of the leaning	16	9	7
4	Walking in Place (WIP)	Increase the speed of WIP	11	6	5
5	Arm-swinging in a circular motion with both hands	Swinging arms faster	9	5	4
6	Press the leg as accelerating (a car)	Increase the press towards the floor surface	4	2	2
7	Finger walking in the air – Using the index and middle finger to perform walking motion in the air.	Moving the fingers faster.	3	2	1

**Table 3.2: A set of user-centric gestures identified for VE 2 (virtual travel with selection & manipulation of one virtual object).**

Sr. No.	User-performed gestures for virtual travel	Gesture for increasing the speed	Total frequency	Frequency of 1 <sup>st</sup> preference	Frequency of 2 <sup>nd</sup> preference
1	Torso leaning	Increase the angle of the leaning	20	13	7
2	Calling Gesture – Cyclic movement of the right hand.	Increase the speed of calling Gesture	19	9	10
3	Deictic pointing	Open five fingers with the palm facing the ground	17	12	5
4	WIP	Increase the speed of WIP	13	5	8
5	Press the leg as accelerating (a car)	Increase the press towards the floor surface	6	1	7
6	Tapping the thigh with both hands alternatively	Increase the speed of Tapping	3	1	2

**Table 3.3: A set of user-centric gestures identified for VE 3 (virtual travel with object selection and manipulation of two virtual objects)**

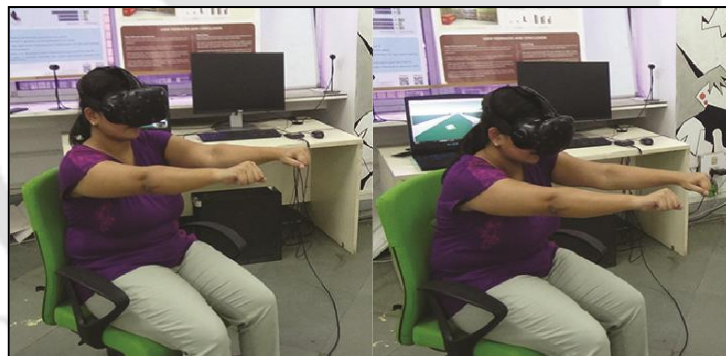
Sr. No.	User-performed gestures for virtual travel	Gesture for increasing the speed	Total frequency	Frequency of 1 <sup>st</sup> preference	Frequency of 2 <sup>nd</sup> preference
1	Tapping the legs alternatively with heels on the ground	Increase the speed of Tapping	21	10	11
2	WIP	Increase the speed of WIP	20	13	7
3	Torso leaning	Increase the angle of the leaning	12	7	5
4	Wiping the legs on the floor surface	Increase the speed of wiping	8	5	3
5	Head bobbing	Increase the speed of head bobbing	6	1	5
6	Gaze for 2 seconds to move	Gaze at a farther position for 2 seconds to travel to that point	5	3	2



(a)



(b)



(c)

Figure 3.6: Gestures for VE1 (with only travel task) (a) Calling gesture (b) Leaning Gesture (c) Bike Riding Gesture for walking and Leaning to increase the speed in a VE.



(a)



(b)

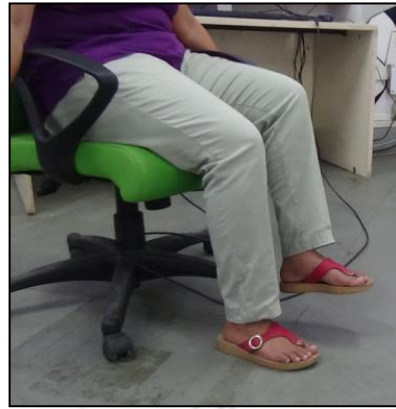


(c)

**Figure 3.7: Gestures for VE2 (virtual travel with one selection and manipulation of a virtual object) (a) Calling gesture (b) Leaning Gesture (c) Pointing gesture for walking and opening all five fingers for running.**



(a)



(b)



(c)

**Figure 3.8: Gestures for VE3 (virtual travel with selection and manipulation of two virtual objects) (a) Leaning gesture (b) WIP Gesture (c) Tapping Gesture**

**3.2.10 Discussion:** Body parts such as one hand, two hands, one leg, two legs, head, eye, and torso were used to create the gestures. It was observed that there was greater involvement of the hands in VE 1 and VE 2 while performing the desired gestures. In VE 3, participants made gestures with their legs and torso while performing the object selection and manipulation task with both hands. Because the experiment was conducted in a seated position using an office chair, many participants experienced sensations similar to VR driving simulators. The rotational movement of the chair was also used to steer the direction of travel. As a result, many people performed gestures like "Bike-Riding" and

"TapAccelerator." One participant stated, "I'd like to make a bike-riding gesture while sitting." Another user commented, "We bend when we move forward, so leaning is natural." Other user statements included, "Driving a bike gesture: This is my favorite. I don't feel tired because we ride our bikes for long distances in real life, and our hands don't ache." "Tap Accelerator: Just like in a car, I would accelerate with my leg." The "Deictic pointing" in VE 2 was inspired by how taxi drivers receive instructions. The user advances by pointing their index finger forward; by opening all five fingers with the palm facing downward, the velocity of movement increases. In all three VEs, the leaning gesture was performed. Participants perceived the leaning gesture as more effortless, increasing their sense of self-motion perception (vection). "As I am sitting, I don't want to perform complicated gestures for travel in VE, so I would just lean to move forward," one participant explained. The "calling" gesture refers to the repeated movement of the arms in a cyclic motion to explore the environment, which is similar to the arm cycling method discussed by Coomer et al., (2018), but without the use of controllers. Participants felt as if they were pulling the VE towards them rather than traversing it while performing this gesture. This gesture was used for unimanual as well as bimanual navigation. The *WIP* and *Tapping* gestures were the most commonly used gestures in VE 3. Participants felt the *WIP* gesture was the most natural and intuitive when both hands were occupied. Because both hands were occupied with the manipulation task, this gesture took advantage of using the legs to perform the virtual travel task, thereby keeping the hands free to use for other interactions.

### 3.3 Study 2: Evaluation of the proposed gestures for VE1, VE2, and VE3

A new group of 40 participants rated each VE's extracted gestures on four dimensions in this study: preference, appropriateness, ease of use of gesture, and effort. The gestures for VEs were chosen based on these variables and the qualitative feedback from the participants.

**3.3.1 Participants:** The experiment included a new group of 40 university students (22 male and 18 female). The participants' mean age was 25.68 (SD = 4.33) years. They were all right-handed. There were no motor impairments. All the participants had moderate experience with VR, and sixteen were experts in using VR. An open email was used to invite participants to participate in the study. After finishing the study, they were rewarded with sweets. We included both experts and moderate experience VR users to derive comprehensive and better understanding of the gestures usability, effectiveness, and overall user experience. Users with extensive VR experience helped in providing insights into advanced functionalities, potential challenges, and opportunities for improvement on the gestures. On the other

hand the moderate experience users represented a broader user base and helped in highlighting issues that were more common among the general population.

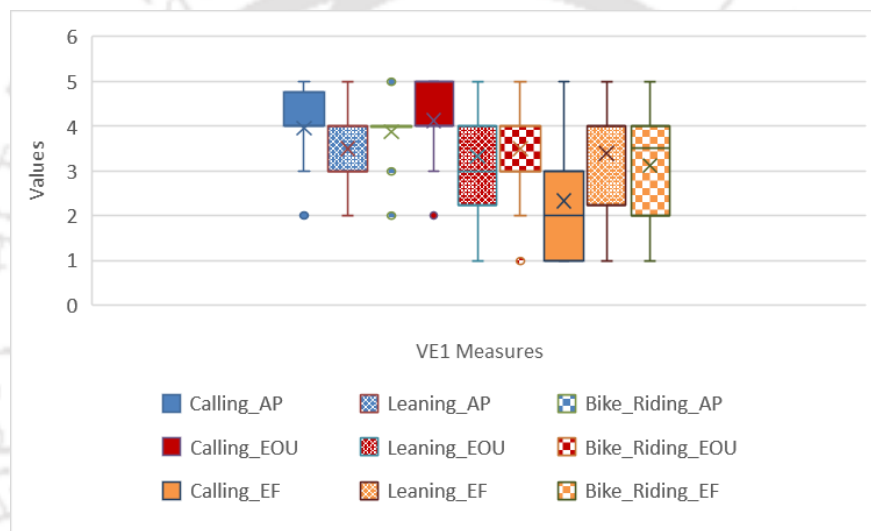
**3.3.2 Procedure:** This experiment was carried out in five steps. The experiment began with a pre-study questionnaire in which participants filled out their initial profile details, such as age, gender, and VR usage expertise. They were asked questions related to their vision, such as whether they wear glasses or contact lenses, and have had recent eye exams. It was ensured that participants can adequately see and read the content displayed in the VR environment. Second, the study objectives were explained to the participants so that they had a better understanding of the study. The participants then went through a training session. They were instructed to familiarize themselves with and practice the selection and manipulation task in all three VEs. The VEs presented during the training session were not the same as those used in the experiment. Then, as in Study 1, a video and description of the specific gesture were displayed on the screen, and the participants were given an unlimited amount of time to understand the VE, tasks in each VE, and gestures. Fourth, the task was introduced to the participants. The task at hand was to perform gestures for virtual travel from point A to point B. Participants were asked to perform the corresponding gesture for each VE; additionally, if they performed the gesture incorrectly, the experimenter informed and corrected them. Finally, they were asked to use a questionnaire to rate the performed gestures in terms of appropriateness, ease of use, and effort (subjective fatigue). After completing all gestures related to the corresponding VEs, the participants ranked the gestures in order of preference. The three VEs and their associated gestures were shown in random order. The experiment was videotaped. The participants were asked for permission ahead of time. The video recordings were later analyzed qualitatively. The entire experiment took about 30 minutes.

**3.3.3 Subjective Ratings: Preference, Appropriateness, And Ease of use, and Effort:** The experiment consists of three VEs. Three gestures in each VE were rated by 40 participants, which equals 360 trials (3x3x40). After completing all gestures for a given VE, subjects rated their gestures on four dimensions: preference, appropriateness, ease of use, and effort. A 5-point Likert scale (1 = strongly disagree to 5 = strongly agree) was used to gather feedback for appropriateness: "The gesture is a good match for its intended purpose." The statement "The gesture is easy to perform." was also used to rate the ease of use (1 = low to 5 = high). The effort data were also collected using ratings (1 = easy to 5 = difficult). Participants ranked their top three preferred gestures for each VE.

**3.3.4 Results of evaluation of gestures:** This section discusses the results of the subjective ratings for the different gestures based on appropriateness, effort, ease of use, and user preference for the three VEs. A Shapiro–Wilk test was performed on the dependent variables of appropriateness, effort and ease of use to check the normality. The results showed that the data were not normally distributed. Therefore, Friedman tests and Wilcoxon signed-rank tests were used for statistical analyses. A Bonferroni corrected p-value of  $0.05/3 = 0.016$  was used as the significance threshold.

**A. RESULTS OF VE1**

A Shapiro-Wilk tests showed that the data for appropriateness ( $W(120) = 0.84, p < 0.01$ ), effort ( $W(120) = 0.89, p < 0.01$ ) and ease of use ( $W(120) = 0.88, p < 0.01$ ) were not normally distributed for VE1.



**Figure 3.9: Results of VE1 gestures- Appropriateness, Effort, and Ease of use**

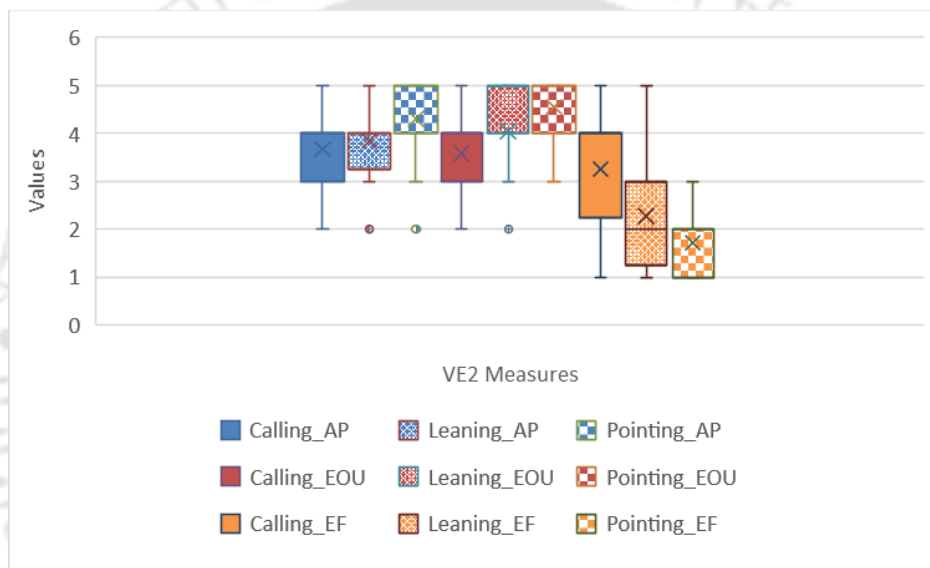
**Appropriateness** -For the appropriateness, the Friedman test showed a statistically significant effect of locomotion gesture ( $\chi^2 = 6.248, p < 0.044, W = 0.078$ ). The results of pairwise comparisons showed that the calling gesture was more appropriate than the leaning gesture ( $p=0.011, r=0.23$ ). There was no statistically significant difference between the leaning and bike-riding gestures or between the calling and bike-riding gestures.

**Effort**–The results of the Friedman test showed a statistically significant effect of locomotion gesture for effort ( $\chi^2 = 15.474, p < 0.01, W = 0.193$ ). The results of pairwise comparisons showed that the calling gesture had significantly less effort than the leaning gesture ( $p=0.001, r = 0.31$ ) and bike riding gesture ( $p= 0.004, r = 0.26$ ). There was no statistically significant difference in effort between the *leaning* gesture and the *bike-riding* gesture.

**Ease of use**—For ease of use, the Friedman test showed a statistically significant effect of the locomotion gesture ( $\chi^2= 14.05$ ,  $p =0.001$ ,  $W = 0.176$ ). The results of pairwise comparisons showed that the calling gesture had significantly higher ease of use than the leaning gesture ( $p=0.001$ ,  $r = 0.31$ ) and bike riding gesture ( $p= 0.003$ ,  $r = 0.27$ ). There was no statistical difference in the ease of use between *leaning* and *bike riding* gestures.

**B. Results of VE2**

A Shapiro-Wilk tests showed that the data for appropriateness ( $W (120) = 0.83$ ,  $p < 0.01$ ), effort ( $W (120) = 0.88$ ,  $p < 0.01$ ) and ease of use ( $W (120) = 0.81$ ,  $p < 0.01$ ) were not normally distributed for VE2.



**Figure 3.10: Results of VE2 gestures- Appropriateness, Effort, and Ease of use**

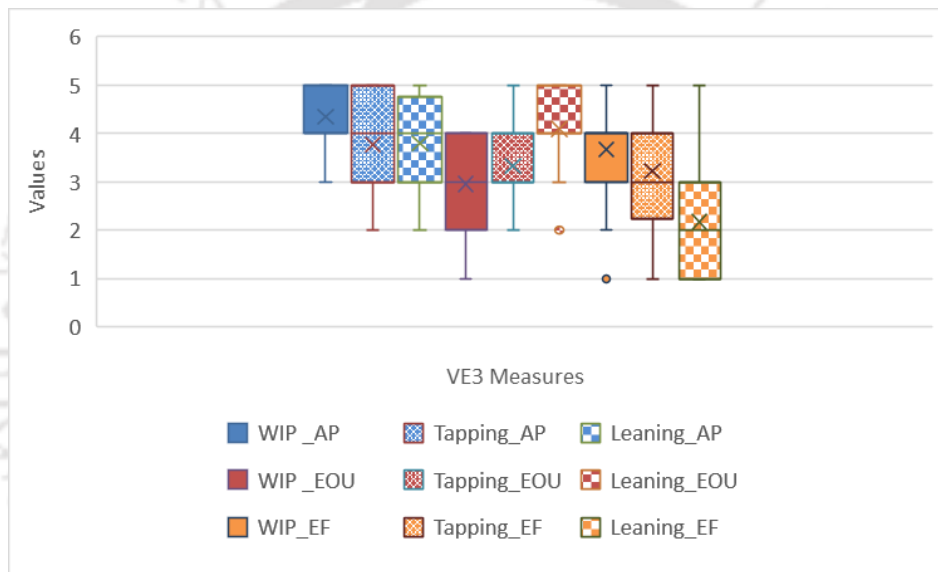
**Appropriateness** - For the appropriateness, the Friedman test showed a statistically significant effect of locomotion gesture ( $\chi^2= 13.62$ ,  $p = 0.001$ ,  $W = 0.17$ ). The results of pairwise comparisons showed that the pointing gesture was more appropriate than the calling gesture ( $p=0.003$ ,  $r=0.26$ ) and leaning gesture ( $p=0.012$ ,  $r= 0.22$ ). There was no statistical significant difference between *leaning* and *calling* gesture.

**Effort** - The results of the Friedman test showed a statistically significant effect of locomotion gesture for effort ( $\chi^2 = 38.87$ ,  $p < 0.001$ ,  $W = 0.486$ ). The results of pairwise comparisons showed that the pointing gesture had significantly less effort than the calling gesture ( $p<0.001$ ,  $r=0.46$ ) and leaning gesture ( $p=0.06$ ,  $r=0.24$ ). The leaning gesture was found to statistically having less effort than the calling gesture ( $p < 0.001$ ,  $r = 0.32$ ).

**Ease of Use** - For ease of use, the Friedman test showed a statistically significant effect of the locomotion gesture ( $\chi^2= 20.53$ ,  $p < 0.001$ ,  $W = 0.257$ ). The results of pairwise comparisons showed that the *pointing* gesture had significantly higher ease of use than the *calling* gesture ( $p < 0.001$ ,  $r = 0.4$ ) and *leaning* gesture ( $p = 0.012$ ,  $r = 0.22$ ). There was no statistical difference in the ease of use between *leaning* and *calling* gestures.

### C. Results of VE3

A Shapiro-Wilk tests showed that the data for appropriateness ( $W(120) = 0.84$ ,  $p < 0.01$ ), effort ( $W(120) = 0.89$ ,  $p < 0.01$ ) and ease of use ( $W(120) = 0.88$ ,  $p < 0.01$ ) were not normally distributed for VE3.



**Figure 3.11: Results of VE3 gestures- Appropriateness, Effort, and Ease of use**

**Appropriateness** - For appropriateness, the Friedman test showed a statistically significant effect of locomotion gesture ( $\chi^2= 9.28$ ,  $p = 0.010$ ,  $W = 0.11$ ). The results of pairwise comparisons showed that the WIP gesture was more appropriate than the tapping gesture ( $p = 0.002$ ,  $r = 0.28$ ) and the leaning gesture ( $p = 0.004$ ,  $r = 0.26$ ). There was no statistical significant difference in appropriateness between *tapping* and *leaning* gesture.

**Effort** - The results of the Friedman test showed a statistically significant effect of locomotion gesture for effort ( $\chi^2 = 24.52$ ,  $p < 0.001$ ,  $W = 0.307$ ). The results of pairwise comparisons showed that the leaning gesture had significantly less effort than the WIP gesture ( $p < 0.001$ ,  $r = 0.37$ ) and tapping gesture ( $p =$

0.005,  $r = 0.25$ ). There was no statistical significant difference in effort between *tapping* and *leaning* gesture.

**Ease of Use** - For ease of use, the Friedman test showed a statistically significant effect of the locomotion gesture ( $\chi^2 = 32.28$ ,  $p < 0.001$ ,  $W = 0.404$ ). The results of pairwise comparisons showed that the *leaning* gesture had significantly higher ease of use than the *WIP* gesture ( $p < 0.001$ ,  $r = 0.42$ ) and *tapping* gesture ( $p < 0.001$ ,  $r = 0.34$ ). There was no statistical difference in the ease of use between *WIP* and *tapping* gestures.

Below tables 3.4, 3.5, and 3.6 represents the pairwise p values for appropriateness, effort and ease of use in VE1, VE2 and VE3.

**Table 3.4: Results of the Wilcoxon signed-ranks test in pairs between the different gestures for locomotion in VE1 (\*= $p < 0.016$ )**

Measures	Calling - Leaning	Leaning- Bike Riding	Calling-Bike Riding
Appropriateness	0.011*	0.02	0.695
Effort	0.001*	0.111	0.004*
Ease of Use	0.001*	0.354	0.003*

**Table 3.5: Results of the Wilcoxon signed-ranks test in pairs between the different gestures for locomotion in VE2 (\*= $p < 0.016$ )**

Measures	Calling - Leaning	Leaning-Pointing	Calling-Pointing
Appropriateness	0.305	0.012*	0.003*
Effort	<0.001*	0.006*	<0.001*
Ease of Use	0.024	0.012*	<0.001*

**Table 3.6: Results of the Wilcoxon signed-ranks test in pairs between the different gestures for locomotion in VE3 (\*= $p < 0.016$ )**

Measures	WIP-Tapping	Tapping-Leaning	WIP-Leaning
Appropriateness	0.002*	0.879	0.004*
Effort	0.031	0.005*	<0.01*
Ease of Use	0.068	<0.001*	<0.001*

**3.3.5 User Preference:** The *calling* gesture was chosen as the most preferred gesture by 22 participants in VE1. The *leaning* gesture was the second most preferred, and the *bike-riding* gesture was preferred the least. The *pointing* gesture was chosen as the most preferred gesture by 23 participants in VE2. The *leaning* gesture was the second most preferred, and the *calling* gesture was the least preferred Gesture in VE2. The *leaning* gesture was chosen as the most preferred gesture by 24 participants in VE3. The *tapping* gesture was the second preferred gesture, and the *WIP* gesture came in third.

**Table 3.7: User Preference for VE1**

VE1 Gesture	1st Preference	2nd Preference	3rd preference
Calling	22	12	6
Leaning	11	11	18
Bike Riding	7	16	17

**Table 3.8: User Preference for VE2**

VE2 Gesture	1st Preference	2nd Preference	3rd preference
Calling	2	15	23
Leaning	15	11	14
Pointing	23	14	3

**Table 3.9: User Preference for VE3**

VE3 Gesture	1st Preference	2nd Preference	3rd preference
WIP	3	16	21
Tapping	13	13	14
Leaning	24	11	5

**3.3.6 Discussions:** According to the statistical analysis, the *calling* gesture had the highest appropriateness, ease of use, user preference, and lowest effort for VE1. The *pointing* gesture had the highest appropriateness, ease of use, user preference, and lowest effort in the VE2. The *WIP* gesture had the highest appropriateness in the VE3, but the *leaning* gesture was easier to use and required less effort than the *WIP* and *tapping* gestures. For VE1, some participants felt that the *Bike riding* gesture required more effort because there was no tangible handle to rest their hands on. They found the *Calling* gesture more playful and exciting because they had to repeat it for virtual travel. During the

turns, the *bike riding* and the *leaning* gestures were discovered to be very smooth and directly related to the riding movement. For VE2, the participants thought the *leaning* gesture was less explicit than the *pointing* gesture, but they thought it was more natural and made them feel more immersed. Some participants also believed that constant leaning for virtual travel could cause back pain and pose difficulties for obese users. They also suggested a back-leaning posture rather than a front-leaning posture. For VE3, the *leaning* gesture was found to give the participants more control over travel speed. Participants believed that the *leaning* gesture could be an inclusive gesture that disabled users could use for virtual travel. The *tapping* gesture was found to be more entertaining and preferred for use in exer games; however, during turns, speed manipulation was a problem with the *WIP* and *Tapping* gestures.

Based on the results of the two experiments, a set of virtual travel gestures was proposed. The proposed gestures included movements of the hand, legs, and upper body parts, indicating the importance of including body movements other than hand motion in future gestural design for natural interaction. Participants preferred hand movements, particularly using one hand to complete the travel task. Participants proposed gestures such as *calling*, *leaning*, *WIP*, and *tapping* that required continuous movement of the body part. Some qualitative feedback also emphasizes that participants preferred more playful and exciting gestures, despite requiring more effort to perform. All of the gestures had a natural correspondence with actual travel.

### **3.4 Analysis of Body-Gestures Elucidated through Elicitation Study for Natural Locomotion in Virtual Reality**

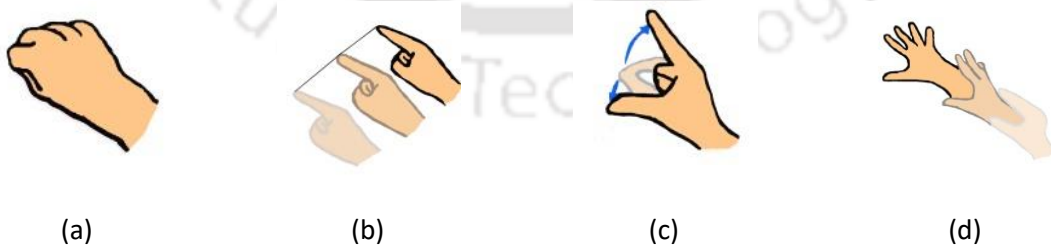
As a result of the gesture elicitation study, a total of 394 gestures were obtained. Based on the gesture extraction, 24, 24, and 9 unique full-body gestures were obtained for VE1, VE2, and VE3, respectively. This analysis study classified these gestures into upper and lower body gestures. They were further analyzed and classified based on hand usage and gesture form. The objective of analyzing these user-defined gestures was to gain insight into the users' mental models. Using these findings, designers can adopt the proposed gesture categories and expand on them to suit virtual travel tasks requiring one or two hands.

**3.4.1 Geometric Taxonomy of Gestures:** The gestures were classified along with taxonomies based on hand usage (Brouet et al., 2013) and form (Wobbrock et al., 2009) is presented in Table 3.7.

**Table 3.10: Hand Usage and Gesture Form**

Hand Usage	Unimanual	Only one hand is used to specify the gesture
	Bimanual	Both hands are used symmetrically to specify the gesture
Form	Static Pose	The pose is held in one location
	Static Pose and Path	The pose is held while it moves
	Dynamic Pose	The pose changes at one location
	Dynamic Pose and Path	The pose changes as it moves

**3.4.1.1 Hand Usage:** Hand usage distinguishes between unimanual and bimanual gestures (Wobbrock et al., 2009). Unimanual gestures in navigation correspond to gestures that ensure the user can fully control their position in a virtual space using a single hand. This leaves the second hand to be free for other tasks. Bimanual gestures allow the users to navigate by performing the gesture with both hands at the same time.



**Figure 3.12: Gesture form classification (a) Static Pose (b) Static Pose and Path (c) Dynamic Pose (d) Dynamic Pose and Path (Picture adapted from Arora et al., 2019)**

**3.4.1.2 Gesture Form:** Form classifies if and how the pose and position of the hand vary within a gesture. Table 3.7 briefly describes, and Figure 3.14 illustrates, the four categories (Wobbrock et al., (2009), Arora et al., (2019)). Examples concerning hand include using a closed fist - *static pose* (Figure 3.11a); tracing out a path - *static pose and path*(Figure 3.11b); pinch and release - *dynamic pose* (Figure 3.11c), and throwing objects - *dynamic pose and path* (Figure 3.11d). A bimanual gesture is considered to have a *dynamic pose and/or path* if either of the hands satisfies the respective criteria. This knowledge is extended in the present study to classify travel gestures in VR that involve upper and lower body parts.

**3.4.2 Procedure:** The participants' verbal explanations, mental models, and thought processes gathered from think-aloud sessions were used to categorize the gestures. These meetings were videotaped during Study 1. The gestures for each environment were first classified as upper and lower body gestures. They were further classified based on the hand usage and gesture form as *static pose*, *static pose and path*, *dynamic pose*, *dynamic pose and path*. Any discrepancies in classification were resolved through discussions with two experts. They had in-depth knowledge and expertise in the field related to the study, particularly in the area of gesture analysis, ergonomics and human-computer interaction. They were familiar with relevant literature, theories, and best practices related to gesture classification and had prior experience in conducting similar research involving gesture analysis.

**3.4.3 Results of classification based on gesture form:** The below figure shows the percentage of gestures that fall into different categories of gesture form, such as *static pose*, *static pose and path*, *dynamic pose*, and *dynamic pose and path* for the three VEs.

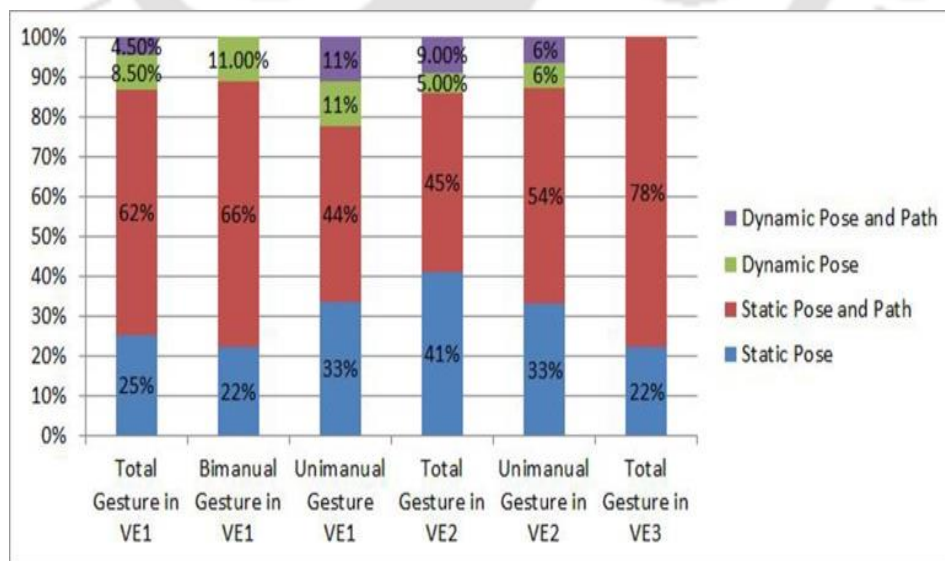


Figure 3.13: Classification of unique gestures based on gesture forms in VE1, VE2, and VE3

### A. Analysis of VE1 (Virtual travel with both hands-free) gestures

As shown in Table 3.8, 24 distinct gestures for VE1 were identified. In this scenario, participants could perform the gesture with both hands. The participants made 19 upper-body gestures (79% of the time) and five lower-body gestures (21% of the time). People preferred upper-body gestures because they felt they were easier and more convenient to perform than lower-body gestures in a sitting position. According to one participant, *"I'd like to sit in VR to avoid fatigue, and would not prefer to perform a lower body gesture as it would increase the physical strain."* In hand usage, nine gestures were bimanual, and nine gestures were unimanual. Because of the symmetrical hand movement, participants felt the bimanual gestures were faster when compared to unimanual gestures and provided a greater sense of spatial awareness. Participants alternately performed bimanual gestures such as arm-swinging, arm-cycling, and deictic pointing with both hands. These gestures allowed interaction while preserving the naturalness of the human gait cycle. Similar to Pai et al., (2018), in which the *pinchmove* gesture was used bimanually, it was found that participants who used bimanual input for locomotion had greater control over the speed of movement, resulting in the desired balance and confidence. *"I feel like I have greater control over the speed while moving if I use both hands and it gives realistic virtual bipedal steps,"* one participant said.

**Table 3.11: Classification of gestures of VE1 based on hand usage and gesture form**

Sr. No	Gesture	Upper Body	Lower Body	Static Pose	Static Pose and Path	Dynamic Pose	Dynamic Pose and Path
1	Deictic pointing with one hand (Unimanual)	x		x			
2	Deictic pointing with both hands alternatively (Bimanual)	x		x			
3	Deictic pointing at a reference point and teleporting to that point (Unimanual)	x		x			
4	Bike-Riding/ Closed fist of both hands (Bimanual)	x		x			
5	Swimming/ Moving both hands in the opposite direction (Bimanual)	x			x		
6	Arm – Cycling (Bimanual)	x			x		
7	Tapping with the palm facing down on the thigh (Unimanual)	x			x		

Sr. No	Gesture	Upper Body	Lower Body	Static Pose	Static Pose and Path	Dynamic Pose	Dynamic Pose and Path
8	Torso leaning	x			x		
9	Finger Tapping on the thigh or arm-rest (Unimanual)	x			x		
10	Cyclic movement of the hands as to calling someone (Bimanual)	x			x		
11	One leg on heels and Tapping		x		x		
12	Place one leg forward for walking		x	x			
13	Sliding the hand from left to right (Unimanual)	x			x		
14	Open hands placed vertically, moving up and down as in the running (Bimanual)	x			x		
15	Arm-swinging (Bimanual)	x			x		
16	Pulling, Grabbing, or Pinching the environment toward the user (Unimanual)	x				x	
17	Tapping with toes/heels on the ground – Tap Accelerator		x		x		
18	Walking-In-Place (WIP)		x		x		
19	Wiping the legs		x		x		
20	Closed fist hands as if rotating steering in a car. (Bimanual)	x			x		
21	Finger-Walking in mid-air (Unimanual)	x					x
22	Showing one finger to walk (Unimanual)	x		x			
23	Zoom In and Out using two fingers (Bimanual)	x					x
24	Moving a closed fist as if pulling up a lever (Unimanual)	x			x		

It was found that of the overall gestures in VE1 *static poses* were observed 25% of the time, *static poses and paths* were observed 62% of the time, *dynamic poses* was observed 8.5% of the time, and *dynamic poses and paths* were observed 4.5% of the time. The *static pose* was observed 22% of the time, the *static pose and path* were observed 66% of the time, and the *dynamic pose* was observed 11% of the time in bimanual gestures. In the unimanual gestures, *static poses* were observed 33% of the time, *static poses and paths* were observed 44% of the time, *dynamic poses* was observed 11% of the time, and *dynamic poses and paths* were observed 11% of the time.

Travel is a continuous activity in which gestures are mapped to movement in the virtual world. As a result, in the elicitation study, participants used more *static poses and path* forms of gesture. The gestures corresponding to the *static pose and path* had a natural correspondence with real-world travel. The Arm-Swinging, Swimming, WIP, Tapping, and Wiping gestures, for example, map to real-world travel gestures. They involve motor body parts used in the gait cycle of walking. "*The WIP gesture and Arm-Swinging gesture seem to be very natural and intuitive as we use them in our real-world walking activity,*" one participant said. Similar to Kim et al., (2010), the *Finger-Walking* gesture was found to improve spatial knowledge in participants, but it also caused physical fatigue in the fingers after some time. Coomer et al., (2018) designed the *point-tugging* method where users grab a point in the VE space to pull the VE towards or away from them. Similarly, the gesture of '*Pulling, Grabbing or Pinching the environment towards the user*' was found to be more tiring and prone to simulation sickness. This could be the reason that the *dynamic pose* and *dynamic pose and path* form were rarely used because they were difficult to perform for a continuous activity like locomotion.

It was also found that the participants used a vehicle metaphor while performing the tasks. 50% of the vehicle metaphor gestures were related to the *static pose and path* form. *Leaning, Tap-Accelerator, and Car Driving* gestures were used to simulate moving in a vehicle. The *Bike-Riding* gesture required more effort because there was no tangible handle to rest the hands on. During the turns, *Bike-Riding* gestures and *leaning* gestures were discovered to be very smooth and directly related to the movement of riding

## **B. Analysis of VE2 (Virtual travel with one hand occupied) gestures**

As shown in Table 3.9, 24 distinct gestures for VE2 were identified. There were 16 upper-body gestures (67%) and eight lower-body gestures (33%). Similar to VE1, upper-body gestures were performed more than lower-body gestures because participants were more comfortable performing gestures with one hand. All of the hand gestures in VE2 were unimanual.

**Table 3.12: Classification of unique gestures of VE2 based on hand usage and gesture form**

Sr. No	Gesture	Upper Body	Lower Body	Static Pose	Static Pose and Path	Dynamic Pose	Dynamic Pose and Path
1	Deictic pointing at a reference point and teleporting to that point	x		x			
2	Deictic pointing with one hand	x		x			
3	Closed fist and open arms	x		x			
4	Cyclic movement of one hand as to calling someone	x			x		
5	Tapping hand with the palm facing down on the thigh	x			x		
6	Raising one leg to walk		x	x			
7	Tapping with the palm facing down on the thigh	x			x		
8	Torso leaning	x			x		
9	Placing both legs forward		x	x			
10	Arm-Cycling with one hand	x			x		
11	Placing one foot forward		x	x			
12	Place one leg on heels for walking		x	x			
13	Show one finger for walking	x		x			
14	Sweeping / sliding one hand from right to left	x			x		
15	Swimming/ Moving one hand from center to side	x			x		
16	Open hand placed vertically and moving up and down as in running	x			x		
17	Pulling, Grabbing, or Pinching the environment toward the user	x				x	
18	Walking-In-Place (WIP)		x		x		
19	Wiping the legs		x		x		
20	Arm-Swinging with one hand	x			x		
21	Tapping with toes/heels on the		x		x		

Sr. No	Gesture	Upper Body	Lower Body	Static Pose	Static Pose and Path	Dynamic Pose	Dynamic Pose and Path
	ground – Tap Accelerator						
22	Finger-Walking in mid-air	x					x
23	Closing fist	x		x			
24	Moving a closed fist as if pulling up a lever	x			x		

It was found that for the overall gestures in VE2, *static poses* were observed 41% of the time, *static poses and paths* were observed 45% of the time, *dynamic poses* was observed 4.1% of the time, and *dynamic poses and paths* were observed 8.2% of the time. Within the 15 unimanual gestures, the *static pose* was observed 33% of the time, the *static pose and path* were observed 54% of the time, and the *dynamic pose* was observed 6.3% of the time.

In VE2, it was found that *static pose* and *static pose and path* form of gesture occurred the most. *WIP*, *Arm-Swinging*, *Tapping*, *Wiping*, and *Swimming* gestures corresponding to the above two forms had natural correspondences to the natural walking gait cycle. Furthermore, the majority of the *static pose* gestures were easier to recognize than *dynamic pose and path* gestures. This finding is similar to the findings of a previous study by Piumsombon et al., (2013), which found that user-defined hand gestures for augmented reality were mostly *static pose* or *static pose and path* because they were easily recognizable. Although the *static pose* gestures such as a 'Closed-Fist' or 'Showing a Finger for Walking' were not very natural, participants felt effortless while performing them. One participant commented, "It is very explicit, very effortless, and easy to perform when I show a single finger for travel." Similar to the findings of Kruijff et al., (2017), where static leaning had a positive effect on self-motion, the Leaning gesture with the *static pose and path* was found to be more natural; it felt more immersed and produced enhanced forward linear vection. Because one hand was occupied with carrying an object, *dynamic pose* and *dynamic pose and path* form of gesture were rarely used. As a result, people in VE preferred simple hand gestures for movement.

One of the participants said, "Performing Finger-Walking gestures in this environment are difficult because my one hand is constantly occupied with an object, and the other hand is used for travel tasks."

We found that similar to VE1, participants had a strong association with the vehicle metaphor while traveling in VE2. Participants used gestures such as '*moving a closed fist*' as if pulling up a lever to imagine themselves traveling by plane or car.

### C. Analysis of VE3 (Virtual Travel with two object selection and manipulation) gestures

As shown in Table 3.10, nine distinct gestures for VE3 were identified. Since both hands were occupied in carrying the object in this scenario, the participants only had the torso and lower body parts to perform the travel gesture. This environment had three upper-body gestures (33%) and six lower-body gestures (66%).

**Table 3.13: Classification of unique gestures of VE3 based on hand usage and gesture form**

Sr. No	Gesture	Upper Body	Lower Body	Static Pose	Static Pose and Path	Dynamic Pose	Dynamic Pose and Path
1	Torso leaning	x			x		
2	Raising both legs up for walking		x		x		
3	Place one leg forward for walking		x	x			
4	Place both legs forward for walking		x	x			
5	Walking-In-Place (WIP)		x		x		
6	Wiping the leg		x		x		
7	Tapping with toes/heels on the ground – Tap Accelerator		x		x		
8	Head bobbing	x			x		
9	Gaze for 2 seconds to move	x		x			

It was found that among the gestures, *static poses* were observed 22% of the time, and *static poses and paths* were observed 78% of the time. There were no gestures associated with *dynamic pose and path* form.

It was noticed that participants performed gestures related to real-world locomotion, such as *WIP*, *Tapping*, and *Wiping*. They also used vehicle metaphor gestures like the *Tap-Accelerator* gesture while traveling, similar to VE1 and VE2. Participants felt the *WIP* gesture was the most natural and intuitive when both hands were occupied. It also made use of the transferability of leg and hand gestures

because both hands were occupied. Furthermore, participants believed that the *leaning* gesture could be an inclusive gesture that disabled users could use for virtual travel when legs or hands could not perform the gestures. Participants proposed *static pose* or *static pose and path* form gestures when the multitasking level varied with virtual travel and both hands were occupied in selection and manipulation

**3.4.4 Contribution to classification of locomotion gestures:** According to the findings, people in VE1 and VE2 elicited more upper-body gestures than lower-body gestures because they felt more comfortable in a seated position. Lower body gestures predominated in VE3 as the level of multitasking with hands increased. The gestures were further classified based on their geometric taxonomy. People preferred *static pose* and *static pose and path* gesture more than *dynamic pose* and *dynamic pose and path* gestures as their level of multitasking varied from VE1 to VE3. It was also found that participants used vehicle metaphors while performing the tasks while sitting on the VE. The vehicle metaphor gesture was made up of 50% *static pose and path* form. When used continuously for travel, it was found that *dynamic pose* and *dynamic pose and path* form gestures caused physical fatigue. Based on these findings, future designers and developers will be able to identify appropriate gesture categories for task-related virtual travel in a seated position in multitasking scenarios.

### 3.5 Summary

Overall this chapter presented two study experiments to gather gesture sets for three different VEs that varied in their multitasking. The first study included 40 participants to extract the different gesture sets for each environment. The first and second most preferred gestures for each environment were considered, and the total frequencies were calculated. The top three high-frequency gestures were chosen as travel gestures for the second study. *Calling, Leaning, and Bike Riding* gestures were the three most preferred gestures for VE1. *Calling, Leaning, and Deictic Pointing* gestures were the three most preferred gestures in VE2. *WIP, Tapping, and Leaning* gestures were the three preferred gestures for VE3. The proposed gestures were further evaluated based on appropriateness, ease of use, effort, and preference. Based on the subjective ratings, these gestures were selected as input modalities for travel in the three VEs. The gesture set was further analyzed and classified based on the upper and lower body part that was used to perform the gesture. They were further classified based on hand usage and gesture form.

In the next chapter, we designed and implemented the calling gesture for the VE1. For the VE2, the deictic pointing gesture was designed and implemented for the travel task. The leaning gesture was

designed and implemented for the VE3. The newly designed gestures were also compared with the tapping and teleportation gestures in the literature. Hence, in this chapter, we have answered the research questions RQ1, RQ2, and RQ3.

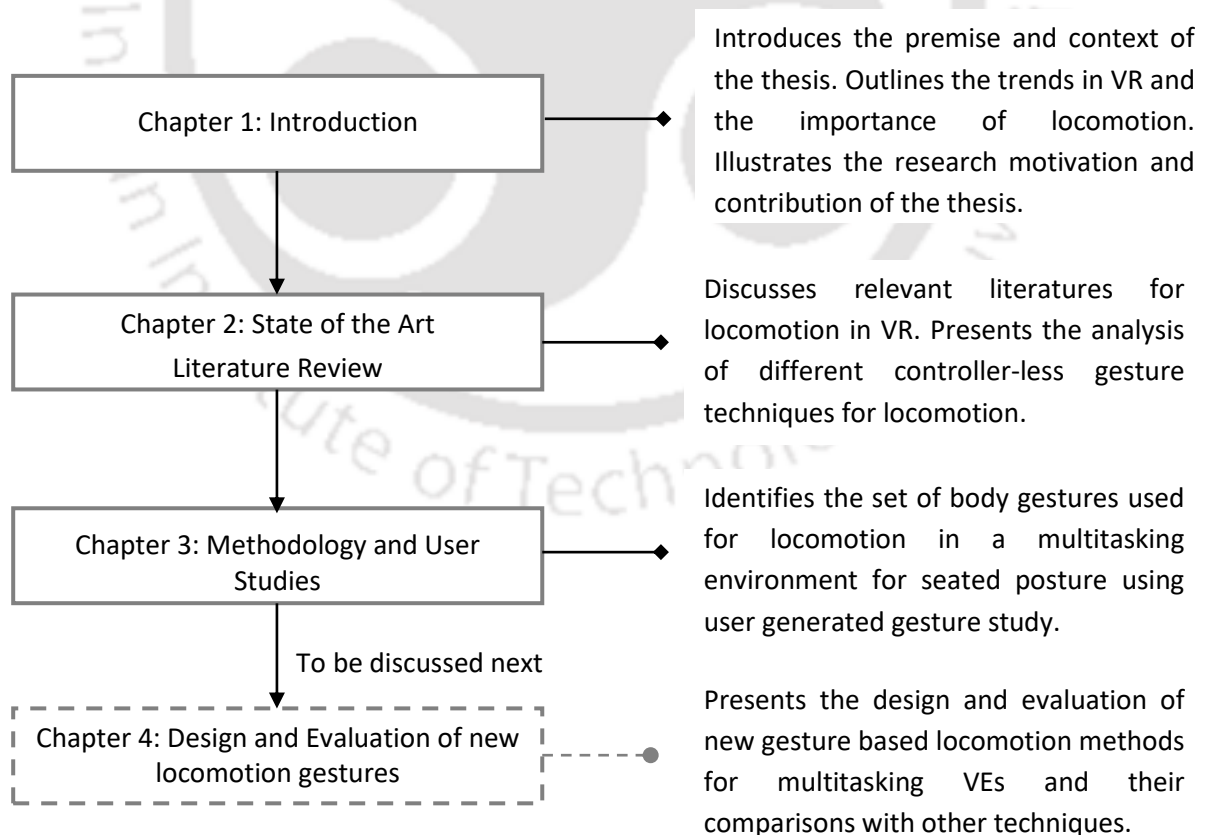
**For RQ1** -We have identified a set of user-centric gestures that are natural for locomotion in a VE when both hands are free in a seated position using the gesture elicitation method. The gestures are tabulated in table 3.1

**For RQ2** - We have identified a set of user-centric gestures that are natural for locomotion in a multitasking VE when one hand is engaged in another interaction, such as selecting or manipulating a virtual object in a seated position, and the results are tabulated in table 3.2

**For RQ3** - We have identified a set of user-centric gestures that are natural for locomotion in a multitasking VE when both hands are engaged in other interactions, such as selecting or manipulating two virtual objects in a seated position and are tabulated in table 3.3

**A quick recap of previous chapters:**

The visual summary of the chapters covered so far is provided as follows:



## CHAPTER 4 – DESIGN AND EVALUATION OF GESTURES FOR LOCOMOTION

In Chapter 3, we presented two experimental studies; the first study investigated suitable body gestures in the seated position for virtual travel in three different VEs that varied in multitasking (Study 1). The second study evaluated the obtained gestures based on appropriateness, ease of use, effort, and preference (Study 2). From the evaluation the Calling gesture for VE1, Deictic Pointing gesture for VE2 and Mirror Leaning gesture for VE3 were selected for design and implementation in this chapter. They are further evaluated in comparison with two other gestures in literature for their task performance, intuitiveness, and comfort, ease of use, performance, presence, simulation sickness, spatial knowledge, perceived workload and user preference.

In this chapter, section 4.1 discusses the research objective for designing new gestures for the three different VEs VE1, VE2, and VE3. Section 4.2 presents the new gesture-based locomotion techniques, i.e., the *Calling* Gesture for VE1, the *Deictic Pointing* gesture for VE2, and the *Mirror Leaning* gesture for VE3. It also presents the *Tapping* and *Teleportation* gesture from literature which was used for comparisons. In section 4.3, we discuss the design of the supermarket VE. Further, in section 4.4, an overview of the model followed for the locomotion gesture recognition and execution is presented. We present an overview of the three experimental studies (Study 3, Study 4, and Study 5) in section 4.5. The apparatus (section 4.5.1), experimental tasks (section 4.5.2); procedure (section 4.5.3), and method of data collection (section 4.5.4) used for the three studies are discussed.

Further, section 4.6 presents the comparative study for VE1 (*Calling* Gesture with *Tapping* and *Teleportation* gestures). Section 4.7 presents the comparative study for VE2 (*Deictic Pointing* Gesture with *Tapping* and *Teleportation* gestures). Section 4.8 presents the comparative study for VE3 (*Mirror Leaning* Gesture with *Tapping* and *Teleportation* gestures). The participant's demography, experiment design, and statistical analysis are discussed in each of the studies. Section 4.9, 4.10 and 4.11 discusses the results of the above three experimental studies.

## 4.1 Research Objective

The main goal of the thesis was to design user-generated locomotion gestures for a seated position suitable for different VEs that varies in the multitasking levels. The multitasking levels are VE1 with simple or no multitasking (locomotion with both hands-free to perform the gesture), VE2 with moderate multitasking (locomotion with one hand occupied in other interaction), and VE3 with complex multitasking (locomotion along with both hands occupied in other interaction). The three new gestures were designed from the previous gesture elicitation study results. From *Study 2* it was found that the *Calling* gesture had the least effort and was significantly higher in ease of use than the leaning and the bike riding gesture. It was also found to be more appropriate than the *leaning* gesture for VE1. Hence the *Calling* gesture was implemented for VE1. From *Study 2* it was found the *pointing* gesture was found to be the most appropriate gesture with less effort and higher ease of use when compared to the leaning and the calling gesture. Hence the *deictic pointing* gesture was implemented for VE2. Similarly the *leaning* gesture was found to have the least effort and higher ease of use than the WIP and tapping gestures. Hence the *mirror leaning* gesture was designed and implemented for VE3. Users could use these gestures without the need for any additional hardware. Further, the three new gestures are studied for their task performance, intuitiveness, comfort, ease of use, performance, presence, load, spatial knowledge, simulation sickness, and user preference in comparison with the locomotion gestures in literature, such as *tapping* and *teleportation*. In this chapter we intend to answer

**RQ4** - *How do the newly designed gesture-based locomotion techniques impact the task completion time, collisions, intuitiveness, comfort, ease of use, perceived workload, motion sickness, spatial knowledge, and presence compared to existing locomotion techniques in a seated position?*

The three studies in this chapter aim to evaluate the new locomotion gestural interfaces and build the characteristic framework for the three different VEs. We believe this would bring a better understanding of the various essential factors that would improve gesture-based locomotion in VR. The interaction designers can appropriately select the gestures for locomotion using the characteristic framework based on the functional and non-functional requirements. To understand the gestures' performance, we incorporated qualitative methods like semi-structured interviews and observations and administered quantitative questionnaires. The collection and analysis of user-reported experiences provide insight into relevant factors influencing gesture-based locomotion and ultimately guide future design iterations. This is significant because many previous interface studies only used behavioral measures of the

locomotion technique to assess usability (Bargas et al., 2011), in which the task consisted of only movement in a maze or sparse environment without any other interaction along with movement. A qualitative and quantitative approach to user experience enables researchers to comprehend on a deeper level why specific behaviors are occurring and how user feelings toward a product may influence behavioral outcomes (Vermeeren et al., 2010). The study also contributes to such research by documenting the interaction features of these new locomotion techniques and by generating data that researchers and developers can use to construct conceptual work and guide the design of new and efficient VR locomotion techniques.

**4.2 Gesture-based locomotion Techniques proposed for a multitasking environment:** The locomotion techniques designed and used for the experiment are described in this section. There were five different locomotion techniques used. The *Calling* gesture, *Deictic Pointing* gesture, and *Mirror Leaning* gesture were all created specifically for VE1, VE2, and VE3, respectively. These gestures were compared to locomotion techniques from the literature, such as *tapping* and *teleportation* gestures. The benefit of these techniques is that they did not necessitate the use of a controller or any other additional hardware interfaces. However, since the gestures are recognized by Oculus hand tracking, the interaction area moves in accordance with the user's head because the sensors are attached to the HMD.

**4.2.1 Calling Gesture – Designed for VE1:** The *calling* gesture is similar to the swipe right gesture (Piumsomboon et al., 2013), except that the hand is positioned vertically opposite to the HMD and moved towards the user. The gesture works by "*calling*" the viewport or any point in space and dragging it towards the user, resulting in a reversed movement that causes the user to translate forward in the desired direction. When the user places the hand in front of the HMD, as shown in Fig 4.1, the gesture is activated, and the initial position of the hand is recorded. As visual feedback, the user is shown a grey laser beam indicating the point to which the user will be moved at the completion of the gesture. The final position is recorded when the user drags their hand toward the HMD. The viewpoint of the user is then moved ahead to the point where the grey laser beam was indicating. The gesture's flow is discrete because the response (user movement) occurs after the gesture is completed. The movement is carried out at a constant speed. To get to their destination faster, the user should perform the gesture more frequently. This unimanual locomotion gives the user complete control over movement in virtual space while freeing up the second hand for other tasks. However, both hands can be used to perform the gesture for travel.

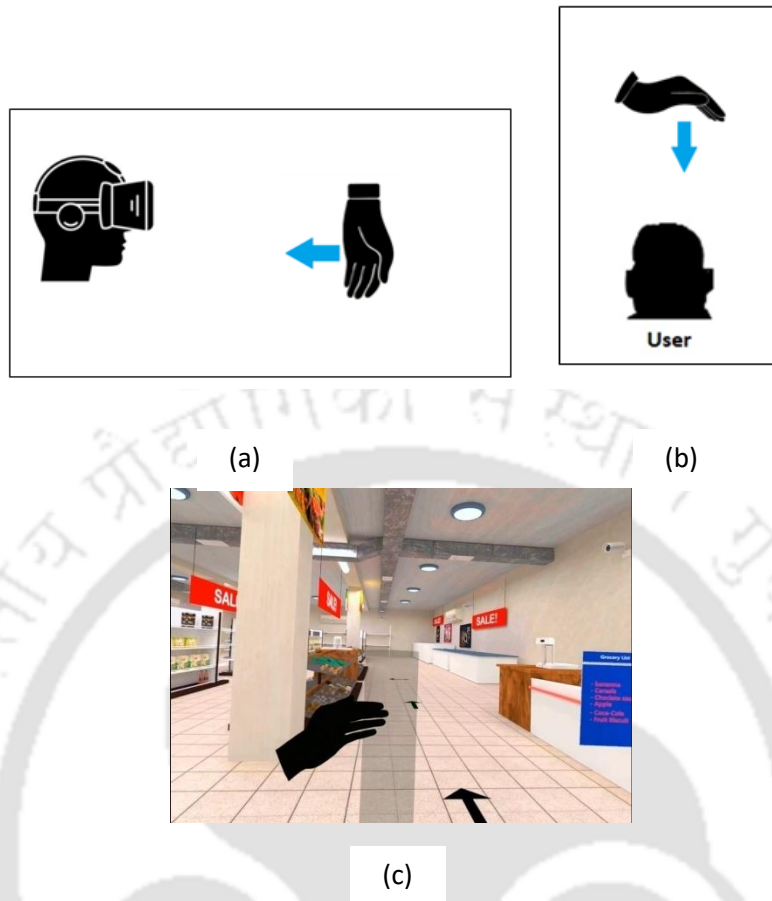
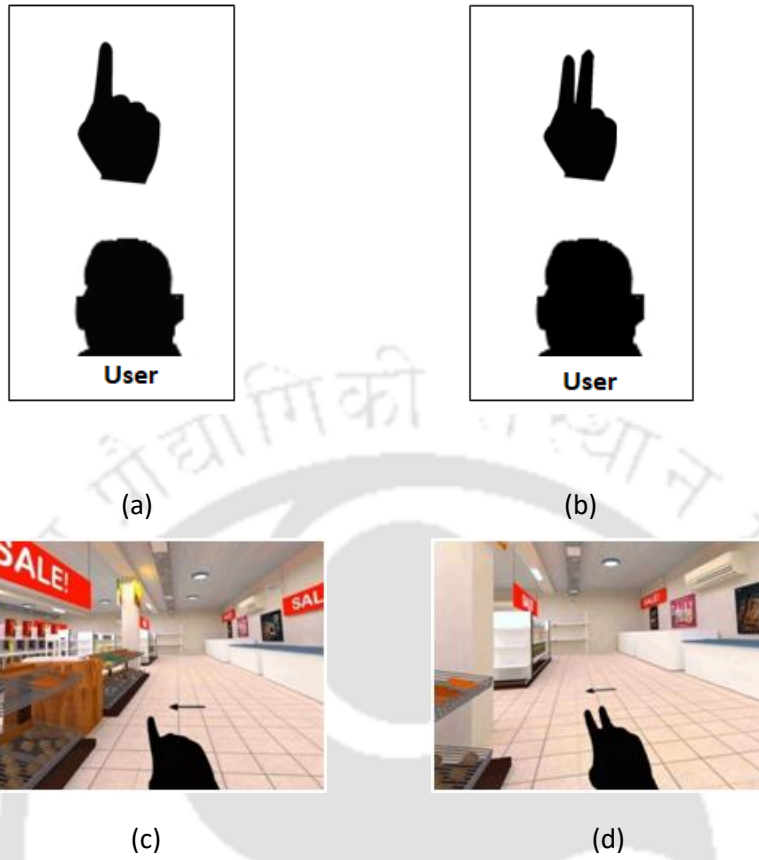


Figure 4.1: Calling Gesture a) Front view of the gesture (b) Top view of the Gesture (c) Gesture performed in VE

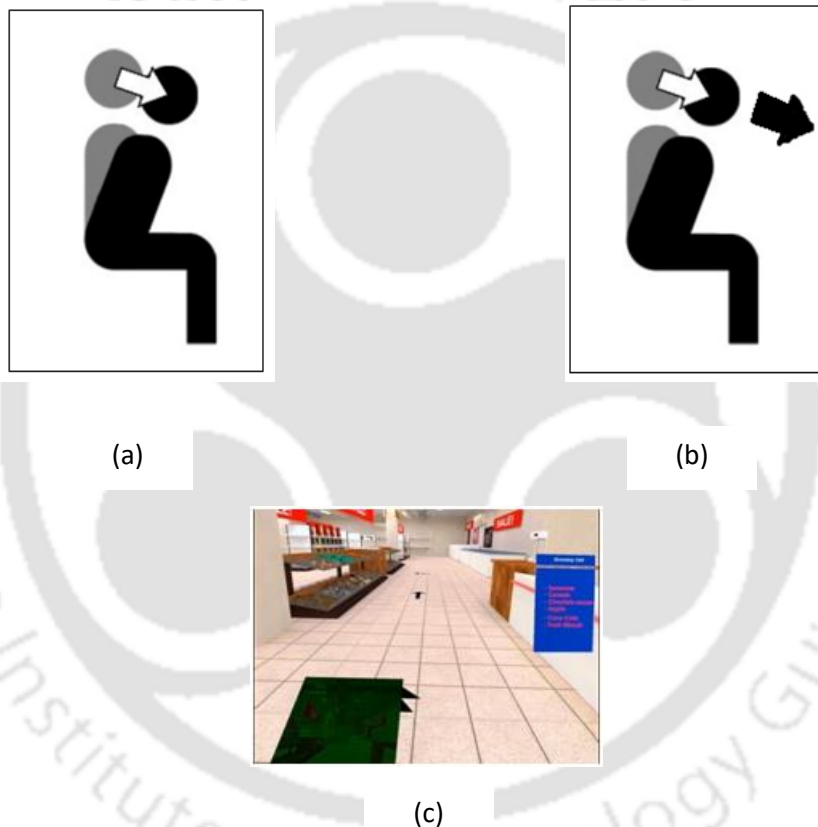
**4.2.2 Deictic Pointing Gesture – Designed for VE2:** The *pointing* gesture commonly used in everyday life is the proposed locomotion gesture for VE2. The user opens the index finger in the HMD's field of view. The vector that moves from the user's head through the crosshair of the index fingertip and the VE defines the translation direction. When the index finger is placed in front of the HMD, the movement begins immediately. The velocity is equivalent to walking at 1.2m/sec (Chou et al., 2009). When the user opens both the index and middle fingers in the FOV of the HMD, the velocity can be changed to running speed at 3.2m/sec, as shown in figure 4.2. While traveling, the velocity can be changed to walking or running. The movement is halted if the user moves the hand that controls the translation out of the FOV of the sensor while traveling.



**Figure 4.2: Top View of Deictic Pointing Gesture (a) Walking Gesture (b) Running Gesture (c) Walking gesture performed in VE (d) Running gesture performed in VE**

**4.2.3 Mirror Leaning Gesture – Designed for VE3:** This gesture is specially designed for VE3. To control their virtual movement velocity, users must move their heads forward toward the target direction, similar to a head joystick (Hashemian et al., 2020). The user's head or HMD orientation is tracked in this technique. For faster movement, users combine head translation and upper-body leaning. After inviting each user to sit in the swivel chair, the resting position (zero point) of the head was calibrated with the back straight and the head facing forward. To avoid involuntary movements, we set a minimum distance of 5 cm, similar to (Hashemian et al., 2020), and did not move the viewpoint. This avoided unnecessary forward translation when the user leaned to grab items or perform another secondary task nearby. The maximum comfortable distance of leaning is set to 35 cm to prevent users from leaning excessively, and the speed does not increase above this point. There were two levels of velocity in this technique. The users were given visual feedback on their velocity by having a single arrow in the ground to indicate that they were moving at walking speed and two arrows in the ground to indicate that they were moving at running speed. Users can control their leaning and thus their velocity

based on the visual feedback. The movement stops when the user returns to the zero point or the resting position. A mirror view for the user was one of the gesture's main visual design additions. During leaning, the user is more likely to notice the lower ground surface, while the upper part of the VE is only partially visible. While searching for targets in VE, such as supermarkets, the upper view is also important. To view the upper portion, the user must stop the motion and take a look at the VE. This would reduce the sense of immersion while interfering with movement. To address this, the user is presented with a mirror window showing the higher portions of the VE while traveling. Thus, *mirror leaning* can provide visual cues for velocity and an upper view of the VE while the user is traveling.



**Figure 4.3: Leaning gesture a) Walking gesture (b) Running Gesture (c) Leaning gesture performed in VE**

**4.2.4 Tapping Gesture:** *Tapping* gesture controls locomotion using tapping motions of the fingers. This method is analogous to the tapping gesture described by (Ferracani et al., 2016). As the system did not include any other sensing devices, the initial design revealed that using fingers to tap in the air to simulate walking motion and to control locomotion speed had the problem of detecting the peaks of the index fingertip. As a result, the gesture was modified such that the users tap their fingers up and down on a hovering button. This provided the user with visual feedback when the button was pressed. The

user is moved at a constant distance in the VE for each tap. The user must increase the frequency of taps to reach the target faster. This technique allows the user to rotate their head/body and move in the direction in which they are facing.

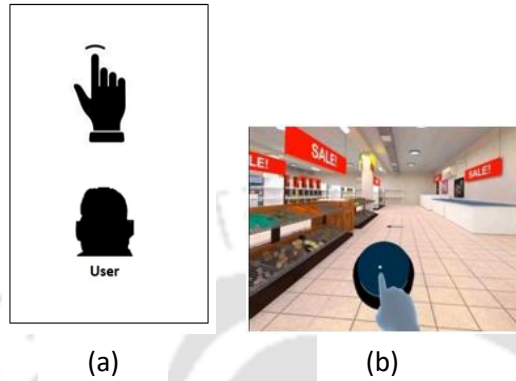


Figure 4.4: (a) Top view of the Tapping Gesture (b) Tapping gesture performed in VE

**4.2.5 Teleportation Gesture:** The '*point and teleport*' locomotion method discussed in Bozgeyikli et al., (2016) was used to implement this technique. To perform the gesture, the user has to place the hand in the FOV of the HMD with the palm facing upward and only the index finger and thumb open. The user has to point to a location on the VE's ground where a placeholder would be shown, as in Figure 4.5. The virtual viewpoint will be teleported to that location when the index finger is closed. The closing of the index finger activates teleportation. A virtual laser beam emanates from the open index finger and points to the ground as a visual cue. A blue ring placeholder is placed on the pointed position so that users can easily see the destination location to which they will be teleported. If there are any obstacles in the path, such as walls or supermarket shelves, a red laser beam appears to indicate that they will be unable to teleport to the desired location. During teleportation, the user's orientation is maintained. In the real world, the user can adjust the orientation by physically rotating their body.

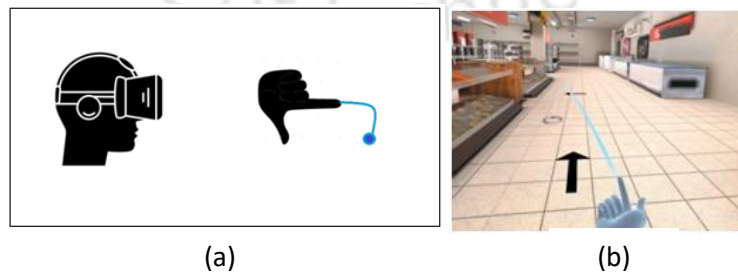
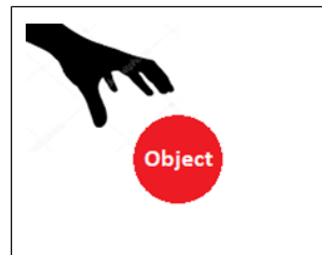


Figure 4.5: (a) Teleportation Gesture (b) Teleportation gesture performed in VE

**4.2.6 Direct touch and Grab Gesture:** The users perform the interaction in the VE through the direct touch and grab gesture. The object gets selected when the user touches an object in the VE with their bare hands and performs the *grab* gesture. Both hands can perform the *grab* gesture. This gesture is considered the most natural gesture, although, in direct touch-grab interaction, the users can only interact with objects that are within their arms' reach. Hence while interacting, the user must move near the object and perform the *touch-and-grab* gesture (Kang et al., 2020).



**Figure 4.6: Direct touch and grab gesture**

### **4.3 Design of Virtual Environments**

Many VR applications present complex VEs requiring the user to navigate while avoiding obstacles and performing multitasking tasks like selection or manipulation. One such application is a virtual supermarket, which requires the user to explore and reach targets while also grabbing items from various heights. Supermarkets are common and familiar environments, making them relatable to users. Testing locomotion in a setting that people encounter in their daily lives enhances the realism of the VR experience. Supermarkets typically have diverse layouts with aisles, shelves, and open spaces. They often present navigation challenges, such as sharp turn around the aisles, narrow spaces, and varying floor textures. They are places where people of different ages and skills navigate. Testing locomotion techniques in this setting allows us to study accessibility for various user demographics, helping design inclusive VR experiences. Supermarkets involve interactions with products on shelves. They can be mentally stimulating environments due to the need for navigation, decision-making, and interacting with various stimuli. Testing locomotion techniques in such environments allows researchers to assess the cognitive load imposed on users and optimize for a comfortable experience. A cluttered scenario with different depth cues is also present in the supermarket environment. As a result, a VR supermarket

environment has been designed in this research to investigate the performance of the newly designed gesture-based locomotion techniques in various levels of multitasking scenarios. The multitasking level in VE1 is simple, with the user having both hands free to perform the locomotion gesture and select the objects in the list with any hand using the *grabbing* gesture. In VE2, the multitasking level is considered moderate because one hand is used to grab the object while only one hand and other body parts are available to perform the locomotion gesture. In VE3, the multitasking level is complex because both of the user's hands are occupied with other activities, leaving the user with only the other body parts to perform the locomotion gesture. This VE more closely resembles a realistic use case found in current consumer VR experiences, such as hands being occupied in shooting games or interacting with objects while the user travels using gesture-based locomotion. In all of the VEs above, the user performs the locomotion gesture while in a seated position. Figure 4.7 below shows the lateral view of the supermarket designed for our experiments, and Figure 4.8 and Figure 4.9 shows some shelves in the VE.

Some of the other applications that are similar to supermarkets are architectural walkthroughs in urban environments such as cityscapes and public places. Indoor spaces such as malls and office buildings also help in testing the locomotion techniques in a commercial setting. Simulating amusement parks with rides, attractions, and crowds can be useful for testing locomotion in dynamic and entertaining environments.



**Figure 4.7: Lateral view of the supermarket VE**

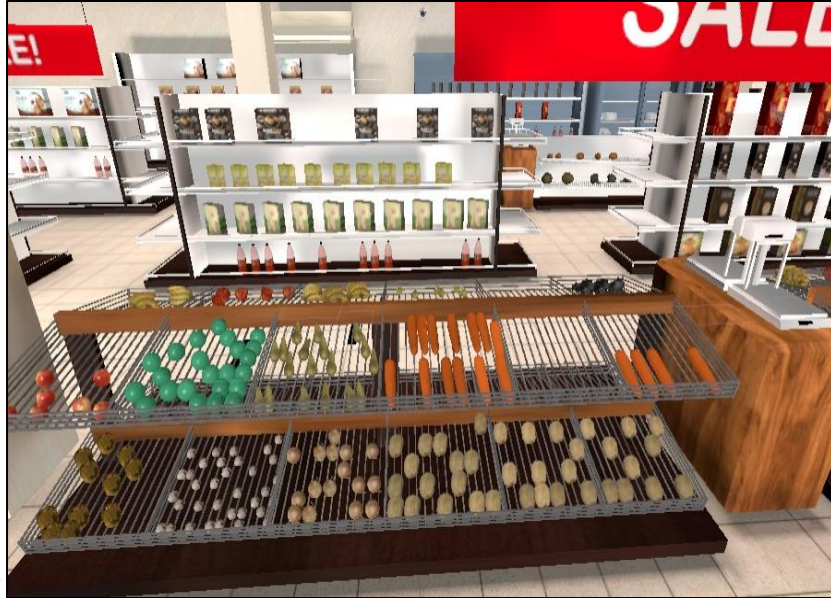
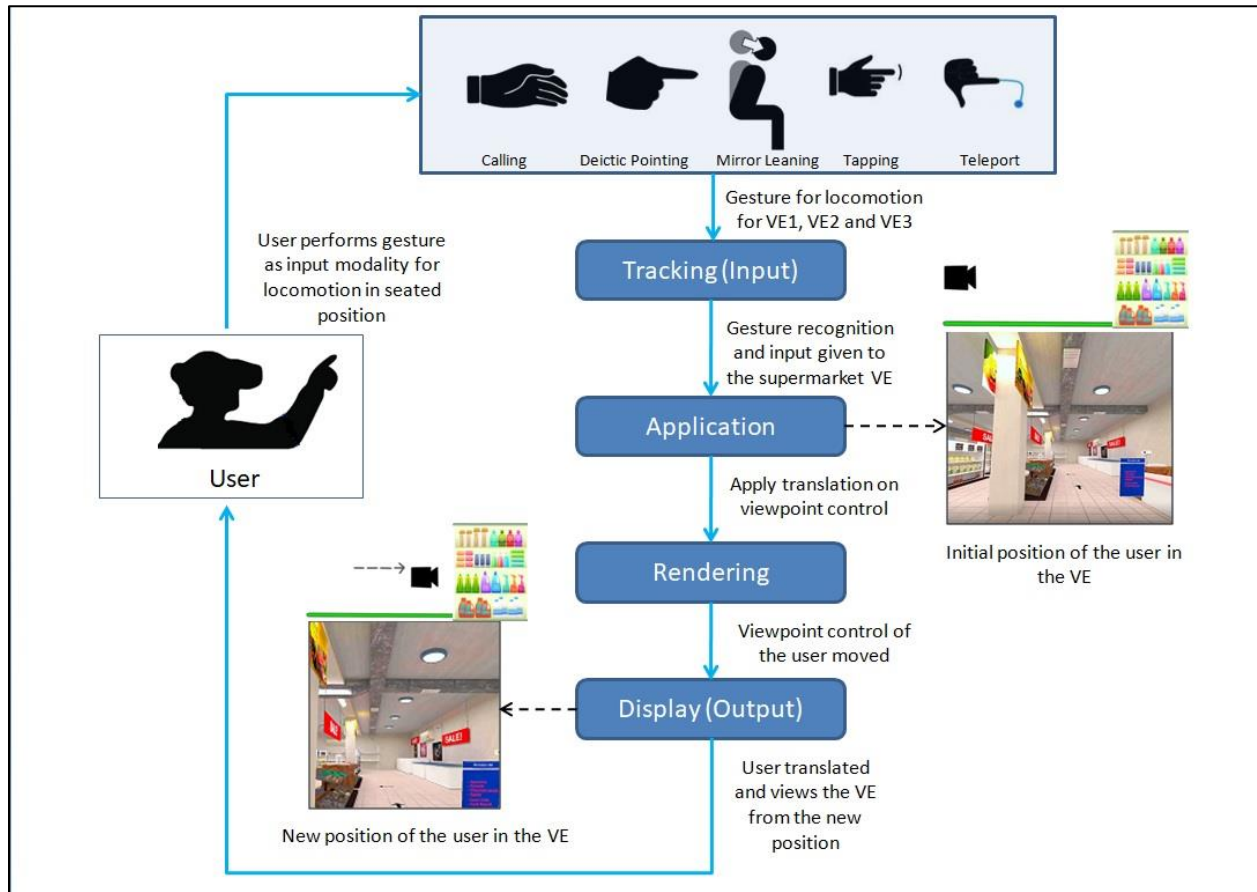


Figure 4.8: Shelves in the supermarket



Figure 4.9: Shelves in the supermarket

#### 4.4 Overview of the model for gesture-based locomotion technique



**Figure 4.10: Overview of the model for gesture-based locomotion technique**

The model followed in the implementation of the gesture-based locomotion technique is shown in figure 4.10. The user performs the gesture as an input modality for locomotion in a seated posture. The different gestures used in the system are *calling gestures*, *deictic pointing*, *mirror leaning*, *tapping* and *teleportation* based on the VE (VE1, VE2, and VE3) used. The gestures are recognized and given as input to the application, which is the supermarket in this case. The required translation is applied to the viewpoint control of the user, and it is rendered in the scene. The user in the VE is moved to the new position based on the speed. The user is translated into the VE and can view the supermarket from the new position. The direction of the user's movement is based on the user's head orientation. This cycle repeats for the continuous and the discontinuous locomotion techniques. Each gesture supports two speeds, such as walking and running. The system records the travel time and the collision of the user with the shelves.

## 4.5 User Study

Three separate lab experiments, each for three different VEs (VE1, VE2, and VE3), were conducted to investigate the newly designed gestures. The gestures were assessed using both quantitative and qualitative metrics. Participants were university students aged 21 to 35 years old. Both male and female participants were included in the study. Participants with good eyesight and also corrected eyesight (using contact lenses or glasses) were included in the study. Participants who played 3D first-person view video games daily or weekly were included. Participants with motor disabilities were excluded from the study. Participants with prior experience with any of the locomotion techniques, including the gesture-based teleportation method, were excluded from the study.

**4.5.1 Apparatus:** The PC used for the user study was a VR Ready computer with a 64-bit Windows 10 operating system, an Intel Core i5-10300H 8GB processor, and an Nvidia Geforce GTX 1650 graphics card. The computer was used as a development platform to create the VR supermarket environment and implement the locomotion techniques. It was also used for rendering the VR content in real-time during the user study. Hand gestures were made possible by using the Oculus Quest headset. With 6DOF, the headset tracks both head and hand movement and then translates it into VR with realistic precision. There were no external sensors required. The fast switch LCD Displays with 1832x1920 resolutions per eye and a refresh rate of 90Hz were used. The headset came with two touch controllers, but they were not used in the experiment because locomotion and selection were accomplished solely through freehand gestures. The VR supermarket and locomotion techniques were created using the Unity game engine. The techniques were written in C# and with the Oculus Hand Tracking Support SDKs.

**4.5.2 Experimentation Tasks:** The tasks assigned to the participants were designed to address three aspects that an effective locomotion technique should support: a) Movement in a straight line path, b) Movement in a directed path to reach the target, and c) Movement in an undirected path to reach the target. The execution of tasks in a given scenario was accessed via a set of metrics, which can be either objective (based on measurements automatically collected by the VR application) or subjective (when based on user-provided answers). Figure 4.11 below shows the location of the six objects that the user needs to grab from the shelves, and figure 4.12 shows the grabbing gesture performed to select the objects.

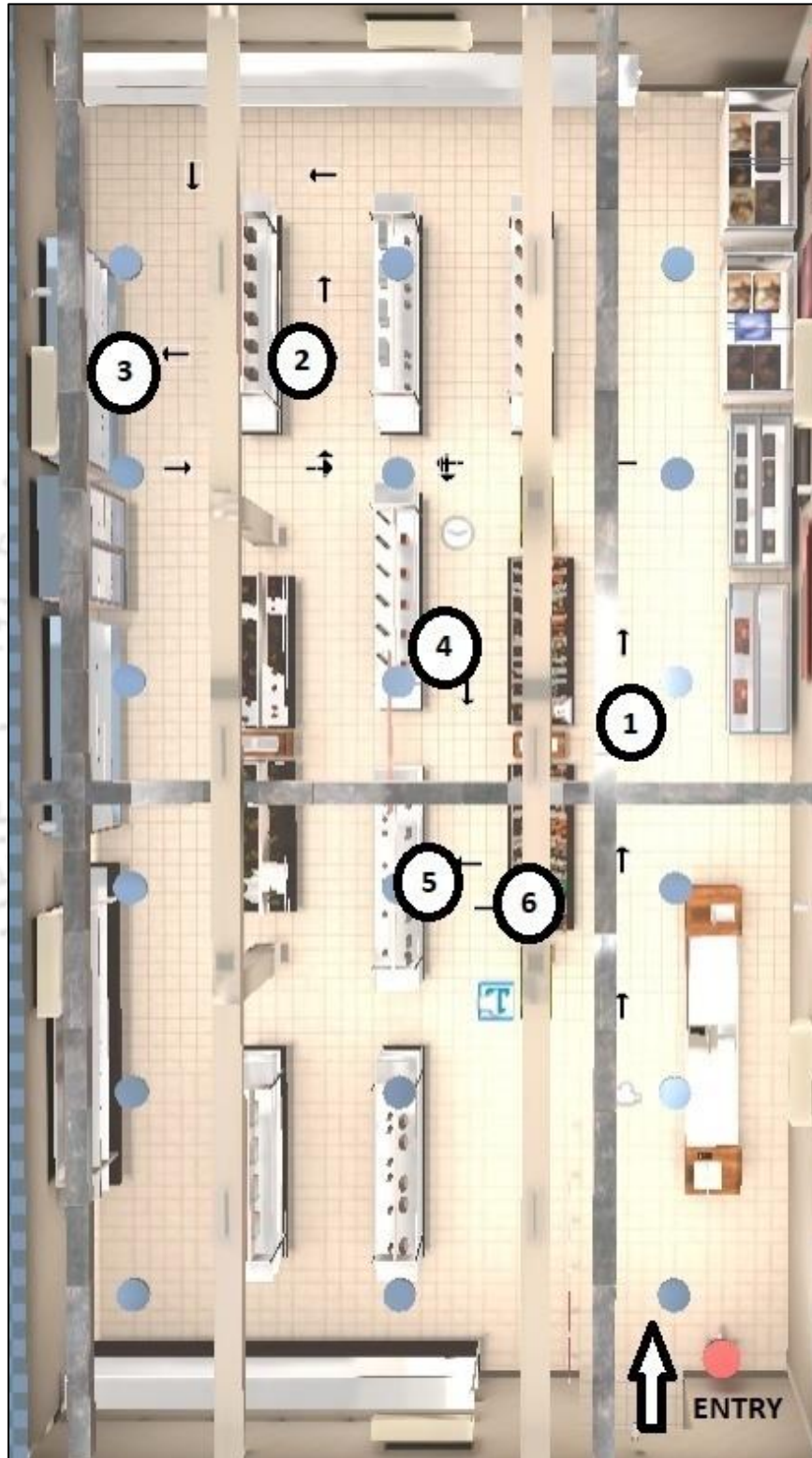


Figure 4.11: Top view of the supermarket along with the position of six objects



Figure4.12: User selects the glowing object using the Direct Touch and Grab Gesture

**4.5.2.1 Task #1: Movement in a Straight-Line Path:** This task is intended to investigate the technique under the most basic locomotion condition, in which there is no directional change or interaction with objects. Such a task is very common in VR applications, where the user may be required to move in a straight line path to take a stroll through the VE or reach definite targets in a straight line, as in Nabiyouni et al., (2015). In this task as shown in figure 4.13, the user begins at position A in the supermarket and travels in a straight line to position B. The system recorded the time taken for the user to move from position A to position B in a simple straight line.

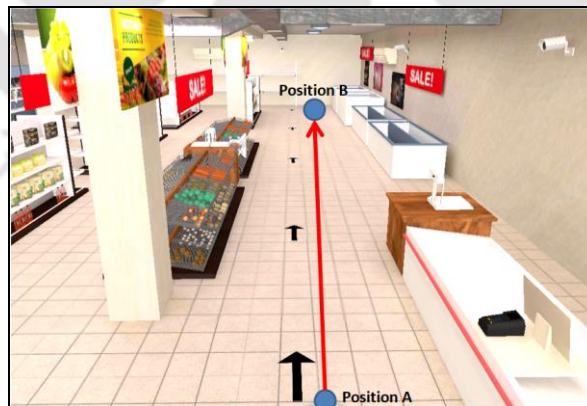


Figure 4.13: Straight line path in the supermarket

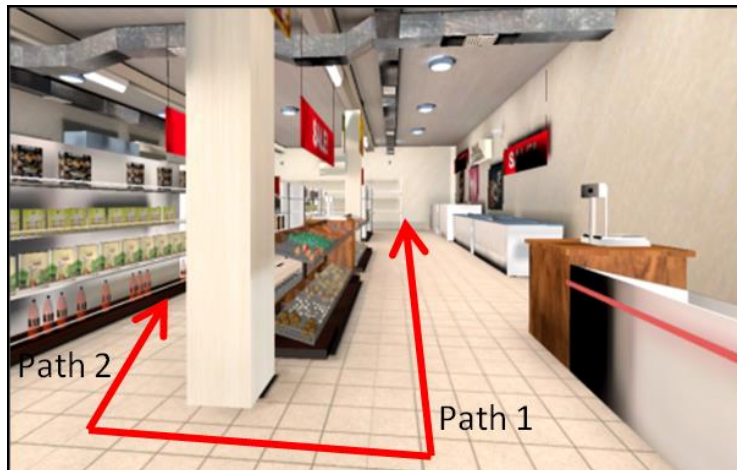
**4.5.2.2 Task #2: Move in a directed path to the targets:** This task is intended to assess the locomotion technique during the execution of a scenario involving paths that change direction. This task

requires movement as well as object interaction. Participants must travel in a straight line and make multiple direction changes in the form of turns in the supermarket. Participants must adhere to a predefined path depicted to the user as black arrows on the ground, as shown in figure 4.14. While moving, users should maintain the center of the path and avoid colliding with the shelves. This task is similar to the user studies in Nabiyouni et al., (2015) and Paris et al., (2017) that used multiple path segments with turns to traverse a VE. A golden glow around the item highlights the target item. The user selects the item using the grab gesture. The items to be selected are placed at different heights on the shelves. The total completion time and the number of collisions with the objects are recorded for this task.



Figure 4.14: Directed path in the supermarket

**4.5.2.3 Task #3: Move in an undirected path to the targets:** This task is intended to assess the locomotion technique by requiring the user to travel different paths with varying direction changes without any guidance in the form of a predefined path, as shown in the figure 4.15. The task entails travel as well as object interaction. This scenario was inspired by the search tasks of Ruddle et al., (2006) and Coomer et al., (2018), in which users travel through a section of town in search of hidden treasure in fifteen chests scattered throughout the environment. In our experiment, participants move into the supermarket independently to select the items on the list without any guidance. The items in the list are placed at different heights and are highlighted with a golden glow. The user selects the item using the grab gesture. The total completion time and the number of collisions with the objects are recorded for this task.



**Figure 4.15: Undirected paths in the supermarket**

**4.5.3 Procedure:** Study 1, Study 2, and Study 3 were within-group studies and used the same methodology. For each study, 30 participants were recruited. The below five main steps were carried out to conduct the experiment.

- i) Distribution of the background questionnaire to participants
- ii) Presentation of locomotion techniques and explanation of task procedure.
- iii) Participant training in locomotion techniques
- iv) Task completion - Tasks #1, #2, and #3
- v) Questionnaire administration

The participants were given a background questionnaire in the first step, which asked them about their age, gender, as well as their previous experiences with VR, video games, and touchless interfaces. We also inquired about the current status of any physical disorders that the simulation could exacerbate. They were asked questions related to their vision, such as whether they wear glasses or contact lenses, and have had recent eye exams. It was ensured that participants can adequately see and read the content displayed in the VR environment. All of the subjects in the experiment were in good health. The questionnaire, along with the answers to a few questions, took a total of 2 minutes to complete. In the second step, the procedure for the various tasks in the experiment was explained, and a video of the locomotion technique and selection gesture interaction modalities was shown to the participants. The participants were then asked to sit in a swivel chair (office chair) and go through a training session for different locomotion techniques in a separate VE that was not used in our experiment. The participants

practiced each locomotion technique used in the study until they were comfortable with it. When the participants were ready, they completed the fourth step of task execution while in a seated position. Each participant performed the locomotion gesture in a different order based on the Latin square. The participants had to complete each task as quickly and accurately as possible. Participants had to complete Tasks #1, #2, and #3 using one locomotion technique followed by another. The tasks were always assigned in the following order: Task #1 (Movement in a Straight Line Path), Task #2 (Movement in a Directed Path to reach the targets), and Task #3 (Movement in an undirected path to reach the targets). The task order was not changed because the goal was to compare locomotion techniques rather than tasks. As the fifth step, after completing each task with a specific locomotion technique, the participants were given a questionnaire to evaluate the subjective metrics. Following the completion of the experiment, a user preference questionnaire was used to determine the user's preferred technique, and a semi-structured interview was conducted to gain a deeper understanding of the participant's responses.

**4.5.4 Method of data collection:** The three user studies use objective measures for task completion time and the number of collisions and subjective measures for the measure of intuitiveness, comfort, ease of use, simulation sickness, presence, perceived workload, spatial knowledge, and user preference.

**4.5.4.1 Task Performance:** Task performance is measured by the completion time and the collisions involved while traveling. The completion time is the total time taken by the user from the start until the end of the task. The collisions denote the number of times the user collides with the shelves or any other objects in the supermarket while traveling. The system automatically calculates the total completion time and the collisions for the three tasks.

**4.5.4.2 Intuitiveness:** In the three studies below, the degree of intuitiveness is the relation of the naturalness of the gesture performed for the specific functionality of locomotion (Cannavò et al., 2020) was assessed. The user's feedback for the intuitiveness of the gesture was obtained by asking them to rate "I felt the gesture to be intuitive for locomotion in this VE" on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree).

**4.5.4.3 Comfort:** Comfort is the user's ability to maintain a comfortable pose and perform the locomotion gesture as well as other interaction tasks in VR for an extended period of time. On a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree), the feedback for comfort, "I felt the gesture to be comfortable to use for a longer period of time," was gathered.

**4.5.4.4 Ease of Use:** The complexity of the gesture from the user's perspective is referred to as ease of use. The data on the ease of use was gathered by asking respondents to rate "I felt the gesture was easy to perform for completing the given task" on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree).

**4.5.4.5 Measurement of Simulation Sickness:** The cybersickness caused by the VR experience was assessed using an SSQ questionnaire (Kennedy et al., 1993). The questionnaire has 16 variables that are rated on a four-point Likert scale, where 0 means "none" and three means "severe." It divides the variables into three groups and assigns different weights to each item. The various groups are

- a) Oculomotor (O) - Variables related to problems with eye function (eyestrain, difficulty focusing, blurred vision, headache).
- b) Disorientation (D) - Variables associated with a loss of orientation or similar sensations (dizziness, vertigo)
- c) Nausea (N) - Symptoms of stomach upset or similar reactions (nausea, stomach awareness, increased salivation, burping).

The total score obtained from these clusters determines the final value of the simulation sickness. A higher total score indicates that the user is experiencing worse symptoms while experiencing the VE.

**4.5.4.6 Presence:** Various questionnaires are available to assess the user's presence in a VE. The presence questionnaire developed by Slater-Usuh-Steed (SUS) (Slater et., 1994) was used for our experiments. The items in the presence questionnaire are graded on a 7-point Likert scale, with 0 indicating "completely disagree" and six indicating "completely agree." Some questions are inverted to corroborate, with six representing "completely disagree" and 0 representing "completely agree." Three indicators are used in the questionnaire.

- a) The user's "sense of being there" to record the user's overall psychological state in relation to the environment.
- b) The level of immersion the user has in the VE.
- c) The "locality," or the extent to which the VE is thought of as a place visited rather than just a collection of images.

The sum of the three indicators yields the final score. The higher the value, the more immersive the user feels in the VE.

**4.5.4.7 Perceived Workload:** Using the NASA-TLX questionnaire, we calculated the overall perceived workload (Hart & Staveland, 1988). The assessment includes six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each dimension is graded on a 20-grade scale along a low-high continuum (poor-good for each performance item).

**Table 4.1: Description of NASA-TLX subscales. Source adapted from (Hart & Staveland, 1988)**

NASA-TLX Subscales	Description
Mental Demand (MD)	This scale gives the subjective measure of how much mental and perpetual activity was required to perform the task thinking, deciding, calculating, and remembering)
Physical Demand (PD)	This gives the subjective measure of physical activity required to perform the task (e.g., grabbing, turning, controlling)
Temporal Demand (TD)	Time pressure the participants felt for the completion of the tasks
Performance (P)	How successful was the participant in accomplishing the goals of the task
Effort (E)	How hard the participant felt (mentally and physically) to accomplish the level of performance
Frustration (F)	How discouraged, irritated, stressed, insecure, and annoyed the participants felt during the performance of the task.

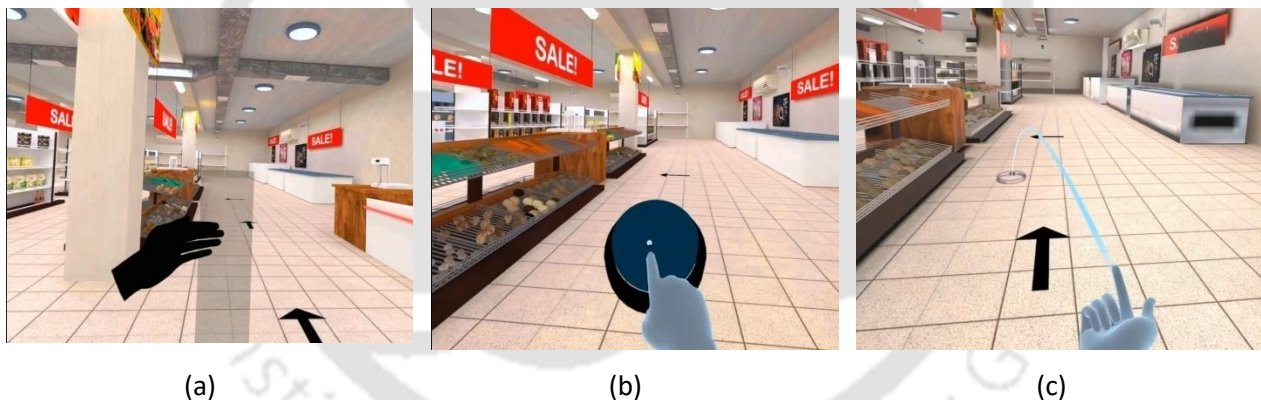
**4.5.4.8 Spatial Knowledge:** When the users explore the VE using different locomotion techniques, they must get a reasonable knowledge of the VE. Acquiring spatial knowledge is called cognitive map building (Bowman et al., 2004). It is important to find out how the locomotion technique might influence the cognitive map-building of the user. To analyze the effect of different locomotion techniques on cognitive map building, participants answered a set of five different questions regarding the placement of objects on different shelves, the advertisements on the walls, and the recollection of objects in the supermarket. The users had to sketch the layout of the supermarket, similar to Billinghurst et al., (1995), Cliburn et al., (2009), and Langbehn et al., (2018).

**4.5.4.9 User Preference:** Aside from the overall rank, the participants' preferences for several aspects of their experience were also gathered. The users were asked to pick a preferred technique for navigation, a technique that was helpful for looking for items in the supermarket, a technique that was helpful for moving near the item while interacting (grabbing) items, and a technique that helped in avoiding collisions, increased comfort, and effortlessness.

## 4.6 Study 3: Comparison of Calling, Tapping, Teleportation gestures for VE1

**4.6.1 Participants:** Thirty university students (13 females) aged 21-32 ( $M = 25.33$ ;  $SD = 3.83$ ) took part in Study 3. Eight participants (26.66%) had corrected eyesight (contact lenses or glasses), 22 (73.33%) played 3D first-person view video games daily or weekly, eight (26.6%) had no prior experiences with HMDs, and none had a motor disability and prior experience with any of our locomotion techniques including gesture-based *teleportation* method.

**4.6.2 Experimental Design:** We used a within-subject design, with each participant completing three training sessions (one for each locomotion technique) and nine main trials, which consisted of a factorial combination of three locomotion techniques (*Callinggesture Vs.TappingGesture Vs.Teleportation*) X three tasks (Task #1, Task #2, and Task #3). We reversed the order of the interface conditions across participants. Participants completed the three tasks in the same order, as dictated by the interface. VE1 was the virtual environment used for the task. The experiment procedure outlined above was followed. Below, figure 4.16 shows the three gestures (a) the *Calling Gesture*, (b) the *Tapping Gesture* (c) the *Teleportation Gesture* used in VE1.



**Figure 4.16: Gesture Comparison in VE1 (a) Calling gesture (b) Tapping gesture (c) Teleportation Gesture**

**4.6.3 Statistical analysis:** The task completion time and the collision data was found to be normally distributed using Shapiro–Wilk test. The data were analyzed with SPSS using one-way ANOVA. The statistical significance level was set to  $\alpha = 0.05$ . A Tukey's post hoc test was used to determine the significance when a pairwise comparison was carried out. For intuitiveness, comfort, ease of use, simulation sickness, perceived workload, presence and spatial knowledge the normality was checked using Shapiro–Wilk tests. The results showed that the data were not normally distributed. Therefore, Friedman tests and Wilcoxon signed-rank tests were used for statistical analyses. A Bonferroni corrected p-value of  $0.05/3 = 0.016$  was used as the significance threshold.

**4.6.3.1 Task Performance:** Task performance is measured by the total time (speed) and accuracy (collisions) with which the user completes the task.

**Task #1 - Task completion time:** For Task#1, the task performance was measured only with the completion time of the travel from point A to point B. The data was found to be normally distributed with the overall mean and SD ( $M=32.96$ ,  $SD=10.31$ ). The results of movement in a straight line path were found to be ( $F(2, 90) = 45.62$ ,  $p < 0.01$ ). A post hoc analysis showed that the teleportation gesture was significantly faster in movement than the *calling* gestures ( $p < 0.01$ ) and *tapping* gesture ( $p < 0.01$ ).

**Task #2 - Task completion time and collision:** For Task#2, the task performance was measured with the task's completion time and the number of collisions. The data was found to be normally distributed with the overall mean and SD of total time completion ( $M=157.36$ ,  $SD=34.56$ ). The results completion time was found to be ( $F(2, 90) = 3.45$ ,  $p = 0.036$ ). A post hoc analysis showed a significant difference in movement between *calling* gestures and *tapping* ( $p=0.046$ ). The calling gesture was found to be faster than the tapping gesture. There was no significant difference between the other techniques. The data for the collision was found to be normally distributed with the overall mean and SD of total time completion ( $M=10.26$ ,  $SD = 3.85$ ). The collision results were found to be ( $F(2, 90) = 42.78$ ,  $p < 0.01$ ). A post hoc analysis showed that the *teleportation* technique had the least number of collisions than the *calling* gesture ( $p < 0.01$ ) and *tapping* gesture ( $p < 0.01$ ) significantly.

**Task #3 - Task completion time and collision:** For Task#3, the task performance was measured with the task's completion time and the number of collisions. The data was found to be normally distributed with the overall mean and SD of total time completion ( $M=177.36$ ,  $SD=30.06$ ). The results completion time was found to be ( $F(2, 90) = 7.169$ ,  $p = 0.001$ ). A post hoc analysis showed that the *calling* gesture took significantly lesser time completion when compared to the *tapping* ( $p=0.001$ ) and *teleportation* techniques ( $p=0.047$ ). The data for the collision was found to be normally distributed with the overall mean and SD of total time completion ( $M=10.92$ ,  $SD = 4.14$ ). The results were ( $F(2, 90) = 47.45$ ,  $p < 0.01$ ). The *teleportation* gesture had significantly lesser collisions than the *Calling* ( $p < 0.01$ ) and *tapping* gestures ( $p < 0.01$ ).

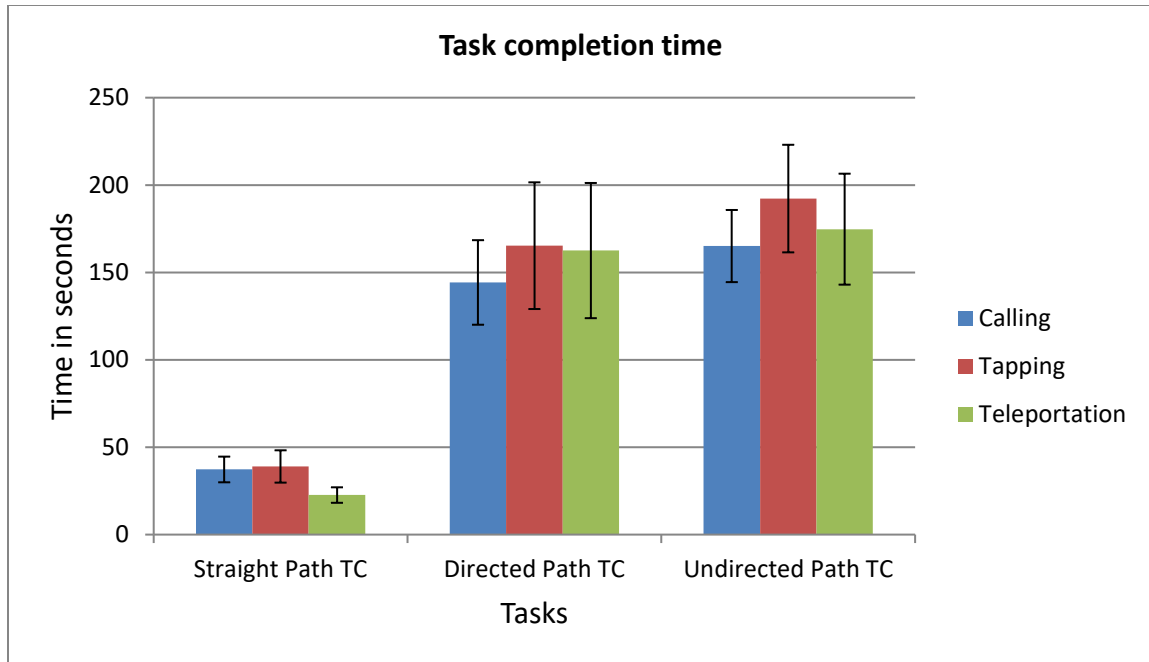


Figure 4.17: Task Completion Time in VE1

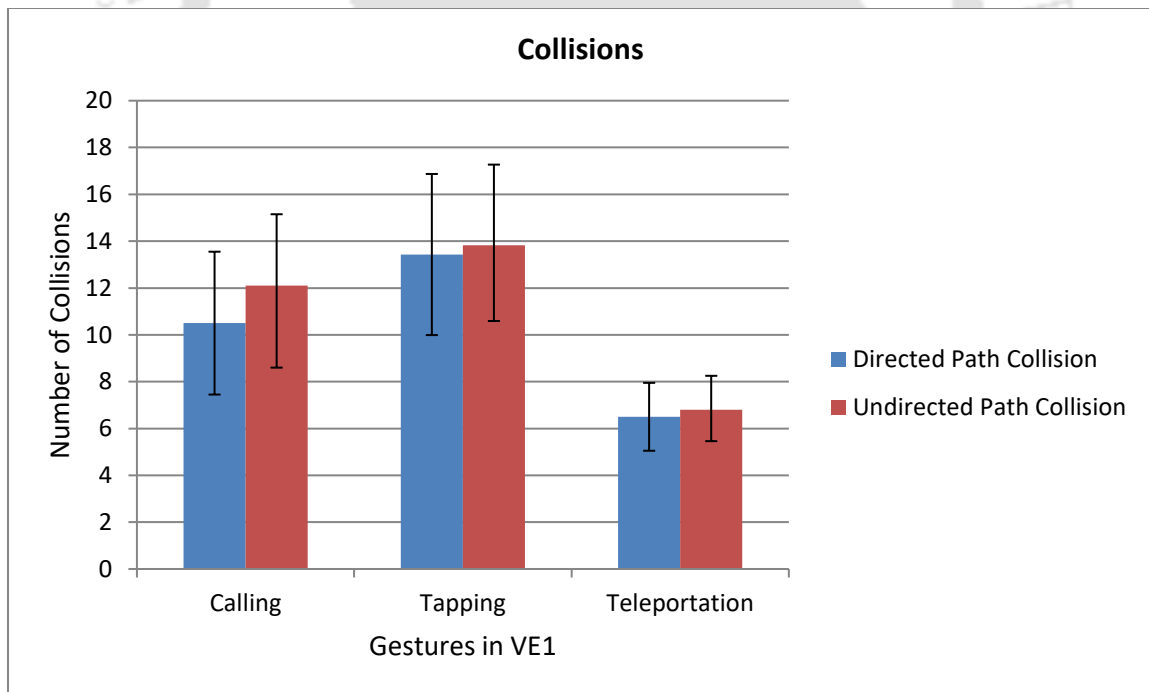


Figure 4.18: Collision using gestures in VE1

**4.6.3.2 Intuitiveness:** For intuitiveness, the Friedman test showed a statistically significant effect of locomotion gesture ( $\chi^2 = 7.38$ ,  $p = 0.025$ ,  $W = 0.123$ ). The results of pairwise comparisons showed that

the *calling* gesture was found to be a significantly more intuitive gesture than the *teleportation* gesture ( $p=0.015$ ,  $r=0.106$ ). There was no significant difference in other pairwise comparisons.

**4.6.3.3 Comfort:** Analysis showed that there was no significant difference in the comfort measure between the locomotion techniques ( $\chi^2= 1.095$ ,  $p = 0.57$ ,  $W = 0.018$ ).

**4.6.3.4 Ease of use:** The results for the ease of use were found to be ( $\chi^2= 3.93$ ,  $p = 0.14$ ,  $W = 0.066$ ). There was no significant difference found between the locomotion techniques.

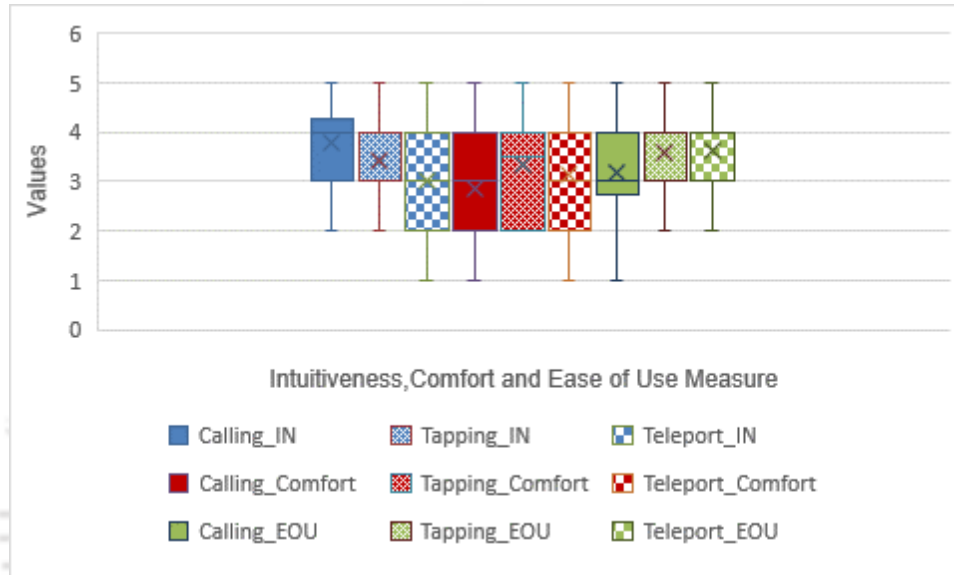
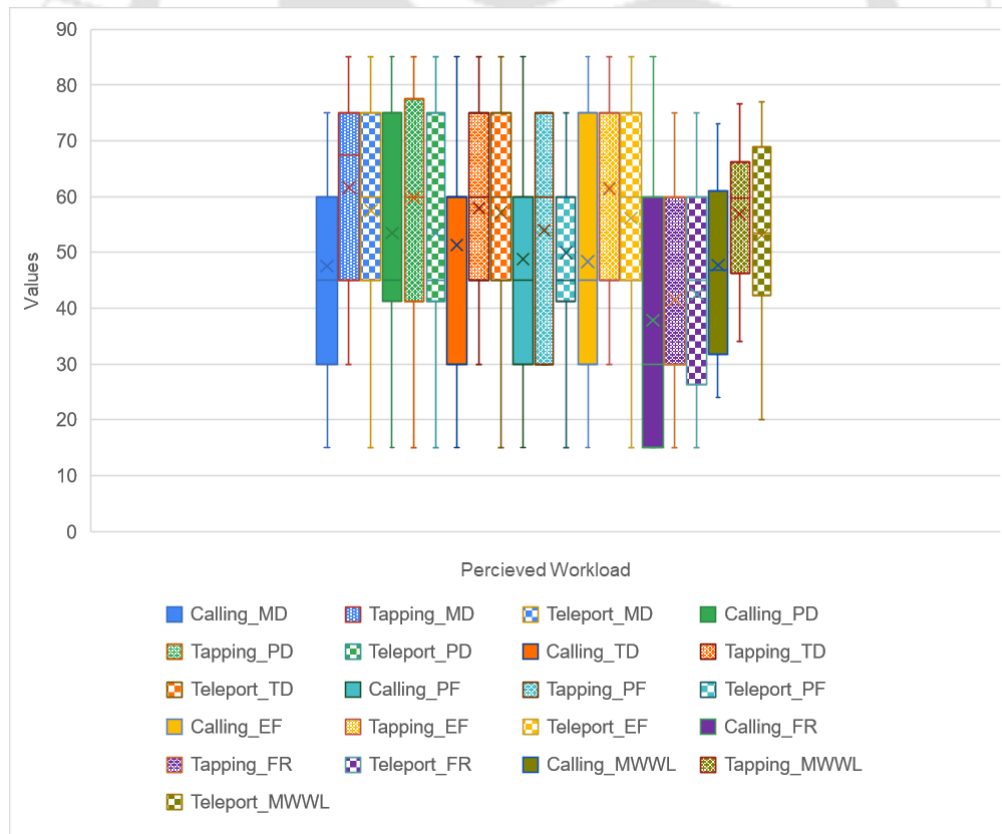


Figure 4.19: Intuitiveness, Comfort, and Ease of use for gestures in VE1

**4.6.3.5 Perceived Workload:** The results of the Friedman test showed a statistically significant effect of locomotion gesture for mental demand ( $\chi^2 = 11.347$ ,  $p = 0.003$ ,  $W = 0.189$ ). The results of pairwise comparisons showed that the *calling* gesture was found to be significantly less in mental demand ( $p=0.003$ ,  $r=0.31$ ) when compared to the *tapping* gesture. There was no difference in the physical demand ( $\chi^2 = 0.614$ ,  $p = 0.736$ ,  $W = 0.01$ ) between the techniques. There was no significant difference in the temporal demand ( $\chi^2 = 3.546$ ,  $p = 0.176$ ,  $W = 0.059$ ) between the techniques. There was no significant difference in the performance scores ( $\chi^2 = 0.813$ ,  $p = 0.66$ ,  $W = 0.014$ ) between the techniques. For the effort scores ( $\chi^2 = 6.811$ ,  $p = 0.033$ ,  $W = 0.114$ ), there was no significant difference between the techniques. The techniques did not significantly differ in the frustration scores ( $\chi^2 = 2.102$ ,  $p = 0.35$ ,  $W = 0.035$ ). There was a no significant difference in the Mean Weighted Workload ( $\chi^2 = 6.2$ ,  $p = 0.045$ ,  $W = 0.103$ ) between the techniques.

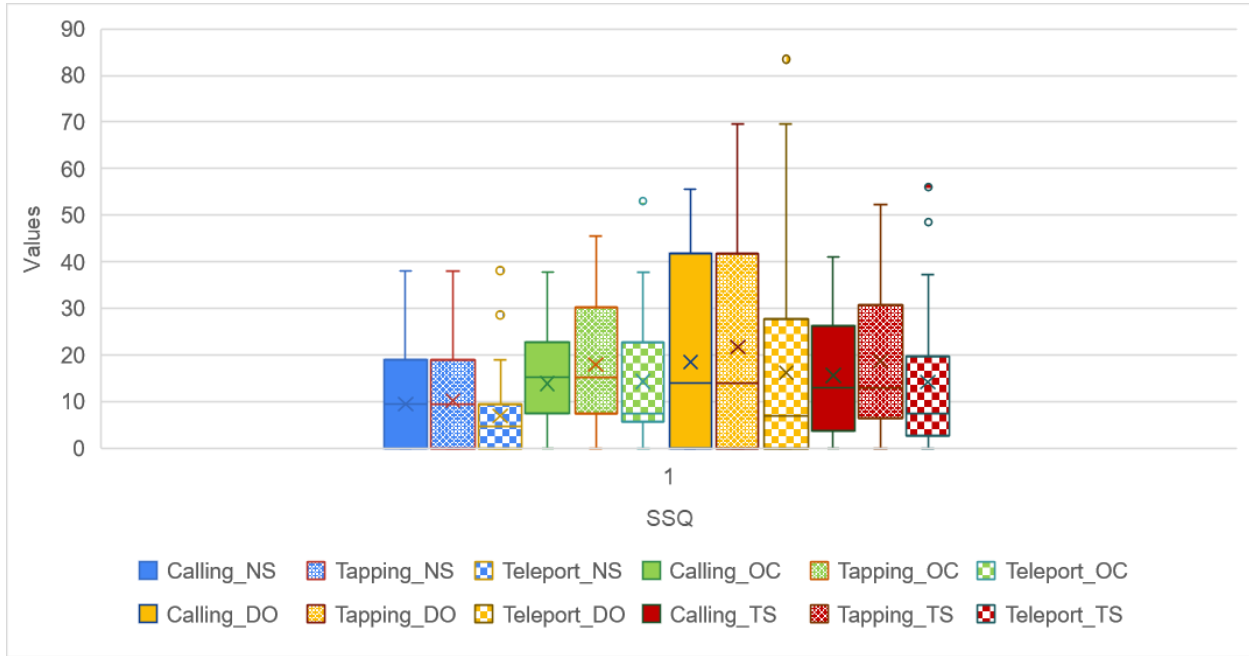
**Table 4.2: Descriptive Statistics of NASA-TLX dimensions scale (0=Low to 100=High)**

Workload Type	N	Calling Gesture		Tapping Gesture		Teleportation Gesture	
		Mean	SD	Mean	SD	Mean	SD
Mental Demand	30	47.50	16.28	61.67	17.44	57.50	19.60
Physical Demand	30	53.50	20.60	59.83	22.19	53.50	19.83
Temporal Demand	30	51.33	18.84	58.00	15.95	57.17	18.79
Performance	30	48.83	19.33	54.00	18.31	50.00	17.76
Effort	30	48.33	20.78	61.50	19.30	56.17	18.60
Frustration	30	37.83	19.94	41.50	19.96	42.50	21.96
MWWL	30	47.76	9.14	56.91	12.67	53.09	16.26



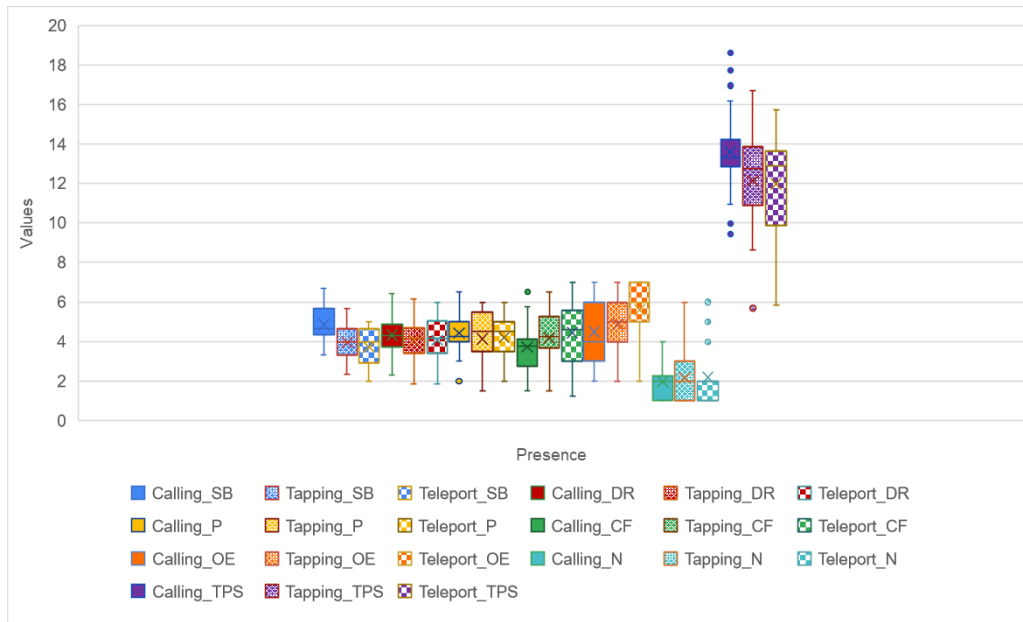
**Figure 4.20: Comparison of Perceived Workload in VE1**

**4.6.3.6 Simulation Sickness:** We found no significant difference in simulation sickness with a total score ( $\chi^2 = 2.074$ ,  $p = 0.35$ ,  $W = 0.035$ ). There was no significant difference found in the variables nausea ( $\chi^2 = 3.522$ ,  $p = 0.169$ ,  $W = 0.059$ ), oculomotor ( $\chi^2 = 3.54$ ,  $p = 0.17$ ,  $W = 0.059$ ), and disorientation ( $\chi^2 = 6.35$ ,  $p = 0.042$ ,  $W = 0.106$ ) between the locomotion techniques.



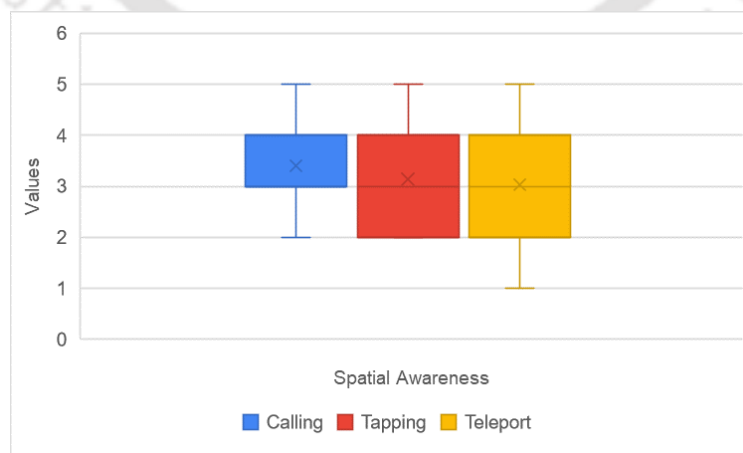
**Figure 4.21: Comparison of Simulation Sickness in VE1**

**4.6.3.7 Presence:** Our analysis for total presence showed that there was a statistical difference in presence between the techniques ( $\chi^2 = 6.867$ ,  $p = 0.032$ ,  $W = 0.114$ ). A pairwise analysis showed that there was a significant difference in the presence between the *Calling* and the *teleportation* technique ( $p=0.001$ ,  $r=0.28$ ) and also between the *Calling* and *tapping* gesture ( $p=0.008$ ,  $r=0.34$ ). The *calling* gesture had a better presence than the *teleportation* gesture and *tapping* gesture. There was no significant difference between the other gestures. The questions were grouped under the following categories - SB stands for "Sense of being in Supermarket," DR – "the extent to which the VE becomes the dominant reality," P- "the extent to which the VE is remembered as a place," CF – Control Factors (ease to navigate, move near objects and avoid collisions), OE =Overall Enjoyment, N - Nausea, TPS- Total Presence Score.



**Figure 4.22: Comparison of Presence in VE1**

**4.6.3.8 Spatial Knowledge:** The spatial knowledge of the supermarket while traveling in VE1 using different techniques was measured using five sets of questions (such as placement of an object, advertisements on the boards, etc.) for each technique. Our analysis for spatial knowledge was found to be ( $\chi^2 = 3.2$ ,  $p = 0.2$ ,  $W = 0.05$ ). No significant difference was found in the user's spatial knowledge when traveling using the *calling*, *tapping*, and *teleportation* gestures. However, when users used the *calling* gesture, 65% of users came up with the right layout of the supermarket. For the *tapping* gesture, 61% of the users came up with the right layout, and 57% came up with the right layout of the supermarket for the *teleportation* gesture.

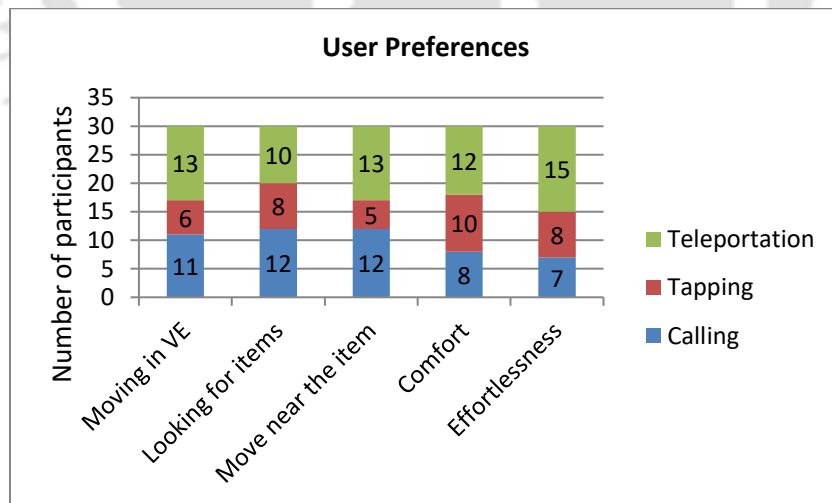


**Figure 4.23: Comparison of Spatial Knowledge in VE1**

**4.6.3.9 User Preference:** When participants were asked for an overall ranking of the locomotion technique suitable for the VE1, *teleportation* was ranked first as the most preferred gesture (13 of 30 participants), the *calling* gesture was ranked second(11 of 30 participants), and the *tapping* gesture as a third preferred gesture. Participants also expressed preferences for individual aspects such as navigation, searching for items in the supermarket, moving closer to the items to grab them, avoiding collisions, comfort, and ease of use. The responses are displayed in Table 4.3 below. Most of the users preferred the teleportation gesture for moving in the VE with comfort and effortless travel. Calling gesture was preferred by most of the users for looking for items in the supermarket. Both the calling and teleportation gestures were preferred by the users to move near the supermarket shelves to pick the items.

**Table 4.3: User Preference for VE1**

User Preferences	Calling	Tapping	Teleportation
Moving in VE	11	6	13
Looking for items	12	8	10
Moving near the item	12	5	13
Comfort	8	10	12
Effortlessness	7	8	15



**Figure 4.24: Comparison of User Preference in VE1**

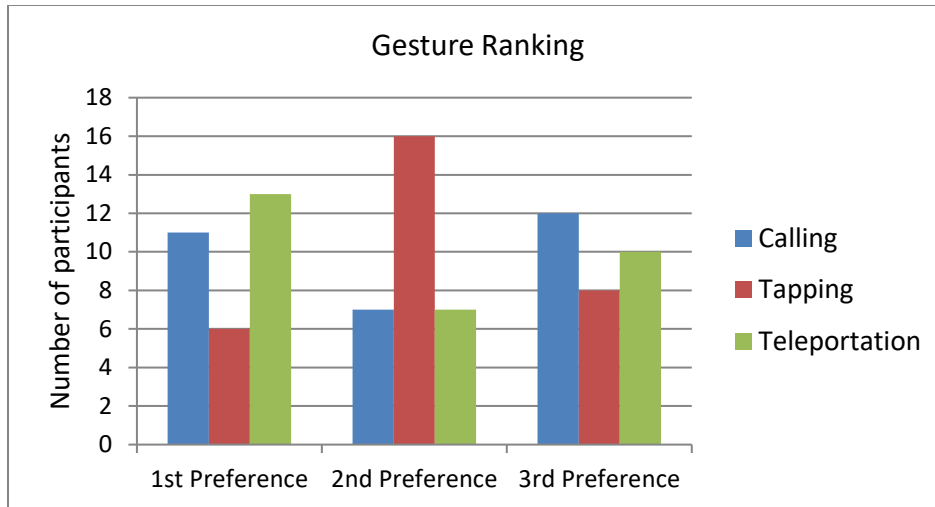


Figure 4.25: Gesture Ranking in VE 1

Table 4.4: Pairwise p-values for task completion time and collision for locomotion gestures in VE1 (\*= $p < 0.05$ )

Measures	Calling - Tapping	Tapping- Teleportation	Calling - Teleportation
Straight Line Travel Time	0.635	<0.01*	<0.01*
Directed Line Travel Time	0.046*	0.944	0.096
Directed Collision	<0.01*	<0.01*	<0.01*
Undirected Line Travel Time	0.001*	0.047*	0.384
Undirected Collision	0.059	<0.01*	<0.01*

Table 4.5: Results of the Wilcoxon signed-ranks test in pairs for locomotion gestures in VE1 (\*= $p < 0.016$ )

Measures	Calling - Tapping	Tapping- Teleportation	Calling - Teleportation
Intuitiveness	0.132	0.252	0.015*
Comfort	0.06	0.551	0.267
Ease of Use	0.119	0.769	0.091
Perceived Workload	Physical Demand	0.183	0.187
	Mental Demand	0.003*	0.224
	Temporal Demand	0.194	0.86
	Performance	0.309	0.428
	Effort	0.034	0.259
	Frustration	0.398	0.814
	Total Score	0.019	0.318
SSQ	Nausea	0.627	0.04
	Oculomotor	0.064	0.098
	Disorientation	0.205	0.068
	Total Score	0.177	0.054
Presence	0.008*	0.586	0.001*
Spatial Knowledge	0.181	0.618	0.139

#### 4.6.4 Discussion for VE1

**4.6.4.1 Intuitiveness:** The calling gesture was found to be significantly more intuitive than the *tapping* gesture. The users enjoyed moving the hand forward and backward as they got both the optical cue and the kinesthetic feedback. This observation is similar to Nilsson et al., (2018), where rhythmic swinging of arms generated the related kinesthetic information. It was also observed that the rhythmic arm movement primes the sensory-motor system to operate on the optical flow. This was consistent with the literature (Williams et al., 2007; Engel et al., 2008) in which movement of body parts triggers the necessary multisensory stimuli. One participant stated, "*The calling gesture required more effort, but I enjoyed performing the gesture as it felt natural to move in the VE.*" Another participant stated, "*I felt calling gesture is intuitive and has a natural pace while moving.*"

**4.6.4.2 Load/Effort:** The *calling* gesture was found to have significantly lower mental demand when compared to *tapping* and the *teleportation* gesture. However, some users reported that since the forearms need to be constantly moved forward and backward, it was found that the *calling* gesture required more effort to perform when used continuously for traversing large VE. This feedback was similar to McCullough et al., (2015), where the constant movement of arms caused fatigue to the users. Though the *calling* gesture gave the user the natural movement experience, it was preferred to be used for movement in smaller VEs. The users felt it difficult to perform the tap gesture repetitively to traverse a large VE.

**4.6.4.3 Ease of use and Comfort:** Results showed that although the *tapping* gesture had a better mean score in ease of use and comfort, similar to the study performed by Ferracani et al., (2016), there was no statistical significance compared to the *calling* gesture and *teleportation*.

#### 4.6.4.4 Task Completion Time

##### Task #1 – Straight Line Path Travel

a) **Task Completion Time:** The *teleportation* gesture was instantaneous, so no velocity was defined with this gesture. Users were able to jump long distances in a single gesture performance. Hence in the straight line path, the *teleportation* gesture had significantly less task completion time compared to the *Calling* and *tapping* gesture. There was no significance in the completion time between the *Calling* and the *tapping* gesture.

##### Task #2 – Directed Path Travel

a) **Task Completion Time:** The *calling* gesture performed significantly better than the *tapping* gesture. However, for the *calling* gesture during the path traversal, at the reach of turns, the user had to

stop and then turn in the required direction and once again perform the gesture. This two-step process increased the completion time of the task. One participant commented, "*While I am approaching the turns, I need to stop and turn again in the needed direction and move forward.*" Users felt it was difficult when the path consisted of multiple turns. Hence *calling* gesture is not an ideal gesture when the path has several bends and turns.

**b) Collisions/Accuracy:** The *calling* gesture had a significantly lesser number of collisions than the *tapping* gesture. The *tapping* gesture allowed the user to move a constant distance for every tap. The constant step length also led to several collisions with the shelves. One of the participants commented, "*With tapping gesture when I want to move near the shelf for a distance less than a step, to grab an object, I collide with the shelf unexpectedly.*" The *tapping* gesture had the largest number of collisions when compared to the *calling* and *teleportation* technique. The *teleportation* technique had a significantly lesser number of collisions compared to the *Calling* and *tapping* gesture. The users felt it easier to reach the target object to grab with the *teleportation* technique, and this caused a lesser number of collisions, similar to Bozgeyikli et al., (2016), in which *the point and teleport* technique had the least collisions for moving in a path with obstacles when compared to *joystick* and *WIP*.

### **Task #3 – Undirected Path Travel**

**a) Task Completion Time:** The *calling* gesture performed significantly better than the *tapping* gesture. Users mostly used landmark navigation for *calling* gestures to update their current position when a known landmark was identified. This updating also helped them build a cognitive map of the environment, similar to Bruns et al., (2019), in which users traversed an unknown environment by recalling the landmarks. Using the *calling* gesture, the users felt it was easy to identify and reach the target objects with low visibility in a densely populated environment, such as a supermarket. During our physical examination during the experiment, we observed that the number of revisits was less than the *teleportation* technique. Hence the total distance traveled in identifying the targets was less for *calling* gestures than for the other two techniques. This was also observed in our qualitative analysis, in which 12 of 30 users preferred the *calling* gesture for looking for items in the supermarket.

The *tapping* gesture significantly performed the least compared to the *calling* and *teleportation* technique. Though the users were able to build a cognitive map of the supermarket, and the task of locating the target was better than the *teleportation* technique, reaching the items was difficult due to the constant step distance for every tap. The users had to maintain their relative distance from the

shelves considerably to reach the target items from the shelves without collision, which also increased the completion time.

The *teleportation* gesture had a significantly lesser task completion time than the *tapping* gesture for the undirected path travel. In the search task, locating the glowing objects was more difficult than the movement itself. This finding was similar to Coomer et al., (2018), where *teleportation* took longer completion time than *armcycling* and *pointed tugging* methods for locating the glowing objects. Often after each *teleportation*, the user had to reorient to find the object. If the object remained unidentified, the users' teleported further, changing their view. The number of revisits was also high while searching for the objects. Hence users used shorter teleportation distances to avoid destination misses. Therefore, identifying a low-visibility object in a highly dense environment was difficult using the *teleportation* technique. One of the participants commented, "*In the directed path, I was able to teleport longer distances in one jump as I know the path, but in the undirected path, I felt I might miss the target object; hence I took shorter jumps.*"

**b) Collisions/Accuracy:** The *teleportation* technique had significantly fewer collisions than the *calling* and *tapping* gesture in undirected path travel. The constant step length for the *Calling* and *tapping* gestures resulted in several collisions with the shelf.

**4.6.4.5 Presence:** The results also show that the *calling* gesture had significantly better presence when compared to the *tapping* and *teleportation* gestures. This increase in presence might be due to the spatiotemporal continuity available in the *calling* gesture that has enhanced the degree of immersion. While using *calling* gestures, continuous knowledge acquisition might positively affect the mental spatial representation of the user. Since *teleportation* does not provide the experience of the journey between locations, it is likely that it negatively affects the mental spatial representation and its continuity and connectedness, as specified in Riecke et al., (2021). As opposed to *calling* and *tapping* gestures, in *teleportation* gestures, users also reported that they had to mentally prepare for the spatial context switching and reorient themselves rapidly after each jump. This induced breaks in the presence of *teleportation* gestures.

**4.6.4.6 Control of Locomotion:** Users felt that with the *calling* gesture, they could control the movement better when compared to the *tapping* gesture in straight-line travel. The users indicated the current movement direction and knew the step length in the form of a visual beam (for every step) to the point they would be reaching next which increased the users' locomotion control. One of the participants commented, "*With calling, I had more control to move as I know where I will be moving next. The movement was seamless and continuous*". Since the *calling* gesture and *tapping* gesture had a

fixed step length, this caused most of the collisions with the shelves while grabbing the objects. Hence moving the users for a short distance that was less than a step was very difficult with the *Calling* and *tapping* gestures. Users suggested that these short step-length movements were also required to select the objects from the shelves. We further suggest a future research can include proposing a technique that provides shorter step lengths. This can be a hybrid technique that uses a bimanual *calling* gesture in which right-hand *calling* gesture can be used to move with bigger step lengths, and the left-hand *calling* gesture can be used to move with smaller step lengths. However the technique needs to be evaluated for its performance and user experience. With teleportation, the users could easily control their movement to large and small distances.

**4.6.4.7 Motion Sickness:** The *teleportation* gesture lacked self-motion cues as the user felt only stationary throughout the travel, as Zielasko et al., (2021) reported. Hence, there was no dynamic sensory conflict. Therefore, it had the least motion sickness, although there was no significant difference between the gestures.

**4.6.4.8 Spatial Knowledge:** There was no difference in the spatial knowledge acquired while traveling using different locomotion techniques in VE1. However, using *calling* gestures, users could sketch the supermarket's layout better than the other techniques. Like Langbehn et al., (2018), *teleportation* had reduced cognitive map-building capability due to the spatial disorientation caused by discontinuous travel.

**4.6.4.9 User Preference:** For VE1 users (13 of 30) preferred the *teleportation* gesture suitable for travel while interacting with the objects. The *teleportation* gesture was the most preferred gesture for moving around the supermarket and interacting with items with more comfort and less effort. 11 of 30 users preferred the *calling* gesture. 12 of 30 users preferred the *calling* gesture for looking for items in the supermarket.

In summary, for VE1, the teleportation gesture was found to be suitable for travel while interacting with the objects. Users found the gesture useful when the target object's location was known ahead of time but difficult to use when searching for the target objects in a dense environment with an undefined path. For a dense environment with no predefined path, the *calling* gesture can be used to locate the target objects. Furthermore, the *calling* gesture can be used in VR applications when less effort and less exertion are not one of the main goals. Sometimes effort may promote the feeling of accomplishment when time is not a critical factor in terms of experience gained from the VE, completion of a task, and the spatial presence of knowing the environment, as in Riecke et al. (2021). In a casual strolling

environment where users have more time to experience and enjoy the travel in such scenarios *calling* gestures can be used as a mode of travel. Also, the *calling* gesture can be used in applications such as exergames where high effort is desirable. Such a gesture for locomotion can motivate the users and enhance user enjoyment while using the application.

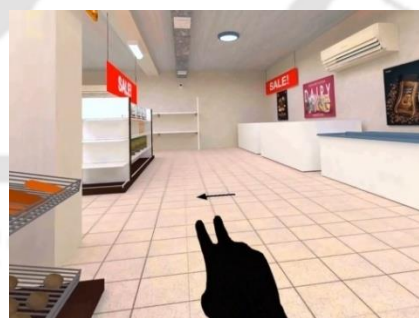
#### 4.7 Study 4: Comparison of Deictic Pointing, Tapping, Teleportation gestures for VE2

**4.7.1 Participants:** Thirty university students (12 females) between 21-34 years old ( $M = 25.9$ ;  $SD = 3.98$ ) participated in Study 4. Five participants (16.66%) had corrected eyesight (contact lenses or glasses), 20 of them (66.66%) played 3D first-person view video games on a daily or weekly basis, ten of them (33.33%) had no prior experiences with HMDs, and none of them had a motor disability and prior experience with any of our locomotion techniques.

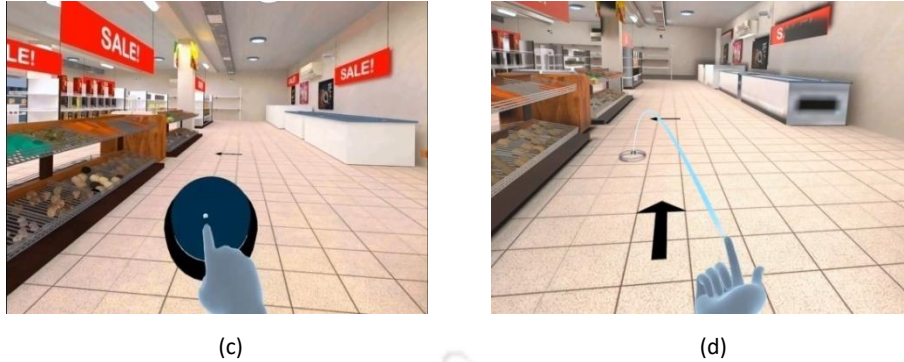
**4.7.2 Experimental Design:** We used a within-subject design, where each participant completed three training sessions (one for each locomotion technique) and nine main trials, consisting of a factorial combination of three locomotion techniques {*Deictic Pointing* gesture Vs *Tapping* gesture Vs *Teleportation*} X three tasks {Task#1, Task#2, Task#3}. We counterbalanced the order of interface conditions across participants. Participants performed the three tasks in the same order, blocked by the interface. The virtual environment used for the task was VE2. The above experiment procedure was followed. Figure 4.26 shows the four gestures (a) the Deictic Pointing Gesture for walking, (b) the Deictic Pointing Gesture for Running, (c) the Tapping Gesture, (d) the Teleportation Gesture used in VE2.



(a)



(b)



**Figure 4.26: Gesture Comparison in VE2 (a) Deictic Pointing Gesture for Walking (b) Pointing Gesture for Running (c) Tapping Gesture (d) Teleportation Gesture**

**4.7.3 Statistical analysis:** The task completion time and the collision data was found to be normally distributed using Shapiro–Wilk test. The data were analyzed with SPSS using one-way ANOVA. The statistical significance level was set to  $\alpha = 0.05$ . A Tukey's post hoc test was used to determine the significance when a pairwise comparison was carried out. For intuitiveness, comfort, ease of use, simulation sickness, perceived workload, presence and spatial knowledge the normality was checked using Shapiro–Wilk tests. The results showed that the data were not normally distributed. Therefore, Friedman tests and Wilcoxon signed-rank tests were used for statistical analyses. A Bonferroni corrected p-value of  $0.05/3 = 0.016$  was used as the significance threshold.

**4.7.3.1 Task Performance:** Similar to the previous study, task performance is measured by the total time (speed) and accuracy (collisions) with which the user completes the task.

**Task #1 - Task completion time:** For Task#1, the task performance was measured only with the completion time of the travel from point A to point B. The data was found to be normally distributed with the overall mean and SD ( $M=30.58$ ,  $SD=9.6$ ). The results of movement in a straight line path were found to be ( $F(2, 90) = 91.48$ ,  $p < 0.01$ ). A post hoc analysis showed that *pointing* gesture was significantly faster in movement than the *tapping* gesture ( $p < 0.01$ ). Similarly teleportation gesture was faster in movement than the *tapping* gesture ( $p < 0.01$ ).

**Task #2 - Task completion time and collision:** For Task#2, the task performance was measured with the completion time of the task along with the number of collisions. The data was found to be normally distributed with the overall mean and SD of total time completion ( $M=144.90$ ,  $SD=46.02$ ). The results completion time was found to be ( $F(2, 90) = 30.97$ ,  $p < 0.01$ ). A post hoc analysis showed that there was a significant difference in movement between the *pointing* gesture ( $p < 0.01$ ) and *tapping*. There was also a significant difference between the *pointing* gesture ( $p < 0.01$ ) and *teleportation*. The data for the

collision was found to be normally distributed with the overall mean and SD of total time completion (M=7.82, SD = 4.8). The collision results were found to be (F (2, 90) =191.20, p < 0.01). A post hoc analysis showed that the *pointing* technique had the least number of collisions than the *tapping* gesture (p<0.01) and *teleportation* (p=0.001) significantly. There was a significant difference in the collision between the *teleportation* and the *tapping* gesture (p<0.01).

**Task #3 - Task completion time and collision:** For Task#3, the task performance was measured with the completion time of the task along with the number of collisions. The data was found to be normally distributed with the overall mean and SD of total time completion (M=165.18, SD=36.39). The results completion time was found to be (F (2, 90) = 21.55, p < 0.01). A post hoc analysis showed that the *pointing* gesture took significantly lesser time completion when compared to the *tapping* (p<0.01) and *teleportation* technique (p=0.001). The *teleportation* technique took lesser time completion when compared to the *tapping* (p=0.025). The data for the collision was found to be normally distributed with the overall mean and SD of total time completion (M=8.43, SD = 4.6). The results were (F (2, 90) =229.76, p < 0.01). The *pointing* gesture had significantly lesser collisions than the *tapping* gesture (p<0.01), and the *teleportation* gesture had significantly lesser collisions than the *tapping* gesture (p<0.01).

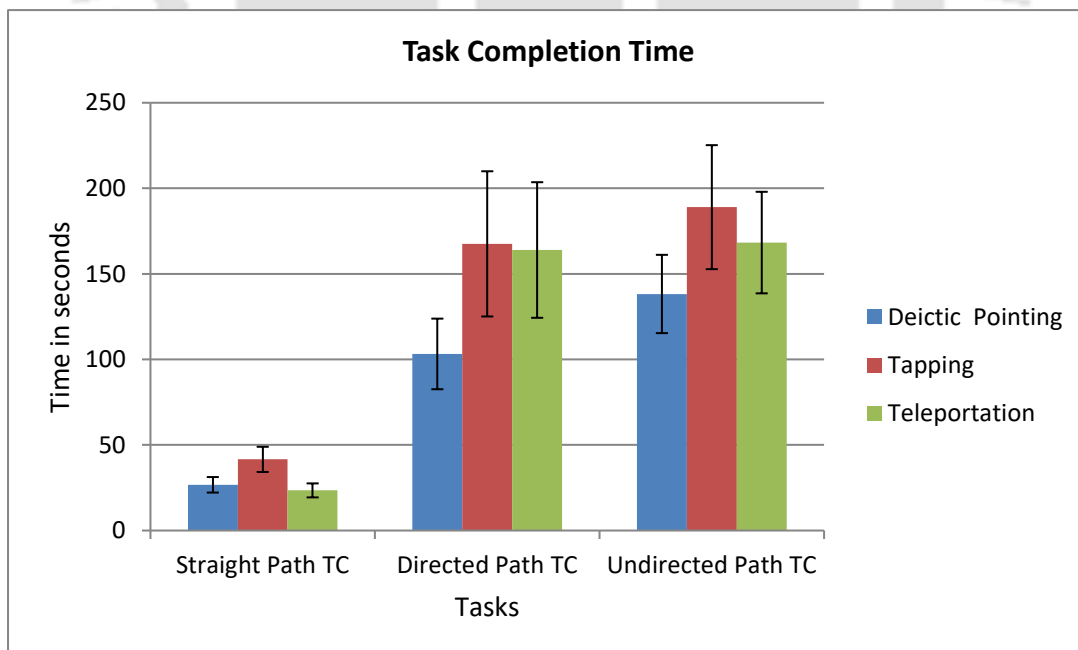


Figure 4.27: Task Completion Time in VE 2

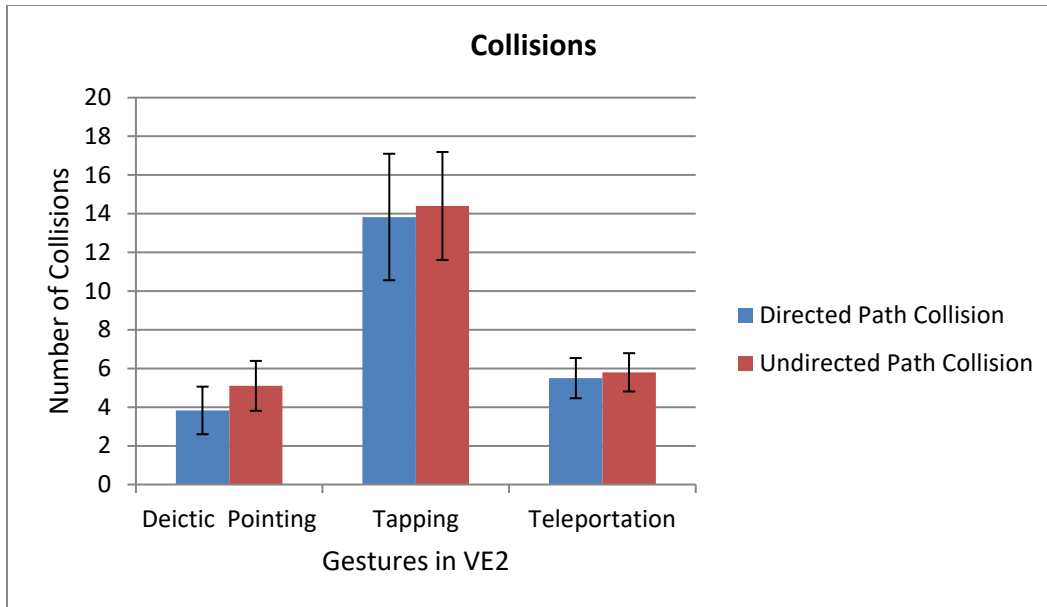


Figure 4.28: Collision using gestures in VE 2

**4.7.3.2 Intuitiveness:** For intuitiveness, the Friedman test showed a statistically significant effect of locomotion gesture ( $\chi^2= 32.133$ ,  $p < 0.01$ ,  $W = 0.536$ ). The results of pairwise comparisons showed that the *pointing* gesture was found to be significantly more intuitive than the *tapping* gesture ( $p<0.001$ ,  $r= 0.44$ ) and *teleportation* gesture ( $p<0.001$ ,  $r= 0.45$ ).

**4.7.3.3 Comfort:** Analysis showed that there was a significant difference in the comfort measure between the locomotion techniques ( $\chi^2= 18.69$ ,  $p<0.01$ ,  $W = 0.312$ ).The results of pairwise comparisons showed that the *pointing* gesture was found to be significantly more comfortable than the *tapping* gesture ( $p<0.001$ ,  $r=0.44$ ) and *teleportation* gesture ( $p=0.001$ ,  $r= 0.35$ ).

**4.7.3.4 Ease of use:** For ease of use, the Friedman test showed a statistically significant effect of locomotion gesture ( $\chi^2= 44.98$ ,  $p < 0.01$ ,  $W = 0.75$ ). The results of pairwise comparisons showed that the *pointing* gesture had significantly better ease of use than the *tapping* gesture ( $p<0.001$ ,  $r= 0.5$ ) and the *teleportation* ( $p<0.001$ ,  $r=0.48$ ).

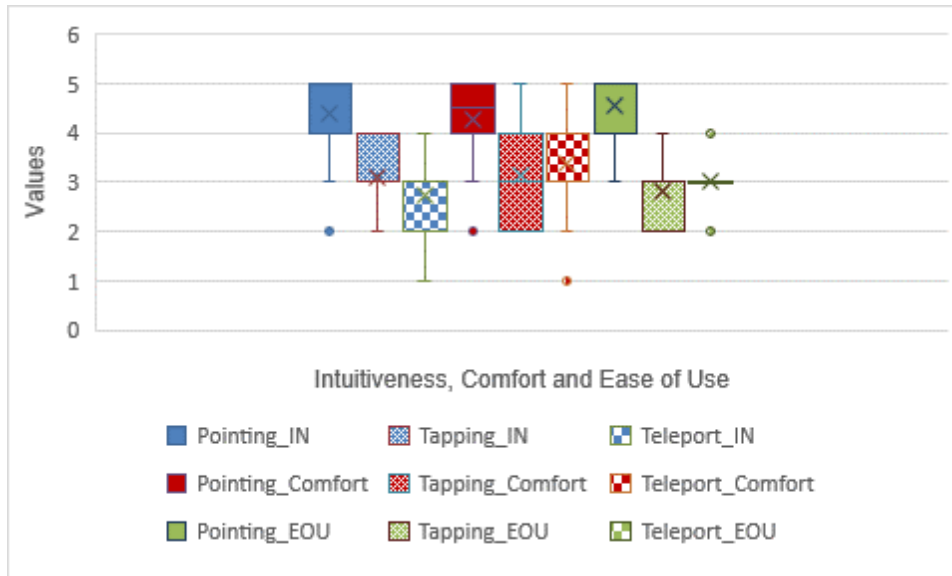
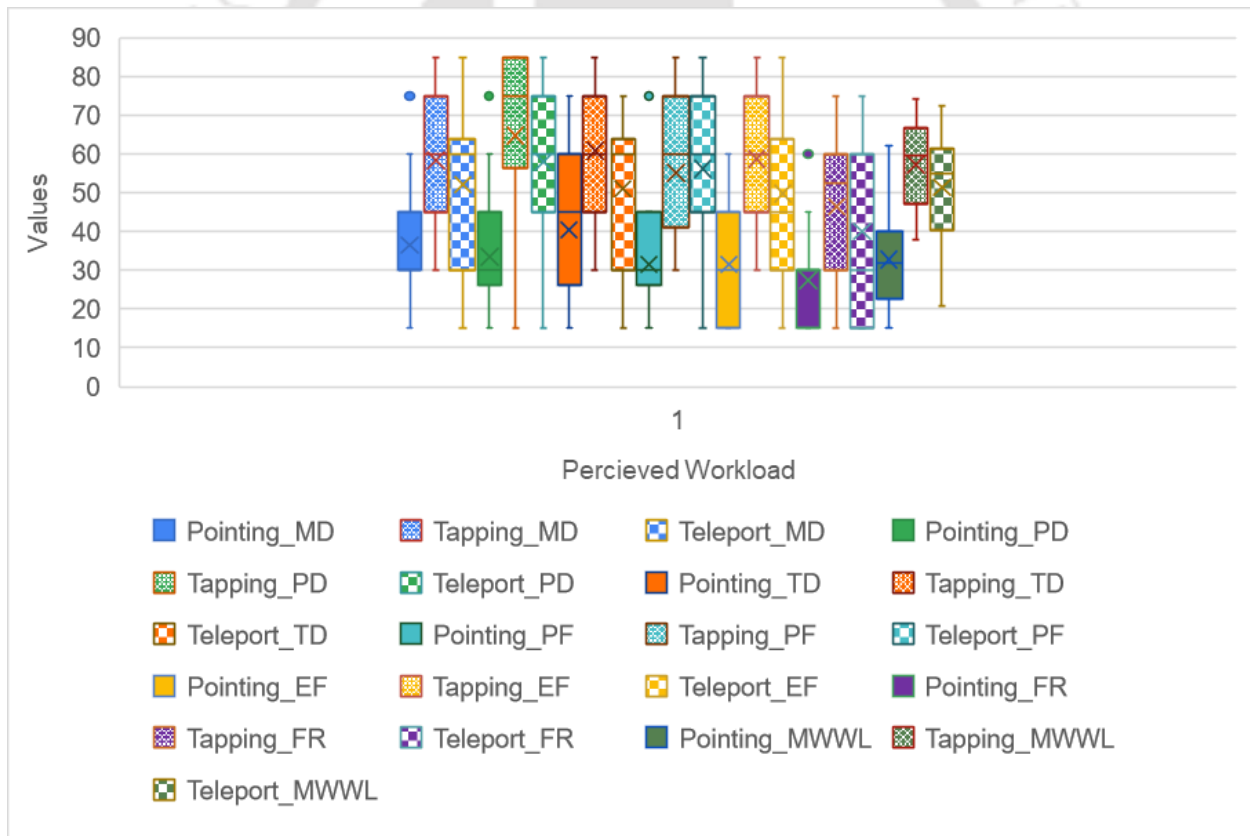


Figure 4.29: Intuitiveness, Comfort, and Ease Of Use for gestures in VE 2

**4.7.3.5 Perceived Workload:** The results of the Friedman test showed a statistically significant effect of locomotion gesture for the mental demand ( $\chi^2 = 25.12$ ,  $p < 0.001$ ,  $W = 0.419$ ). The results of pairwise comparisons showed that the *pointing* gesture was found to have significantly less mental demand when compared to the *tapping* gesture ( $p < 0.001$ ,  $r = 0.43$ ) and *teleportation* ( $p = 0.001$ ,  $r = 0.34$ ). The analysis for the physical demand was found to be ( $\chi^2 = 32$ ,  $p < 0.001$ ,  $W = 0.533$ ). A pairwise analysis showed that *pointing* gestures had significantly lesser physical demand when compared to *tapping* ( $p < 0.001$ ,  $r = 0.5$ ) and *teleportation* ( $p < 0.01$ ,  $r = 0.43$ ). The analysis for the temporal demand was found to be ( $\chi^2 = 15.34$ ,  $p < 0.001$ ,  $W = 0.256$ ). There was a significant difference in the *pointing* and *tapping* gestures ( $p = 0.001$ ,  $r = 0.4$ ). The analysis for the performance scores was found to be ( $\chi^2 = 32.02$ ,  $p < 0.001$ ,  $W = 0.534$ ). The *pointing* gesture was found to be performing better than the *tapping* ( $p < 0.001$ ,  $r = 0.5$ ) and the *teleportation* gesture ( $p < 0.001$ ,  $r = 0.44$ ). The effort scores were found to be ( $\chi^2 = 29.636$ ,  $p < 0.001$ ,  $W = 0.49$ ), and the *pointing* gesture was found to be having significantly lesser effort than the *tapping* gesture ( $p < 0.001$ ,  $r = 0.5$ ) and *teleportation* gesture ( $p < 0.001$ ,  $r = 0.37$ ). The frustration scores were found to be ( $\chi^2 = 16.23$ ,  $p < 0.001$ ,  $W = 0.27$ ), and the *pointing* gesture was found to be having significantly less frustration than the *tapping* gesture ( $p < 0.001$ ,  $r = 0.4$ ) and *teleportation* gesture ( $p = 0.012$ ,  $r = 0.3$ ). There was a significant difference in the Mean Weighted Workload ( $\chi^2 = 39.267$ ,  $p < 0.001$ ,  $W = 0.654$ ) between the techniques. The *Deictic Pointing* gesture was found to have significantly less MWWL when compared to the *tapping* gesture ( $p < 0.001$ ,  $r = 0.5$ ) and *teleportation* gesture ( $p < 0.001$ ,  $r = 0.5$ ).

**Table 4.6: Descriptive Statistics of NASA-TLX dimensions scale (0=Low to 100=High)**

Workload Type	N	Pointing Gesture		Tapping Gesture		Teleportation Gesture	
		Mean	SD	Mean	SD	Mean	SD
Mental Demand	30	36.5	16.56	58.33	17.04	52.17	20.54
Physical Demand	30	33.5	16.09	64.83	21.15	58.00	20.24
Temporal Demand	30	40.5	19.75	60.83	17.62	51.00	21.07
Performance	30	31.5	13.27	55.17	18.36	56.17	18.18
Effort	30	31.5	14.39	58.67	17.02	49.83	20.66
Frustration	30	27.5	14.78	46.50	17.33	40.00	21.70
MWWL	30	32.83	12.19	57.24	10.58	51.42	13.16



**Figure 4.30: Comparison of Perceived Workload in VE 2**

**4.7.3.6 Simulation Sickness:** We found a significant difference in simulation sickness with a total score ( $\chi^2 = 13.41$ ,  $p = 0.001$ ,  $W = 0.224$ ). There was a significant difference found in the total score of SSQ

between the *pointing* gesture and *tapping* gesture ( $p=0.001$ ,  $r=0.34$ ) and between tapping and teleportation gesture ( $p=0.014$ ,  $r=0.26$ ). There was a significant difference found in the variables nausea ( $\chi^2 = 8.13$ ,  $p = 0.017$ ,  $W = 0.136$ ). A pairwise comparison showed teleportation gesture had significantly less nausea than the tapping gesture ( $p=0.011$ ,  $r= 0.2$ ). There was a significant difference in disorientation between the locomotion techniques ( $\chi^2 = 7.76$ ,  $p = 0.021$ ,  $W = 0.129$ ). A pairwise comparison showed pointing gesture had significantly less disorientation than the tapping gesture ( $p=0.006$ ,  $r= 0.26$ ). In the oculomotor variable ( $\chi^2 = 13.68$ ,  $p = 0.001$ ,  $W = 0.22$ ), there was a significant difference found between the *pointing* gesture and the *tapping* gesture ( $p=0.001$ ,  $r=0.35$ ).

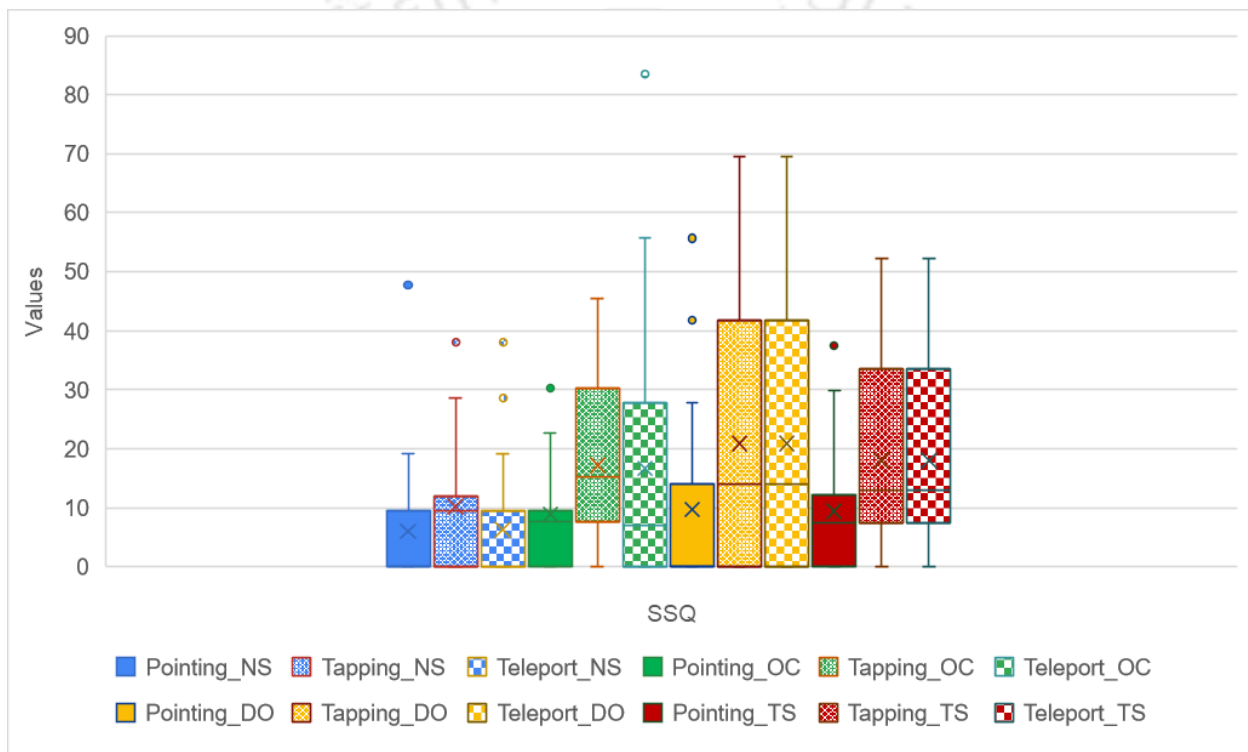
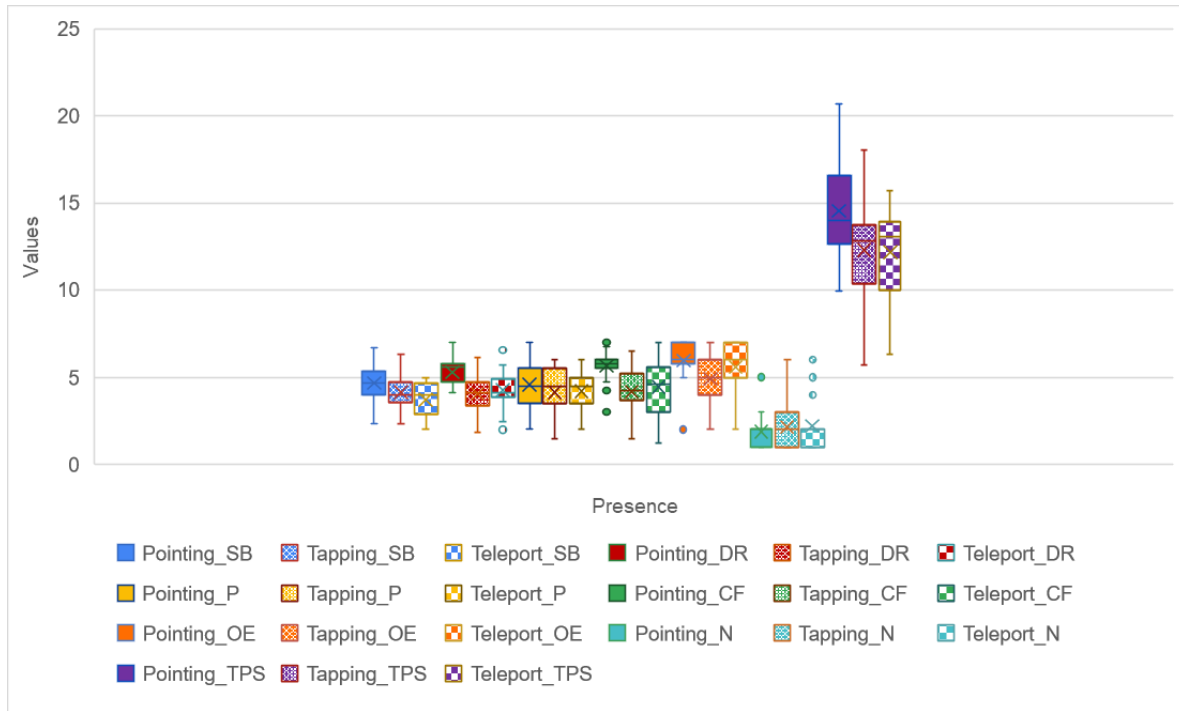


Figure 4.31: Comparison of Simulation Sickness in VE 2

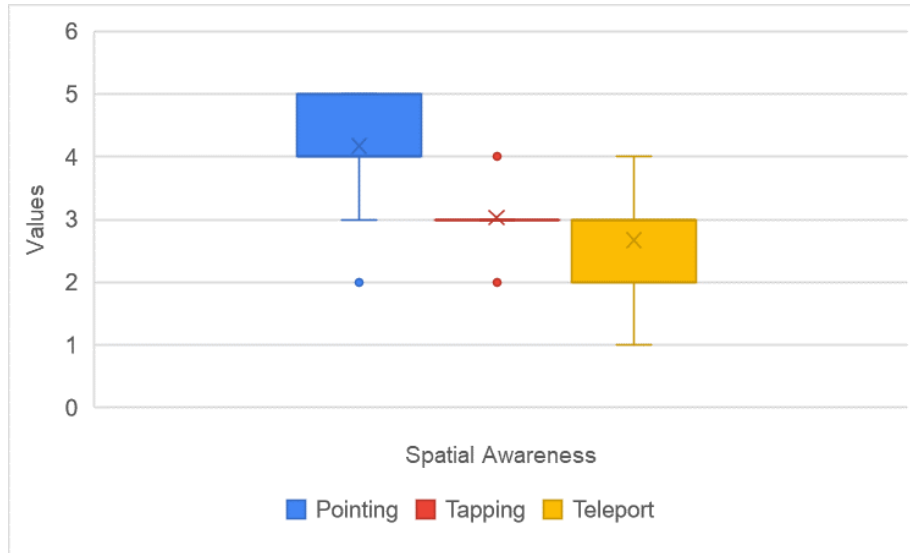
**4.7.3.7 Presence:** The results of the Friedman test showed a statistically significant effect of locomotion gesture for presence ( $\chi^2 = 8.86$ ,  $p = 0.012$ ,  $W = 0.148$ ). A pairwise analysis showed that there was a significant difference in the presence between the *pointing* gesture and the *tapping* gesture ( $p=0.001$ ,  $r=0.35$ ). There was a significant difference in the presence between the *pointing* gesture and the *teleportation* technique ( $p=0.001$ ,  $r= 0.35$ ). The pointing gesture was significantly better in presence than the tapping and teleportation gesture. There was no significant difference in other pairwise comparisons. The questions were grouped under the following categories - SB stands for "Sense of being

in Supermarket," DR – "the extent to which the VE becomes the dominant reality," P- "the extent to which the VE is remembered as a place," CF – Control Factors (ease to navigate, move near objects and avoid collisions), OE =Overall Enjoyment, N - Nausea, TPS- Total Presence Score.



**Figure 4.32: Comparison of Presence in VE 2**

**4.7.3.8 Spatial Knowledge:** The spatial knowledge of the supermarket while traveling in VE2 using different locomotion techniques was measured using five sets of questions (such as placement of an object, advertisements on the boards, etc.) for each technique. The results of the Friedman test showed a statistically significant effect of locomotion gesture for spatial knowledge ( $\chi^2 = 34.94$ ,  $p < 0.001$ ,  $W = 0.58$ ). A pairwise comparison showed a significant difference in spatial knowledge while using the *pointing* and *tapping* gestures ( $p < 0.001$ ,  $r = 0.4$ ). There was also a significant difference in spatial knowledge while using the *pointing* and *teleportation* gestures ( $p < 0.001$ ,  $r = 0.5$ ). It was found that the pointing gesture had better spatial knowledge than tapping and teleportation gestures in VE2. No significant difference was found in the user's spatial knowledge when traveling using the *tapping* and *teleportation* gestures. When users used the *pointing* gesture, 85% of users came up with the right layout of the supermarket. For the *tapping* gesture, 60% of the users came up with the right layout, and 55% came up with the right layout of the supermarket for the *teleportation* gesture.



**Figure 4.33: Comparison of Spatial Knowledge in VE 2**

**4.7.3.9 User Preference:** When participants were asked for an overall ranking of the locomotion technique suitable for the VE2, the *pointing* gesture was ranked first (25 out of 30 participants), the *teleportation* gesture was ranked second (3 out of 30 participants), and the *tapping* gesture as third preferred gesture where only two users preferred the gesture. Participants also expressed preferences for individual aspects such as navigation, searching for items in the supermarket, moving closer to the items to grab them, avoiding collisions, comfort, and ease of use. The responses are displayed in Table 4.5 below. The pointing gesture was most preferred gesture for moving in the VE, for looking for items in the supermarket, for comfort and effortlessness and for moving near the items when compared to the tapping and the teleportation gestures.

**Table 4.7: User Preference for VE2**

User Preferences	Deictic Pointing	Tapping	Teleportation
Moving in VE	26	1	3
Looking for items	24	4	2
Moving near the item	26	1	3
Comfort	27	1	2
Effortlessness	27	1	2

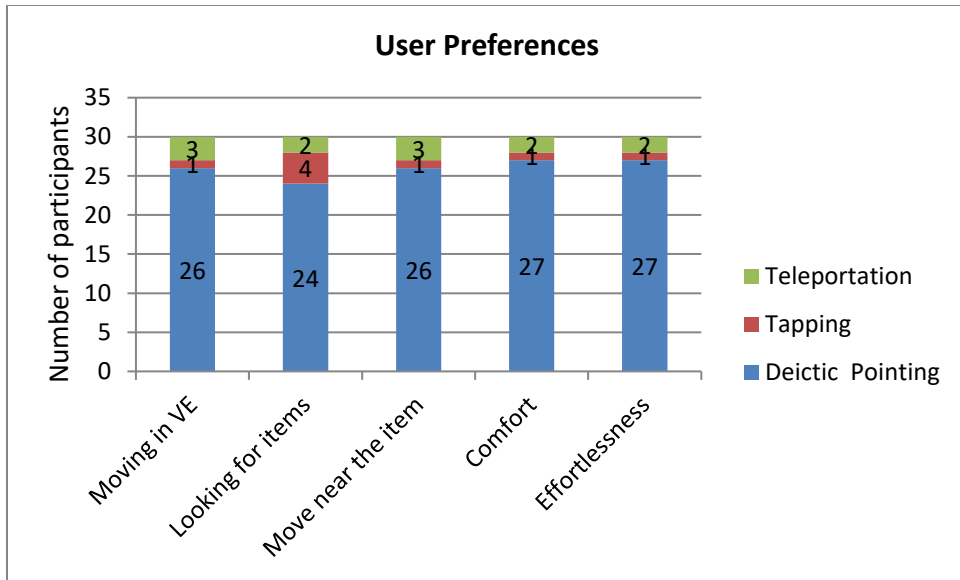


Figure 4.34: Comparison of User Preference in VE 2

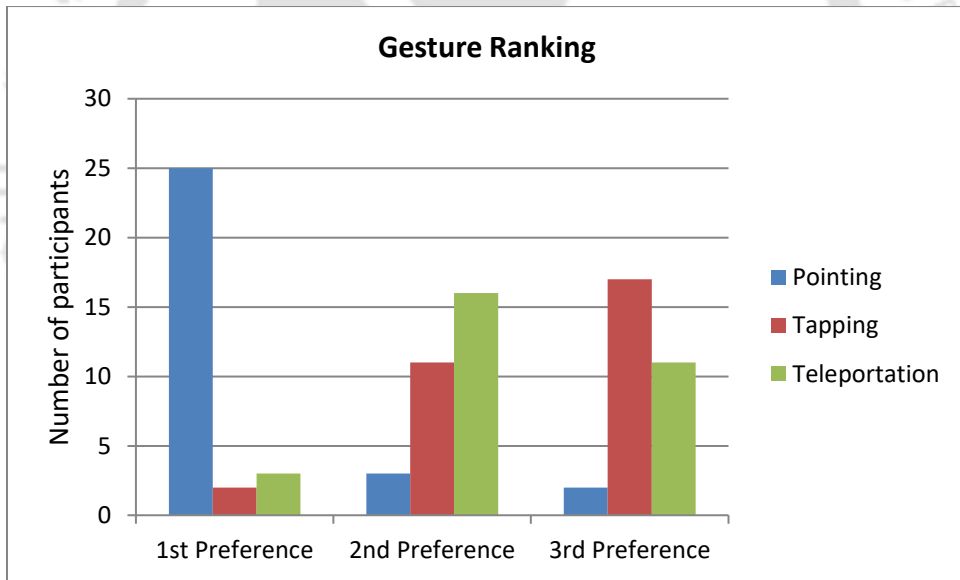


Figure 4.35: Gesture Ranking in VE 2

**Table 4.8: Pairwise p-values for task completion time and collision for locomotion gestures in VE2 (\*= $p < 0.05$ )**

Measures	Pointing - Tapping	Tapping- Teleportation	Pointing - Teleportation
Straight Line Travel Time	<0.001*	<0.001*	0.063
Directed Line Travel Time	<0.001*	0.919	<0.001*
Directed Collision	<0.001*	<0.001*	0.001*
Undirected Line Travel Time	<0.001*	0.025*	0.001*
Undirected Collision	<0.001*	<0.001*	0.321

**Table 4.9: Results of the Wilcoxon signed-ranks test in pairs between locomotion gestures in VE2 (\*= $p < 0.016$ )**

Measures	Pointing - Tapping	Tapping- Teleportation	Pointing - Teleportation
Intuitiveness	<0.001*	0.047	<0.001*
Comfort	<0.001*	0.422	0.001*
Ease Of Use	<0.001*	0.134	<0.001*
Perceived Workload	Physical Demand	<0.001*	0.178
	Mental Demand	<0.001*	0.225
	Temporal Demand	0.001*	0.061
	Performance	<0.001*	0.944
	Effort	<0.001*	0.088
	Frustration	<0.001*	0.115
	Total Score	<0.001*	0.019
SSQ	Nausea	0.034	0.011*
	Oculomotor	0.001*	0.029
	Disorientation	0.006*	0.077
	Total Score	0.001*	0.014*
Presence	0.001*	0.453	0.001*
Spatial Knowledge	<0.001*	0.04	<0.001*

#### 4.7.4 Discussion for VE2

**4.7.4.1 Intuitiveness:** The *pointing* gesture was significantly more intuitive than the *tapping* and *teleportation* gestures. The user experiences continuous locomotion with the *pointing* gesture; therefore, they can enjoy the process of the journey while navigating. One participant commented that "*Pointing gesture felt more natural as it was like a continuous walk. It was easy to adjust with the racks, whereas in others, it was either too far or too close.*"

**4.7.4.2 Load/Effort:** The *pointing* gesture was found to have significantly lesser effort than the *tapping* and *teleportation* method. The *pointing* had significantly less physical demand, less mental demand, less effort, and less frustration than *tapping* and *teleportation*. Similar to VE1, as the *tapping* gesture allowed

the user to move a constant distance for every tap, users felt it difficult to perform the *tapping* gesture repetitively to traverse a large VE. One participant commented, "*I feel difficult to keep tapping to reach my destination though the target object is visible to me. But with pointing, I have a smooth journey without much effort.*"

**4.7.4.3 Ease of use and Comfort:** The *pointing* gesture was found to have significantly higher ease of use and comfort than the *tapping* and *teleportation* gestures. One participant commented, "*The pointing gesture felt very comfortable to hold the hand and was easy even to go for long distance. Once the hand is removed, the locomotion stopped immediately as there was no delay.*"

#### **4.7.4.4 Task Completion Time**

##### **Task #1 – Straight Line Path Travel**

a) **Task Completion Time:** The *pointing* gesture and the *teleportation* were found to have significantly less task completion time than the *tapping* gesture. In this task, the users mostly traveled at running speed using the *pointing* gesture. Similarly, for the *teleportation* gesture, the users took longer jumps to reach the destination. Hence these two gestures had lesser task completion time.

##### **Task #2 – Directed Path Travel**

a) **Task Completion Time:** The *pointing* gesture had significantly less task completion time than the *tapping* and *teleportation* gestures. There was no significance found between the *tapping* and *teleportation* gesture. Since the path was directed, the users were able to control the movement speed. They used running speed when traveling straight paths and switched to walking speeds during the turns.

b) **Collisions/Accuracy:** The *pointing* gesture had significantly less number of collisions than the *tapping* and *teleportation* gestures. The *teleportation* gesture had significantly less number of collisions than the *tapping* gesture. The *pointing* gesture had high accuracy as continuous adjustments in the distance were possible during the locomotion. One of the users commented, "*I was able to move a very short distance with the pointing gesture, which helped me to grab the target objects without colliding with the shelf.*" For the *tapping* gesture, the users could not maintain a relative distance from the shelves while grabbing objects, which also led to the maximum number of collisions compared to the other two gestures. One user commented, "*I felt it tiresome to keep tapping for longer periods of time, and it was difficult to maintain the right distance from the shelf.*" Since the *teleportation* gesture had higher short-distance accuracy, the number of collisions was significantly less than the *tapping* gesture.

### Task #3– Undirected Path Travel

a) **Task Completion Time:** The *pointing* gesture had significantly less task completion time than the *tapping* and *teleportation* gestures. The *teleportation* gesture had significantly less task completion time than the *tapping* gesture. The continuous optic flow feedback with the *pointing* gesture helped the user to identify the glowing object more easily. This was similar to the results that Riecke et al., (2021) stated for continuous travel in the VE. The continuous self-motion cues also helped in path integration and spatial orientation. This helped in the user's spatial updating, which is known to have a low cognitive load. This finding is similar to Zanbaka et al., (2005), where four methods of travel and their effect on cognition and paths taken were compared for IVE. This was also observed when the users had minimal revisits to the locations with the *pointing* gesture. The *pointing* gesture can be used in situations where the users want to move longer distances without high effort and also have a continuous view of the environment. For the *teleportation* gesture, when the destination was not known, the users had to jump shorter distances to avoid any misses in locating the objects. This increased the completion time as people also had to reorient themselves before the next jump.

b) **Collisions/Accuracy:** The *pointing* and *teleportation* gesture had significantly less number of collisions than the *tapping* gesture. Since the *pointing* and the *teleportation* gesture were able to move a shorter distance, this avoided the collision with the shelves as compared to the *tapping* gesture.

**4.7.4.5 Presence:** The results also show that the *pointing* gesture has a significantly better presence when compared to the *tapping* and *teleportation* gestures. This increase in presence is because of the continuous locomotion using the *pointing* gesture. This helps in continuous knowledge acquisition that helps to build the cognitive map of the supermarket. One participant commented, "*With the pointing gesture, because of the continuous movement, I feel like I am moving and interacting in a real supermarket.*" In the *teleportation* gesture, since the user has to reorient them after every jump, it negatively affects the mental spatial representation and its continuity. This was also reported by Riecke et al., (2021), where discontinuous travel like *teleportation* provided multiple breaks in presence, which negatively affected the mental spatial representation.

**4.7.4.6 Control of Locomotion:** While using *pointing* gestures when the user wants to have a conscious effort in navigation in turns and narrow paths, they prefer to travel at a lesser speed to control the movement, similar to Caggianese et al., (2020) which compared controller-based navigation with free hand locomotion technique and required the user to travel paths with different widths. One user commented, "*For the pointing gesture though I was traveling at running speed, I need to reduce the speed in the turns in order to avoid collisions with the shelves.*" With *tapping* gestures controlling the

locomotion was difficult as it had a constant step length. With *teleportation*, the users could easily control their movement to large and small distances.

**4.7.4.7 Motion Sickness:** The *pointing* gesture was found to have significantly less motion sickness than the *tapping* gesture. Users felt less motion sickness, especially with the oculomotor group for the *pointing* gesture. The lack of self-motion cues in *teleportation* led to the lack of any dynamic sensory cue conflict, which reduced motion sickness. These findings were similar to the results of Bonato et al., (2009), where a user study was conducted to analyze cybersickness on stationary participants who perceived visually induced illusions of self-motion. It was found that an increased magnitude of sensory conflict would subsequently result in a higher degree of cybersickness. Since *teleportation* lacks self-motion cues, it has reduced immersion in the VE, as seen in the other user studies conducted by Bakker et al. (2003), Bhandari et al., (2017), and Sarupuri et al., (2017). One user commented, "*It is easy to travel the whole supermarket in less time. But I am unable to get the layout of the supermarket.*"

**4.7.4.8 Spatial Knowledge:** There was a significant difference in the spatial knowledge acquired while traveling using the *deictic pointing* gesture in VE2. Since the *deictic pointing* gesture performed continuous movement for the user, it had better cognitive-map building capability when compared to the *tapping* and the *teleportation* gesture. Most users could also sketch the supermarket layout more accurately after using this locomotion technique.

**4.7.4.9 User Preference:** For VE2, the *pointing* gesture was the most preferred technique (25 of 30 participants) for movement in the supermarket. It was the preferred technique for looking for items (24 of 30 participants) in the supermarket. Only 2 of 30 participants preferred the *tapping*, and 3 of 30 participants preferred the *teleportation* gesture.

Although the users thought the pointing gesture was appropriate for travel, four of the thirty participants had issues with the pointing gesture's running speed. Another difficulty while using the *pointing* gesture was that users had to consciously keep their index finger within the FOV of the HMD. This was similar to the findings of Caggianese et al., (2020) usability evaluation of free hand gestures, which revealed difficulty in managing the hand position with respect to the FOV.

In summary, *deictic pointing* gesture interaction was found to be intuitive, less tiring, and more precise in VE2. This gesture enabled users to travel even short distances, allowing them to precisely control their position in VE. As a result, applications that require accuracy in travel and are time-constrained can benefit from using *pointing* gestures for travel. Users will also acquire better spatial knowledge of the environment using this technique. *Teleportation* can be used in applications requiring the user to travel

longer distances in less time. The *teleportation* gesture can be used in places where the immersion of the users is not the key goal, as the users had breaks in presence due to continuous spatial context switching.

## 4.8 Study 5: Comparison of Mirror Leaning, Tapping, and Teleportation gestures for VE3

**4.8.1 Participants:** Thirty students (13 females) between 21-35 years old ( $M = 26.2$ ;  $SD = 3.87$ ) participated in Study 5. Six participants (20%) had corrected eyesight (contact lenses or glasses), 21 of them (70%) played 3D first-person view video games on a daily or weekly basis, nine of them (30%) had no prior experiences with HMDs, and none of them had a motor disability and prior experience with any of our locomotion techniques.

**4.8.2 Experimental Design:** We used a within-subject design, where each participant completed three training sessions (one for each locomotion technique) and nine main trials, consisting of a factorial combination of three locomotion techniques {*Mirror Leaning* gesture Vs *Tapping* gesture Vs *Teleportation*} X three tasks {Task#1, Task#2, Task#3}. We counterbalanced the order of interface conditions across participants. Participants performed the three tasks in the same order, blocked by the interface. The virtual environment used for the task was VE3. The above experiment procedure was followed. Figure 4.34 shows the three gestures (a) the Leaning Gesture, (b) the Tapping Gesture, and (c) the Teleportation Gesture used in VE3.

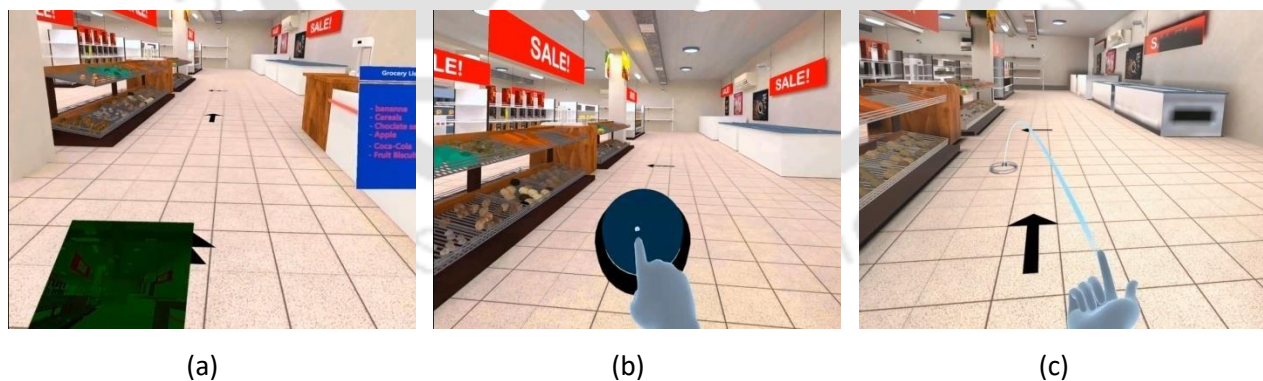


Figure 4.36: Gesture Comparison in VE3 (a) Leaning Gesture (b) Tapping gesture (c) Teleportation Gesture

**4.8.3 Statistical analysis:** The task completion time and the collision data was found to be normally distributed using Shapiro–Wilk test. The data were analyzed with SPSS using one-way ANOVA. The statistical significance level was set to  $\alpha = 0.05$ . A Tukey's post hoc test was used to determine the significance when a pairwise comparison was carried out. For intuitiveness, comfort, ease of use,

simulation sickness, perceived workload, presence and spatial knowledge the normality was checked using Shapiro–Wilk tests. The results showed that the data were not normally distributed. Therefore, Friedman tests and Wilcoxon signed-rank tests were used for statistical analyses. A Bonferroni corrected p-value of  $0.05/3 = 0.016$  was used as the significance threshold.

**4.8.3.1 Task Performance:** Similar to the previous study, task performance is measured by the total time (speed) and accuracy (collisions) with which the user completes the task.

**Task #1 - Task completion time:** For Task#1, the task performance was measured only with the completion time of the travel from point A to point B. The data was found to be normally distributed with the overall mean and SD ( $M=31.67$ ,  $SD=10.02$ ). The results of movement in a straight line path were found to be ( $F(2, 90) = 147.80$ ,  $p < 0.01$ ). A post hoc analysis showed that there was a significant difference in movement between the *mirror-leaning* gesture and the *tapping* gesture ( $p < 0.01$ ). There was a significant difference in movement between the *tapping* gesture and *teleportation* ( $p < 0.01$ ).

**Task #2 - Task completion time and collision:** For Task#2, the task performance was measured with the completion time of the task along with the number of collisions. The data was found to be normally distributed with the overall mean and SD of total time completion ( $M=151.13$ ,  $SD=40.42$ ). The results completion time was found to be ( $F(2, 90) = 24.405$ ,  $p < 0.01$ ). A post hoc analysis showed that there was a significant difference in movement between the *mirror-leaning* gesture ( $p < 0.01$ ) and *tapping*. There was also a significant difference between the *mirror-leaning* gesture ( $p < 0.01$ ) and *teleportation*. There was no significant difference in task completion time between the *tapping* and the *teleportation* gesture. The data for the collision was found to be normally distributed with the overall mean and SD of total time completion ( $M=8.48$ ,  $SD = 4.03$ ). The collision results were found to be ( $F(2, 90) = 99.18$ ,  $p < 0.01$ ). A post hoc analysis showed that the *mirror leaning* technique had significantly less number of collisions than the *tapping* gesture ( $p < 0.01$ ). There was a significant difference in the collision between the *teleportation* and the *tapping* gesture ( $p < 0.01$ ). There was no significant difference in the collision between the *mirror leaning* and the *teleportation* gesture.

**Task #3 - Task completion time and collision:** For Task#3, the task performance was measured with the completion time of the task along with the number of collisions. The data was found to be normally distributed with the overall mean and SD of total time completion ( $M=169.23$ ,  $SD=31.55$ ). The results completion time was found to be ( $F(2, 90) = 12.73$ ,  $p < 0.01$ ). A post hoc analysis showed that the *mirror leaning* gesture took significantly lesser time completion when compared to the *tapping* ( $p < 0.01$ ) and *teleportation* technique ( $p=0.035$ ). The *teleportation* technique took lesser time completion when

compared to the *tapping* ( $p=0.036$ ). The data for the collision was found to be normally distributed with the overall mean and SD of total time completion ( $M=9.69$ ,  $SD = 3.88$ ). The results were ( $F(2, 90) = 113.35$ ,  $p < 0.01$ ). The *mirror-leaning* gesture had significantly lesser collisions than the *tapping* gesture ( $p < 0.01$ ) and the *teleportation* gesture ( $p < 0.01$ ). The *teleportation* gesture had significantly lesser collisions than the *tapping* gesture ( $p < 0.01$ ).

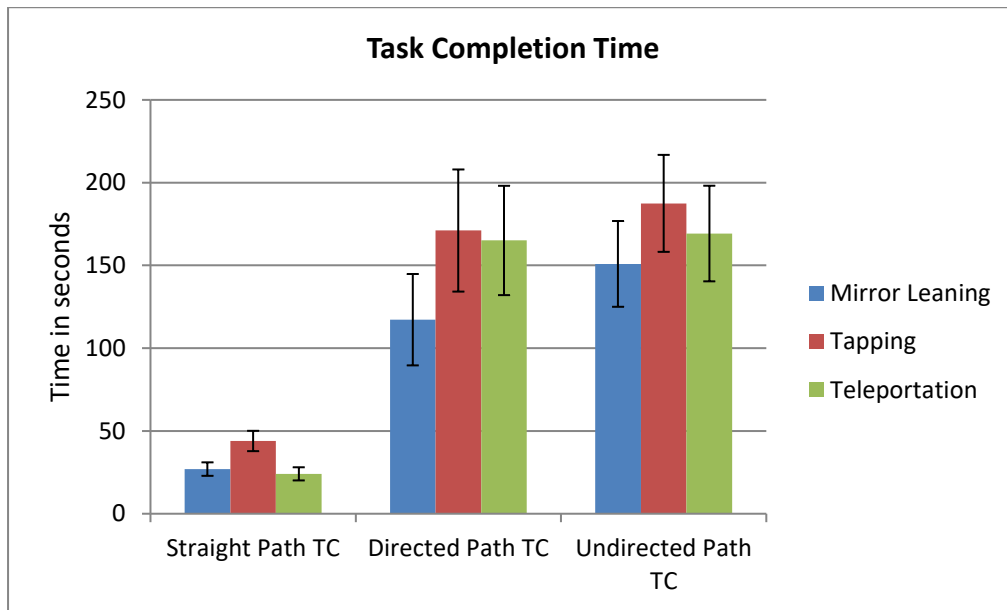


Figure 4.37: Task Completion Time in VE 3

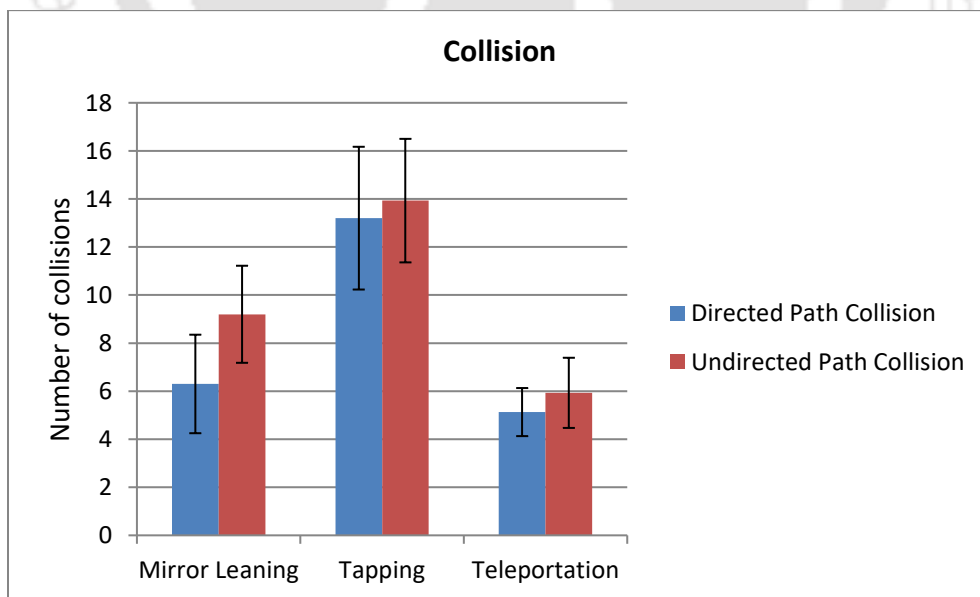


Figure 4.38: Collision using gestures in VE 3

**4.8.3.2 Intuitiveness:** For intuitiveness, the Friedman test showed a statistically significant effect of locomotion gesture ( $\chi^2= 29.31$ ,  $p < 0.001$ ,  $W = 0.48$ ). The results of pairwise comparisons showed that the leaning gesture was more intuitive than the tapping gesture ( $p < 0.001$ ,  $r=0.38$ ). It was also found that the leaning gesture was more intuitive than the teleportation gesture ( $p < 0.001$ ,  $r= 0.4$ ). There was no statistical significant difference in intuitiveness between tapping and leaning gesture.

**4.8.3.3 Comfort:** Analysis showed that there was no significant difference in the comfort measure between the locomotion techniques ( $\chi^2= 1.62$ ,  $p = 0.44$ ,  $W = 0.027$ ).

**4.8.3.4 Ease of use:** The results of the Friedman test showed a statistically significant effect of locomotion gesture for ease of use ( $\chi^2 = 16.84$ ,  $p < 0.01$ ,  $W = 0.28$ ). The results of pairwise comparisons showed that the *mirror leaning* gesture had significantly better ease of use than the *tapping* gesture ( $p=0.001$ ,  $r=0.36$ ) and the *teleportation* gesture ( $p=0.004$ ,  $r=0.3$ ). There was no significant difference between *tapping* and *teleportation* gestures.

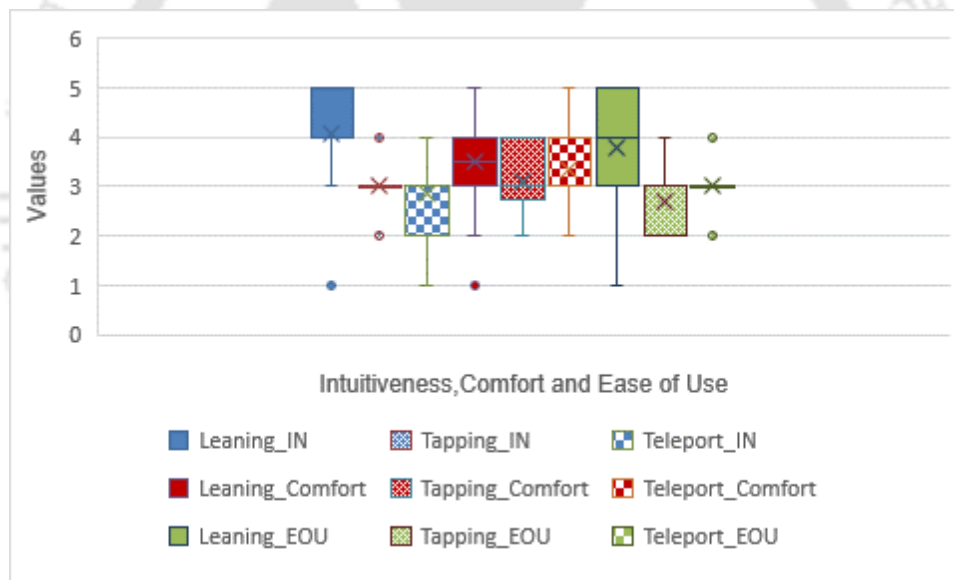


Figure 4.39: Intuitiveness, Comfort, and Ease of Use for gestures in VE 3

**4.8.3.5 Perceived Workload:** The results of the Friedman test showed a statistically significant effect of locomotion gesture for mental demand ( $\chi^2 = 11.78$ ,  $p = 0.003$ ,  $W = 0.196$ ). A pairwise analysis showed that the *mirror leaning* gesture had significantly less mental demand when compared to the *tapping* gesture ( $p < 0.001$ ,  $r= 0.42$ ) and *teleportation* ( $p=0.010$ ,  $r=0.27$ ). The analysis for the physical demand was found to be ( $\chi^2 = 12.50$ ,  $p = 0.002$ ,  $W = 0.208$ ). A pairwise analysis showed that *mirror-leaning* gestures had significantly lesser physical demand when compared to *tapping* ( $p=0.002$   $r=0.3$ ) and *teleportation* ( $p=0.008$ ,  $r=0.3$ ). The analysis for the temporal demand was found to be ( $\chi^2 = 5.87$ ,  $p = 0.053$ ,  $W =$

0.098). There was significantly less temporal demand for the *mirror-leaning* gesture when compared to the *tapping* gesture ( $p=0.011$ ,  $r=0.26$ ). The analysis for the performance scores was found to be ( $\chi^2 = 15.14$ ,  $p = 0.001$ ,  $W = 0.25$ ). The *mirror leaning* gesture was found to be performing better than the *tapping* ( $p=0.001$ ,  $r=0.34$ ) and the *teleportation* gesture ( $p=0.001$ ,  $r=0.36$ ). For the effort scores ( $\chi^2 = 9.32$ ,  $p = 0.009$ ,  $W = 0.155$ ), the *mirror leaning* gesture was found to be having significantly lesser effort than the *tapping* gesture ( $p=0.002$ ,  $r=0.32$ ) and *teleportation* gesture ( $p=0.005$ ,  $r=0.3$ ). For the frustration scores ( $\chi^2 = 6.46$ ,  $p = 0.04$ ,  $W = 0.108$ ), the *mirror leaning* gesture was found to be having significantly lesser frustration than the *tapping* gesture ( $p=0.002$ ,  $r=0.32$ ). There was a significant difference in the Mean Weighted Workload ( $\chi^2 = 13.40$ ,  $p = 0.001$ ,  $W = 0.223$ ) between the techniques. The *Mirror Leaning* gesture was found to have significantly less MWWL when compared to the *tapping* gesture ( $p<0.001$ ,  $r = 0.43$ ) and *teleportation* gesture ( $p=0.002$ ,  $r=0.32$ ).

**Table 4.10: Descriptive Statistics of NASA-TLX dimensions scale (0=Low to 100=High)**

Workload Type	N	Calling Gesture		Tapping Gesture		Teleportation Gesture	
		Mean	SD	Mean	SD	Mean	SD
Mental Demand	30	47.17	22.04	65.67	15.07	60.50	20.14
Physical Demand	30	48.00	17.79	66.83	17.44	61.00	16.99
Temporal Demand	30	46.33	19.47	60.17	15.84	57.67	19.06
Performance	30	38.00	13.49	56.00	18.02	51.50	17.48
Effort	30	44.83	17.64	62.09	19.46	57.17	18.79
Frustration	30	34.00	18.86	50.50	19.49	45.00	21.88
MWWL	30	43.01	14.00	60.52	12.54	55.62	15.73



**Figure 4.40: Comparison of Perceived Workload in VE 3**

**4.8.3.6 Simulation Sickness:** The results of the Friedman test showed a statistically significant effect of locomotion gesture for simulation sickness ( $\chi^2 = 5.58$ ,  $p = 0.049$ ,  $W = 0.093$ ). A significant difference was found in the total score of SSQ between the *mirror-leaning* gesture and the *tapping* gesture ( $p = 0.004$ ,  $r = 0.3$ ). There was no significant difference found in nausea ( $\chi^2 = 3.38$ ,  $p = 0.184$ ,  $W = 0.056$ ). There was statistically significant difference in the disorientation between the techniques ( $\chi^2 = 3.38$ ,  $p = 0.184$ ,  $W = 0.056$ ). A pairwise comparison showed that the mirror leaning gesture had lesser disorientation than the tapping gesture ( $p = 0.002$ ,  $r = 0.32$ ). There was statistically significant difference in the oculomotor variable ( $\chi^2 = 5.08$ ,  $p = 0.081$ ,  $W = 0.084$ ) between the locomotion techniques. The pairwise comparison showed that there was significant difference between the mirror leaning gesture and tapping gesture ( $p = 0.011$ ,  $r = 0.26$ ).

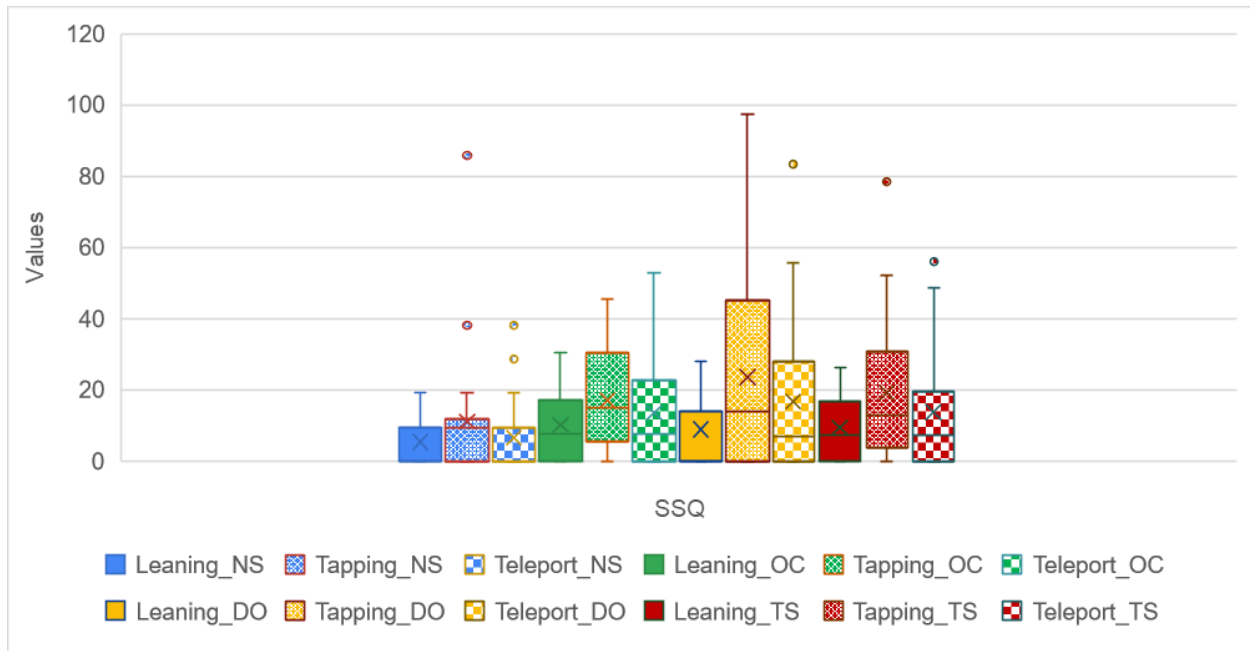
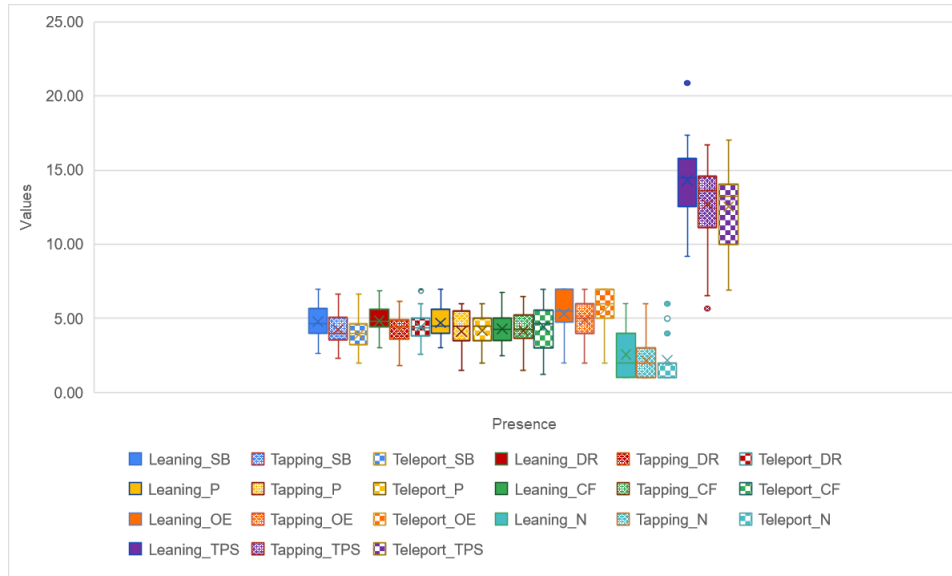


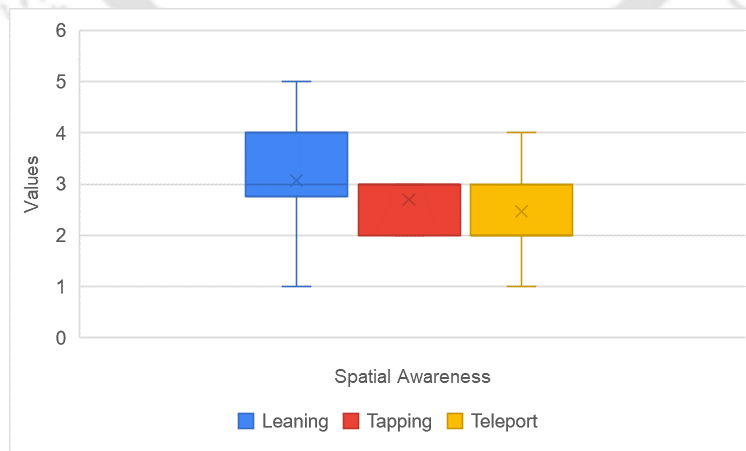
Figure 4.41: Comparison of Simulation Sickness in VE 3

**4.8.3.7 Presence:** The results of the Friedman test showed a statistically significant effect of locomotion gesture for presence ( $\chi^2 = 9.86$ ,  $p = 0.007$ ,  $W = 0.164$ ). A pairwise comparison showed that the *mirror leaning* gesture had a significantly higher presence than the *tapping* gesture ( $p=0.005$ ,  $r=0.3$ ) and the *teleportation* gesture ( $p=0.001$ ,  $r=0.35$ ). There was no significant difference in the presence between the *tapping* and the *teleportation* gesture. The questions were grouped under the following categories - SB stands for "Sense of being in Supermarket," DR – "the extent to which the VE becomes the dominant reality," P- "the extent to which the VE is remembered as a place," CF – Control Factors (ease to navigate, move near objects and avoid collisions), OE =Overall Enjoyment, N - Nausea, TS- Total Presence Score.



**Figure 4.42: Comparison of Presence in VE 3**

**4.8.3.8 Spatial Knowledge:** The spatial knowledge of the supermarket while traveling in VE3 using different locomotion techniques was measured using five sets of questions (such as placement of an object, advertisements on the boards, etc.) for each technique. The results of the Friedman test showed a statistically significant effect of locomotion gesture for spatial knowledge ( $\chi^2 = 9.3$ ,  $p = 0.01$ ,  $W = 0.155$ ). A pairwise analysis showed a significant difference in spatial knowledge while using the *mirror leaning* and *teleportation* gestures ( $p=0.008$ ,  $r=0.28$ ). There was no significant difference in spatial knowledge between the other gestures. When users used the *mirror leaning* gesture, 68% of users came up with the right supermarket layout. For the *tapping* gesture, 53% of the users came up with the right layout, and 51% came up with the right layout of the supermarket for the *teleportation* gesture.

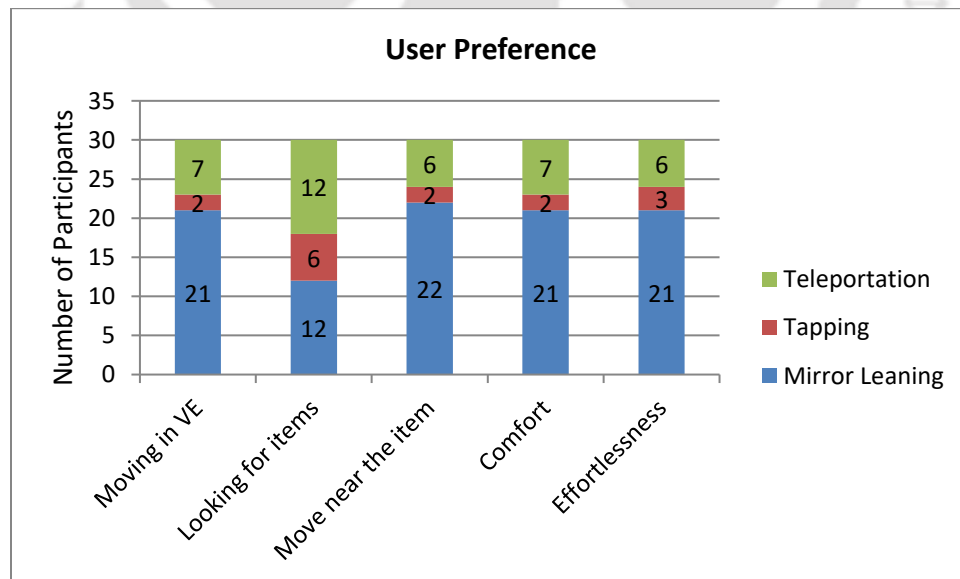


**Figure 4.43: Comparison of Spatial Knowledge in VE 3**

**4.8.3.9 User Preference:** When participants were asked for an overall ranking of the locomotion technique suitable for the VE3, the *mirror leaning* gesture was ranked first (19 out of 30 participants), the *teleportation* gesture was ranked second (9 out of 30 participants), and the *tapping* gesture as third preferred gesture (2 out of 30). Participants also expressed preferences for individual aspects such as navigation, searching for items in the supermarket, moving closer to the items to grab them, avoiding collisions, comfort, and ease of use. The responses are displayed in Table 4.7 below. The mirror leaning gesture was the most preferred gesture for moving in the VE with comfort and effortless travel. The teleportation gesture and the mirror leaning gesture were preferred for looking for items in the supermarket. The mirror leaning gesture was preferred gesture to move near the items in the supermarket.

**Table 4.11: User Preference for VE3**

User Preferences	Deictic Pointing	Tapping	Teleportation
Moving in VE	21	2	7
Looking for items	12	6	12
Moving near the item	22	2	6
Comfort	21	2	7
Effortlessness	21	3	6



**Figure 4.44: Comparison of User Preference in VE 3**

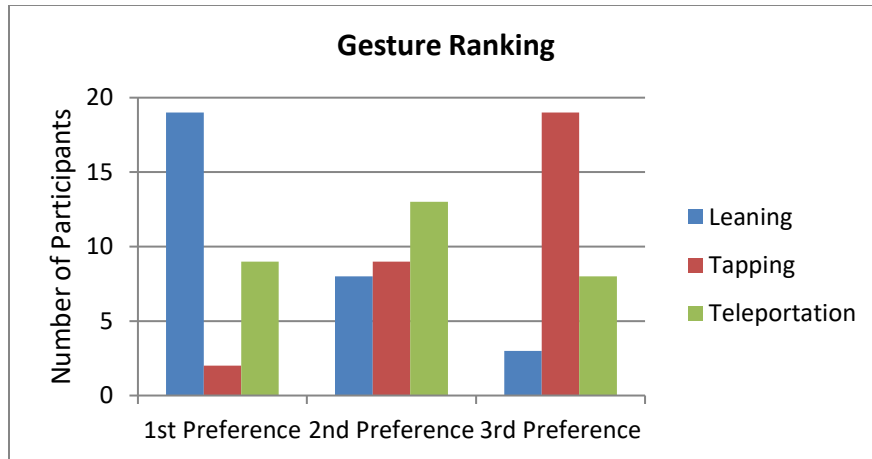


Figure 4.45: Gesture Ranking in VE 3

Table 4.12: Pairwise p-values for task completion time and collision for locomotion gestures in VE3 (\*= $p < 0.05$ )

Measures	Leaning - Tapping	Tapping- Teleportation	Leaning - Teleportation
Straight Line Travel Time	<0.001*	0.06	<0.001
Directed Line Travel Time	<0.001*	0.758	<0.001*
Directed Collision	<0.001*	<0.001*	0.804
Undirected Line Travel Time	<0.001*	0.036*	0.035*
Undirected Collision	<0.001*	<0.001*	<0.001*

Table 4.13: Results of the Wilcoxon signed-ranks test in pairs between locomotion gestures in VE3 (\*= $p < 0.016$ )

Measures	Leaning - Tapping	Tapping- Teleportation	Leaning - Teleportation	
Intuitiveness	<0.001*	0.29	<0.001*	
Comfort	0.122	0.273	0.604	
Ease Of Use	0.001*	0.029	0.004*	
Perceived Workload	Physical Demand	0.002*	0.183	0.008*
	Mental Demand	<0.001*	0.185	0.01*
	Temporal Demand	0.011*	0.648	0.022
	Performance	0.001*	0.405	0.001*
	Effort	0.002*	0.339	0.005*
	Frustration	0.002*	0.305	0.024
	Total Score	<0.001*	0.199	0.002*
SSQ	Nausea	0.035	0.07	0.49
	Oculomotor	0.011*	0.106	0.228
	Disorientation	0.002*	0.055	0.035
	Total Score	0.004*	0.054	0.255
Presence	0.005*	0.614	0.001*	
Spatial Knowledge	0.062	0.165	0.008*	

## 4.8.4 Discussion for VE3

**4.8.4.1 Intuitiveness:** The *mirror-leaning* gesture was found to be significantly more intuitive than the *tapping* and *teleportation* gestures for VE3. The *mirror-leaning* gesture had a continuous optic flow and also induced stronger self-motion cues. It also provided increased vection for locomotion. The gesture can be used for many applications like driving and flight simulations where motion cueing is of high requirement. One participant also commented, "*With mirror-leaning gesture, as I lean, I feel I am really moving in a VE, but with the teleportation gesture, I am unable to feel a natural movement.*" In the *teleportation* gesture, since the proprioceptive cues generated during the movement are minimal, this reduced the sense of embodiment, naturalism, and engagement of the gesture, which was similar to the findings reported by Riecke et al., (2021).

**4.8.4.2 Load/Effort:** The *mirror-leaning* gesture had significantly less load than the *tapping* and *teleportation* gestures. The increased embodiment of the *mirror-leaning* gesture indeed helped in the reduction of the cognitive load. The *mirror-leaning* gesture performed significantly better in physical demand, mental demand, temporal demand, performance, and effort when compared to the *tapping* and *teleportation* gestures. This was similar to the findings of Nguyen et al., (2019), where it was found that translational cues and control had significant effects on various measures, including task performance and task load. The *mirror-leaning* gesture freed up users' hands, which allowed them to move more naturally and use their hands for multitasking interaction. One participant commented, "*In the mirror-leaning gesture, both hands were useful for interaction, and my upper body was useful for locomotion. I felt very engaged during the travel.*"

**4.8.4.3 Ease of use:** The *mirror-leaning* gesture had significantly higher ease of use than the *tapping* and *teleportation* gestures. Since the *leaning* was performed using torso-based movement, the hands of the users were free to perform other tasks in a multitasking environment.

**4.8.4.4 Comfort:** There was no significant difference in comfort between the gestures. This finding was different from the reporting of Buttussi et al., 2021 where in terms of general comfort, the *teleportation* gesture was found to be significantly more comfortable than the *mirror-leaning* gesture. However, in this study, the comparison was between *joystick*, *teleportation*, and *leaning* and the task involved only directed path movement.

#### 4.8.4.5 Task Completion Time

##### Task #1 – Straight Line Path Travel

a) **Task Completion Time:** The *mirror-leaning* and *teleportation* gestures performed significantly faster than the *tapping* gesture for the straight-line task. In the *mirror-leaning* gesture, it was observed that the users traveled at running speed to reach the destination. Similarly, in *teleportation*, the user takes longer jumps to reach the destination.

##### Task #2 – Directed Path Travel

a) **Task Completion Time:** The *mirror-leaning* gesture had significantly less task completion time than the *tapping* and *teleportation* gestures. There was no significance found between the *tapping* and *teleportation* gesture. Since the path was directed toward the *mirror-leaning* gesture, the users were able to control the movement speed. They used running speed when traveling straight paths and switched to walking speeds during the turns. This helped them to complete the task faster than the *teleportation* and *tapping* gestures.

b) **Collisions/Accuracy:** It was observed that the *mirror-leaning* was not accurate for a very minute short distance travel, as in moving a few millimeters near the shelf. This finding was similar to Kitson et al., (2017), in which the *leaning* using navichair was compared with the joystick. It was found that though participants felt more immersive with leaning, they reported better control and accuracy with the joystick. Unintentional *leaning*, such as bending slightly to reach an object caused several unexpected collisions with the shelves while grabbing the objects. However, the *mirror-leaning* gesture and the *teleportation* gesture performed significantly lesser collisions than the *tapping* gesture in the directed path.

##### Task #3– Undirected Path Travel

a) **Task Completion Time:** The *mirror-leaning* gesture was found to have significantly lesser task completion time than the *teleportation* and *tapping* gestures. The *teleportation* gesture had significantly less task completion time than the *tapping* gesture. For the *mirror-leaning* gesture, the users felt that the mirror view for *leaning* was very helpful for looking at the objects in the upper VE shelves and for stopping when the user identified a glowing object, especially in the undirected path travel. One participant commented, "*The mirror view was very helpful, especially for the undirected path travel, as I was constantly looking for a glowing object in the small window.*" We observed that the visual effect of

objects glowing was also one of the contributing factors for the users to reach their destinations while traveling using the leaning gesture. It was observed that the users used running speed during straight-line paths and walking speed during turns and corners. One user commented that "*I reduced my speed during the turns as I was afraid that I might collide with the shelves.*" This illustrates that when the object is in a straight line path, users are confident to move at running speed to reach the destination, thereby reducing the completion time. The *tapping* gesture was found to be difficult to use with both hands used in multitasking. It took longer time for task completion as people traveled at a constant speed and were not comfortable to use during multitasking. Users faced difficulty during looking for items with their hands occupied and were also affected by the path integration while reaching the targets in the undirected path travel. Similarly, it was difficult to perform the *teleportation* gesture with the hands occupied. One participant commented, "*Though I am able to travel a longer distance in a single jump, it was very difficult to perform the teleportation gesture when both my hands are occupied.*" Users felt the gesture could be used when the level of multitasking is less.

**b) Collisions/Accuracy:** The *mirror-leaning* and the *teleportation* gesture performed with significantly lesser collisions than the *tapping* gesture in the undirected path.

**4.8.4.6 Presence:** The results also show that the *mirror-leaning* gesture has significantly better presence when compared to the *tapping* and *teleportation* gestures. This increase in presence is because of thevection and continuous locomotion using the *mirror-leaning* gesture. Similar to the *pointing* gesture in VE2, this continuous movement helped in continuous knowledge acquisition to build the cognitive map of the supermarket. One participant commented, "*With the mirrored feedback as I use leaning, I feel I am traveling in a real supermarket.*"

**4.8.4.7 Control of Locomotion:** The *mirror-leaning* gesture provided continuous locomotion in the VE. The user had better control of the movement using the *mirror-leaning* gesture (Hashemian et al. 2020). The visual effects showing a single arrow for walking speed and a double arrow for running speed were very helpful for the users to control the degree of leaning. This also helped in the process of reducing and increasing the speed of movement and also in the process of stopping. One participant commented, "*The mirror-leaning gesture has good visual cues to specify the speed, which helped me in controlling my leaning angle.*" The *mirror-leaning* gesture had the least latency issues, so the start and stop of the movement were instantaneous in correspondence to the *leaning* angle. Another participant commented, "*With leaning, I find there is no latency for starting and stopping the locomotion.*" With *tapping* and *teleportation* gestures, users felt difficulty in controlling the locomotion in VE3 when both hands are occupied.

**4.8.4.8 Motion Sickness:** The *mirror-leaning* gesture provided some vestibular cues during simulated accelerations, which reasonably helped reduce cybersickness due to the reduced inter-sensory cue conflict. In the seated VR scenario, the *mirror-leaning* gesture allowed physical rotation for direction change, which further reduced the cyber sickness. This result is similar to Farrell et al., (1998); Presson et al., (1994); Hashemian et al., (2021), where the direction change was by physical rotation, and the results were found that allowing full physical rotation may help in reducing motion sickness compared to limited rotation due to reducing the conflict between visual and vestibular cues. It was also quantitatively observed that the *leaning* gesture had significantly less motion sickness than the tapping gesture.

**4.8.4.9 Spatial Knowledge:** There was a significant difference in the spatial knowledge acquired while traveling using the *mirror-leaning* gesture in VE3. Since the *mirror-leaning* gesture also performed continuous movement for the user, similar to the *deictic pointing* gesture, it had better cognitive-map building capability when compared to the *teleportation* gesture. Most users found the mirror view display helpful in viewing the upper view of the supermarket while moving. This also helped them in sketching the layout of the supermarket.

**4.8.4.10 User Preference:** For VE3, the *leaning* gesture was the most preferred (19 of 30 participants). 9 of 30 users preferred the *teleportation* gesture, and two users preferred the *tapping* gesture. Twelve participants preferred *leaning*, and another twelve participants preferred *teleportation* for looking at items in the supermarket.

For VE3, the *mirror-leaning* gesture was the most suitable gesture for the given multitasking scenario. Though the gesture was preferred for moving around the VE, users felt that it would be inconvenient to traverse large VEs because leaning for longer periods would cause fatigue in the form of back pain and discomfort for the users. The mirror view was useful, but some users complained that it obscured the path or items in the directed path search, but this did not interfere with movement or the search task.

In summary, the *mirror-leaning* gestures could be used in environments where users must make decisions while traveling. As the cognitive load for performing the *leaning* gesture is very low compared to other gestures, it helps the user to perform other activities. It can be used in scenarios where the users have a lot of multitasking to be done with both hands, and the experience requires high presence and low motion sickness. However, the *teleportation* gesture can be used for large VEs that involve only travel without many interactions. It can be used in environments where presence is not an important goal and comfort, and ease of use is of utmost priority.

## 4.9 Synopsis of the User Studies

In summary, the below table gives an overview of all the five studies conducted in the course of research and their findings.

**Table 4.14: User Studies and their findings**

User Study	Objective	Participants	Findings
Study 1 – Investigating suitable body gestures for virtual travel	Gesture elicitation study was conducted to identify the most natural and intuitive gestures for travel while in a seated position for VE1, VE2 and VE3	40	<ul style="list-style-type: none"> <li>a) A set of user centric gestures for virtual travel when (i) both hands are free (ii) one hand is occupied in another interaction such as selection and manipulation (iii) both hands are occupied in selection and manipulation.</li> <li>b) Classification of the gesture set based on hand usage and gesture form.</li> </ul>
Study 2 - Evaluation of the top three proposed gestures for VE1, VE2, and VE3	Evaluated the three gestures for VE1, VE2 and VE3 based on four dimensions such as preference, appropriateness, ease of use and effort.	40	<ul style="list-style-type: none"> <li>a) The calling gesture was found to have lesser effort and better ease of use than the other gestures for VE1.</li> <li>b) The pointing gesture was found to be the most appropriate with less effort and better ease of use than the other gestures for VE2.</li> <li>c) The leaning gesture was found to be the most appropriate with lesser effort and better ease of use than the other gestures for VE3.</li> </ul>
Study 3 – Comparison of Calling, Tapping and Teleportation techniques	Evaluate the three techniques for three different search task for their task completion time, collisions, intuitiveness, comfort, ease of use, perceived workload, motion sickness, spatial knowledge, and presence	30	<ul style="list-style-type: none"> <li>a) The task completion time and collision for the teleportation gesture was less when compared to the other techniques.</li> <li>b) The calling technique performed better in undirected path travel as it used landmark navigation.</li> <li>c) Calling technique had better presence due to spatiotemporal continuity.</li> <li>d) The visual beam of calling</li> </ul>

User Study	Objective	Participants	Findings
			<p>technique helped in the locomotion control.</p> <p>e) The teleportation technique was the most preferred gesture for the virtual travel when both hands are free from any interaction.</p>
Study 4 – Comparison of Deictic Pointing, Tapping and Teleportation techniques	Evaluate the three techniques for three different search task for their task completion time, collisions, intuitiveness, comfort, ease of use, perceived workload, motion sickness, spatial knowledge, and presence	30	<p>a) The task completion time and collision for the deictic pointing gesture was less when compared to the other techniques.</p> <p>b) The Deictic pointing technique had high accuracy as continuous adjustments in the distance were possible during the locomotion.</p> <p>c) The continuous optic flow feedback with the Deictic pointing technique helped the user to identify the glowing object more easily.</p> <p>d) The pointing technique had better presence as the continuous locomotion helps in building the cognitive map of the VE.</p> <p>e) The pointing technique had lesser motion sickness and better spatial knowledge.</p> <p>f) The pointing gesture was the most preferred gesture for travel when one hand is occupied with selection or manipulation.</p>
Study 5 – Comparison of Mirror Leaning, Tapping and Teleportation techniques	Evaluate the three techniques for three different search task for their task completion time, collisions, intuitiveness, comfort, ease of use, perceived workload, motion sickness, spatial knowledge, and presence	30	<p>a) The task completion time and collision for the mirror leaning technique was less when compared to the other techniques.</p> <p>b) The mirror view for leaning was very helpful for looking at the objects in the upper VE shelves and for stopping when the user identified a glowing object.</p> <p>c) The mirror leaning technique had higher presence because of</p>

User Study	Objective	Participants	Findings
			vection and continuous locomotion. d) The visual effects showing a single arrow for walking speed and a double arrow for running speed were very helpful for the users to control the degree of leaning. e) The <i>mirror-leaning</i> gesture provided some vestibular cues which reasonably helped to reduce cybersickness. f) The <i>mirror-leaning</i> gesture had better spatial knowledge when compared to other techniques. g) The mirror leaning gesture was the most preferred gesture for travel when both the hands of the user are occupied with selection or manipulation.

#### 4.10 Summary

In this chapter, we have answered research question RQ4.

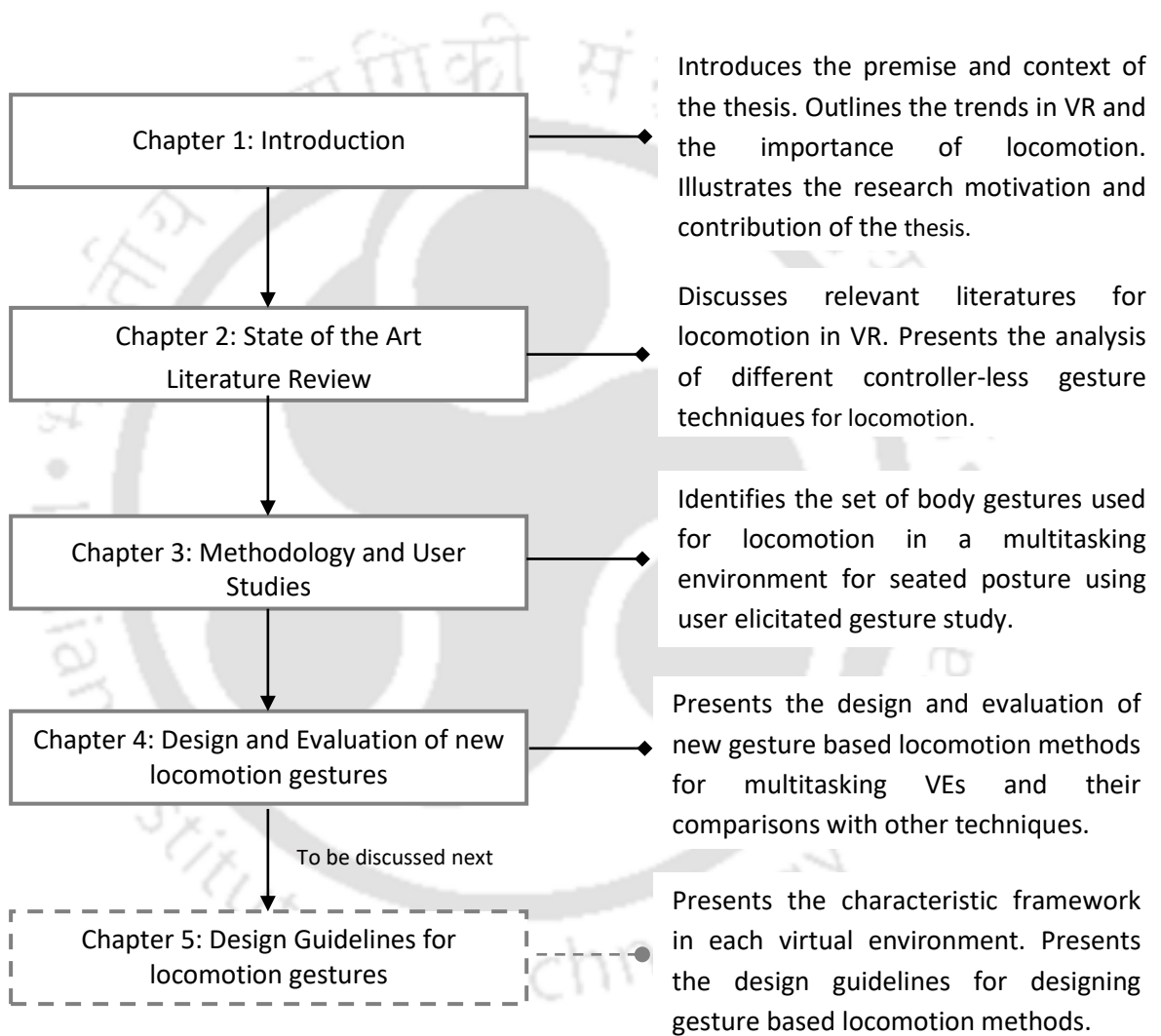
**For RQ4** –*We have investigated the newly designed gesture-based locomotion techniques on task completion time, collisions, intuitiveness, comfort, ease of use, motion sickness, perceived workload, spatial knowledge, and presence compared to existing locomotion techniques in a seated position and has presented the results.*

We presented three comparative study experiments to gather various measures for three different VEs that varied in multitasking. The first study compared the *Calling* gesture, *tapping* gesture, and *teleportation* gesture in VE1 and found that the *teleportation* gesture was the most preferred gesture in this environment. The second study compared the *Deictic Pointing* gesture, *tapping* gesture, and *teleportation* gesture in VE2 and found that the *deictic pointing* gesture was the most preferred gesture in this environment. The third study compared the *Mirror-Leaning* gesture, *tapping* gesture, and *teleportation* gesture in VE3 and found that the *mirror-leaning* gesture was the most preferred gesture in this environment. The three comparative studies contributes in measuring the intuitiveness, performance, comfort, ease of use, perceived workload, presence, motion sickness, and spatial

knowledge of the different locomotion techniques. These results helped us build the characteristic framework discussed in the next chapter.

**A quick recap of previous chapters:**

The visual summary of the chapters covered so far is provided as follows:



## CHAPTER 5 – DESIGN GUIDELINES FOR LOCOMOTION GESTURES

This chapter presents the characteristic framework and the design guidelines from the experimental investigations carried out in this thesis. The first section discusses the characteristic framework of gestural locomotion techniques from the observed results of the three comparative user experiments (Study 3, Study 4, and Study 5) performed. The research findings suggested a set of design guidelines for gestural locomotion techniques. These design guidelines are elaborated on in the second section of the chapter.

### 5.1 A characteristic framework of gestural locomotion techniques

The characteristic framework detailing the benefits and drawbacks of various locomotion techniques is intended to serve multiple usecases: Firstly, when designing a new VR experience, a broad overview of characteristics helps to assist in identifying the most appropriate gesture for a given set of functional and non-functional requirements. Second, new themes were identified and added as a direct implication for gestures used in a multitasking scenario within a virtual supermarket. From the qualitative feedback, we have extracted themes and added them along with the existing characteristics of an ideal locomotion technique. We have presented the framework separately for each VE considered in this research. They are built from the results of the experimental studies discussed in Chapter 4. Each environment has two classifications, first based on the functional requirements that were considered in performing the task, such as a) movement in a straight line task, b) movement in a directed path, and c) movement in an undirected path. The second classification is based on the non-functional requirements that were considered as a part of the locomotion technique in performing the task. These include the measures that were studied subjectively for each locomotion technique in the comparative experiments, such as a) Intuitiveness, b) movement type, c) comfort, d) simulation sickness, e) presence, f) Effort, g) Control, h) Ease of Use i) Perceived Workload. Further, we also discuss other themes for systematic classification, such as searching for items, moving near the targets, comfort while multitasking, enjoyability, and suitability based on VE size based on the qualitative feedback we received after each experiment. We believe that the systematic classification of locomotion technique characteristics aids in identifying the best suitable technique based on one's goal, desired user experiences, individual preferences, or application scenario/context. We have denoted the values in the form given below based on the significance we obtained in the statistical analysis comparing the gestures.

- a) “++” -> denotes highly preferable
- b) “+” -> denotes preferable
- c) "0" -> denotes neutral
- d) "-“ -> denotes not preferable
- e) “--“ -> denotes least preferable

### 5.1.1 Framework for gestures in a virtual environment with no multitasking ( VE1)

**Table 5.1: Classification based on Functional Requirements of a locomotion technique in VE1**

Gestures	Calling	Tapping	Teleportation
Functional Requirement			
Straight Line Path Travel – Task Completion Time	+	+	++
Movement in a directed path –Task Completion Time	+	+	++
Movement in a directed path – Collisions	+	-	++
Movement in an undirected path – Task Completion Time	+	-	+
Movement in an undirected path – Collisions	+	-	++

**Table 5.2: Classification based on Non-Functional Requirements of a locomotion technique in VE1**

Gesture	Calling	Tapping	Teleportation
Non Functional Requirement			
Movement Type	Dis-continuous movement	Dis-continuous movement	Dis-continuous movement
Intuitiveness	++	0	0
Comfort	-	-	++
Ease of Use	+	+	+
Effort	-	--	++
Presence	++	+	-
Spatial knowledge	+	+	-
User Preference	+	0	++
Motion Sickness	+	0	+
Nausea	+	0	++

Gesture	Calling	Tapping	Teleportation
Non Functional Requirement			
Oculomotor	+	-	+
Disorientation	+	0	-
Perceived Workload	++	--	+
Mental Demand	++	0	+
Physical Demand	+	-	+
Temporal Demand	++	+	++
Performance	+	0	+
Effort	+	--	+
Frustration	++	-	-
Searching for items	0	-	--
Move near the target	-	--	++
Comfort while multitasking	-	--	-
Locomotion control	-	--	++
Enjoyability	++	++	+
Locomotion Range – Large VE	+	+	++

The *teleportation* gesture was found to be the fastest for task completion in a straight-line travel task and movement in a directed path task. It had the least collisions in all the three tasks performed. The *Calling* gesture also performed better than the *tapping* gesture for the task completion time and the number of collisions. Hence any application that is time critical and requires greater accuracy of movement can use the *teleportation* gesture for locomotion in VE. All three techniques considered for this VE used discontinuous movement in which the user's viewpoint is moved one step (*calling and tapping*) or a few steps (*teleportation*) after performing the gesture. The *calling* gesture was found to be the most intuitive gesture. The *teleportation* gesture required the least effort and was the most comfortable gesture to travel in this environment. The *Calling* and the *tapping* gesture needed more effort and were not as comfortable as the *teleportation* gesture. In the measure of motion sickness, the *teleportation* gesture had the least nausea but had disorientation compared to the *Calling* and *tapping* gesture. This was also reflected in the measure of presence, where the *calling* and *tapping* gesture had better presence than the *teleportation* gesture. Hence applications that require the user's presence as a main factor and that can compromise on effort, and comfort can use the *calling* and *tapping* gesture as the mode of locomotion. All three techniques performed similarly for spatial knowledge acquisition. For the Perceived Workload, the *calling* gesture performed better than the *teleportation* and *tapping* gestures. It had the least mental demand than the *teleportation* and the *tapping* gesture. While moving in an undirected path, users found it difficult to search the items using *teleportation* and *tapping*

gesture. The *teleportation* gesture was easier to move near the target items to select them, thus avoiding collisions. The *teleportation* gesture had the best locomotion control in this environment and can also be used for moving in large VEs. The *Calling* and *tapping* gesture was more enjoyable to perform in this environment. Hence, applications, such as exergames where high effort is desirable with enhanced enjoyment, can incorporate the *calling* gesture for travel.

### 5.1.2 Framework for gestures in a virtual environment with locomotion and one hand engaged in selection and manipulation (VE2)

**Table 5.3: Classification based on Functional Requirements of a locomotion technique in VE2**

Gestures	Deictic Pointing	Tapping	Teleportation
Functional Requirements			
Straight Line Path Travel – Task Completion Time	++	+	++
Movement in a directed path –Task Completion Time	++	+	+
Movement in a directed path – Collisions	++	-	+
Movement in an undirected path – Task Completion Time	++	-	+
Movement in an undirected path – Collisions	++	-	++

**Table 5.4: Classification based on Non-Functional Requirements of a locomotion technique in VE2**

Gestures	Deictic Pointing	Tapping	Teleportation
Non-Functional Requirements			
Movement Type	Continuous movement	Dis-continuous movement	Dis-continuous movement
Intuitiveness	++	0	-
Comfort	++	-	+
Ease of Use	++	-	+
Presence	++	0	-
Spatial Knowledge	++	+	-
User Preference	++	0	+
Motion Sickness	+	0	+
Nausea	+	-	+
Oculomotor	++	-	+
Disorientation	+	-	-

Gestures	Deictic Pointing	Tapping	Teleportation
<b>Non-Functional Requirements</b>			
Perceived Workload	++	-	+
Mental Demand	++	0	+
Physical Demand	++	-	+
Temporal Demand	++	-	+
Performance	++	0	0
Effort	++	--	+
Frustration	++	-	0
Searching for items	++	-	--
Move near the target	++	--	++
Comfort while multitasking	++	--	-
Locomotion control	++	--	++
Enjoyability	++	+	+
Locomotion Range – Large VE	++	+	++

The *pointing* gesture was found to be the fastest for all three tasks. It had the least number of collisions while selecting the items. The *teleportation* gesture also performed faster for the straight-line task. Hence applications that require faster movement and accuracy can use these locomotion techniques. The *deictic pointing* is the most preferred gesture in this VE. We compared continuous locomotion (*deictic pointing*) and discontinuous locomotion (*tapping and teleportation*) in this environment. In continuous locomotion, the viewpoint of the user is moved continuously at the walking speed or running speed as long as the respective gesture shown is within the FOV of the HMD. Hence the user experiences a continuous movement in the VE as long as the gesture is performed. The locomotion stops once the gesture is moved away from the FOV of the HMD. It was also found that the continuous movement increased the presence and spatial knowledge; hence, the *deictic pointing* had the best immersion and cognitive map building capability than the other two techniques. The *pointing* and the *teleportation* gesture had less motion sickness and better locomotion control when compared to the *tapping* gesture. The *pointing* gesture had the least mental demand, physical demand, temporal demand, effort, and frustration. It was best suited to move near the targets and search the items in the supermarket for the directed and undirected path travel. Participants enjoyed the gesture for its continuous movement in the VE. Both the *pointing* and the *teleportation* gesture could be used for locomotion in a large-sized VE.

### 5.1.3 Framework for gestures in a virtual environment with locomotion and both hands engaged in selection and manipulation (VE3)

**Table 5.5: Classification based on Functional Requirements of a locomotion technique in VE3**

Gesture	Mirror Leaning	Tapping	Teleportation
Functional Requirement			
Straight Line Path Travel – Task Completion Time	++	+	++
Movement in a directed path –Task Completion Time	++	+	+
Movement in a directed path – Collisions	++	-	++
Movement in an undirected path – Task Completion Time	++	-	+
Movement in an undirected path – Collisions	+	--	++

**Table 5.6: Classification based on Non-Functional Requirements of a locomotion technique in VE3**

Gesture	Mirror Leaning	Tapping	Teleportation
Non-Functional Requirement			
Movement Type	Continuous movement	Dis-continuous movement	Dis-continuous movement
Intuitiveness	++	0	-
Comfort	+	-	+
Ease of Use	++	-	+
Presence	++	-	-
Spatial Knowledge	+	-	-
User Preference	++	-	0
Motion Sickness	+	0	+
Nausea	+	-	+
Oculomotor	++	-	+
Disorientation	+	-	-
Perceived Workload	++	-	+
Mental Demand	++	-	-
Physical Demand	++	-	-
Temporal Demand	++	-	-
Performance	++	-	-
Effort	++	--	-

Gesture	Mirror Leaning	Tapping	Teleportation
Non-Functional Requirement			
Frustration	+	-	0
Searching for items	+	-	+
Move near the target	++	--	0
Comfort while multitasking	++	--	-
Locomotion control	++	--	--
Enjoyability	++	-	-
Locomotion Range – Large VE	0	-	++

The *mirror-leaning* gesture was found to be the fastest for all three tasks. It had the least number of collisions while selecting the items in the directed path task. The *teleportation* gesture also performed faster for the straight-line task and had the least number of collisions in the directed and undirected path tasks. The *mirror leaning* gesture was the most preferred gesture in this VE as the hands were free for performing other tasks. In this environment, we compared continuous locomotion (*mirror leaning*) and discontinuous locomotion (*tapping and teleportation*). It was also found that the continuous movement increased the presence; hence, the *mirror leaning* had the best immersion than the other two techniques. As the multitasking increased, users had difficulty acquiring spatial knowledge using *teleportation* and *tapping* gestures. The *mirror-leaning* gesture had better cognitive map-building capability than the *teleportation* gesture. The *mirror leaning* and the *teleportation* gesture had less motion sickness when compared to the *tapping* gesture. The *mirror-leaning* gesture had the least mental demand, physical demand, temporal demand, effort, and frustration. It was best suited to move near the targets and search the items in the supermarket for the directed and undirected path travel. Participants enjoyed the gesture for its continuous movement in the VE. The non-occluding visual representation to aid in deciding the speed and step length while traveling in a VE was helpful in the *mirror leaning* gesture to adjust the angle of leaning for the user. The *teleportation* gesture could be used for locomotion in a large-sized VE. However, the *mirror leaning* gesture could cause inconvenience for traversing large VEs as leaning for longer periods of time would increase fatigue and discomfort for the users. The *mirror leaning* gesture can be used in VEs requiring users to make decisions while traveling with both hands occupied with virtual objects because the cognitive load for performing the gesture for the movement is very low compared to other gestures used in the environment.

## 5.2 Design Guidelines

This section formulates the design guidelines for designing effective gestural locomotion techniques in a multitasking environment when the user is seated. Although the guidelines were developed using the results of the three comparative experiments, they may also be applied to alternative gestural locomotion methods in standing positions and typical virtual settings. These guidelines are made for body-based gesture-enabled locomotion techniques, although few of the guidelines may also be applied to other types of locomotion techniques, such as redirection techniques, repositioning techniques, and artificial locomotion techniques. Following are the proposed guidelines.

**Guideline 1: *The locomotion technique should allow for speed variations while traveling in a VE.***

While using the locomotion technique, the user should be able to control the speed of movement according to the environment in which the user is traveling to avoid unexpected collisions with the objects around. In all three virtual environments (VE1, VE2, and VE3) in the study, it was observed that the users reduced their speed in the path turnings of the supermarket and in places where the path width was narrow in order to avoid collisions with the shelves. However, in the straight-line path travel task and movement in broader paths (devoid of obstacles) of the supermarket, the users traveled with increased speed. In many VR applications, users expect to travel at various speeds. For example, in the Google Maps application, a user travels at a greater speed in a broad street and would reduce the speed in a narrow, congested street to avoid collisions. Similarly, in many gaming applications, the users require different speeds to perform better in terms of lesser task completion time and higher accuracy.

**Guideline 2: *Gestures used in speed variation for locomotion should extend the same gesture space primarily with the change in gesture intensity to support the variations.***

Gestures used for increasing and decreasing the speed should be designed from the same gesture space. It is recommended that the gesture used to change the speed be the same, either by increasing the frequency of the gesture or by adding a slight modification to the original gesture. Since locomotion in a multitasking environment is performed with other interactions, such as selection and manipulation, having different gestures to specify the speed levels would take much more cognitive effort to memorize each gesture. For example, in the *Calling* and *tapping* gesture, the user increases the frequency of the gesture to reach a destination faster. Similarly, in the leaning gesture, the increase or decrease in the leaning angle helps to achieve speed variation during the travel.

**Guideline 3: The locomotion technique should allow variable step lengths to travel in a VE.**

According to the literature (Zatsiorky et al., 1994), walking velocity can be expressed as the product of step frequency ( $f$ ) and step length ( $l$ ):  $|v| = f * l$ . The normal step length ( $l_{norm}$ ) can be represented as  $l_{norm} = h * 0.41$ , where  $h$  represents the user's height (Rubaiyeat et al., 2010). Hence when the VE only requires the user to move around the environment without any other interaction, such as selection or manipulation, the step length can be calibrated based on the individual user's height. However, in many VR applications, the user must interact with objects in front of them in addition to traveling. Some objects may be within hand's reach, while others may be out of reach. Sometimes the object that is out of reach can be slightly less than a step length away and greater than arm's reach. As a result, if the interface uses a constant step length, the user may overshoot the distance and collide with the objects while grabbing them. Since the *calling* and *tapping* gesture incorporated a constant step length for the user, the majority of the collisions have occurred during the selection of objects that are out of hand's reach. Because there was continuous locomotion in the case of the *pointing* and *mirror leaning* gestures, the user could travel very small distances very accurately, reducing the number of collisions. As a result, the locomotion technique is recommended to support both minute step length movement (for selecting out-of-hand reach objects or for near-field navigation) and normal step length movement (for normal traversal). The locomotion system should give the user precise control over their position in the VE, avoiding unintended collisions caused while interacting with the virtual object.

**Guideline 4: The locomotion technique should accommodate a non-occluding visual representation to aid in deciding the speed and step length while traveling in a VE.**

The locomotion technique should include visual cues to facilitate the user in knowing the current speed and the step length. The user can decide to increase or decrease the speed based on this information. As visual feedback, in the *calling* gesture, the user is shown a grey laser beam that illustrates the point to which the user will be moved at the end of the gesture completion. Using this visualization, the user can determine the distance to which the translation occurs. In the case of the *leaning* gesture, the users received visual feedback about the velocity while leaning. A single arrow in the ground indicated that the users were moving with walking speed, and two arrows in the ground indicated that they were moving with running speed. This helped the users to control their angle of leaning and, thus, their velocity based on the visual feedback.

***Guideline 5: When using the free-hand locomotion technique that involves full body rotation for direction change, the system should address the challenges of HMDs FOV.***

Using gestures for locomotion does not require additional hardware to be used or attached to the existing system. However, the locomotion technique must deal with the tracking sensors' limited FOV (Caggianese et al. 2020), especially if the hand is used as the body part for providing gestures. Furthermore, in a seated position, when the locomotion technique involves full body rotation for direction change and because the sensor is anchored to the HMD, the user's interaction area moves in sync with the user's head. The user must place their hand in the sensor's field of view (FOV) to move in the VE. The virtual travel is interrupted if the user's hand that controls the locomotion moves out of the sensor's field of view while rotating in the swivel chair. This, in turn, disrupts the user's immersion while traveling. When the user returns their hand to the sensor's field of view and performs the gesture, the traveling resumes. The user may be completely unaware that the hand is not within the FOV, and the travel would abruptly halt. It is recommended that the system provide a method for communicating with the user when the hand gesture deviates from the FOV. This may be useful for the user to re-align the body part within the FOV in order to perform the gesture and travel without interruption. Users found it difficult to maintain their hands within the FOV during the physical rotations for direction changes in all the VEs. However, as they became accustomed to the technology, this unconscious and unintentional movement of hands out of the sensor's FOV decreased. It is highly preferable in free hand locomotion techniques that the system communicates to the user about the unconscious shifting of the user's hand in control outside the FOV of the sensor, resulting in fewer tracking errors and a better user experience.

***Guideline 6: The locomotion techniques that produce continuous movements provide the user with a better presence than those that produce discontinuous movements.***

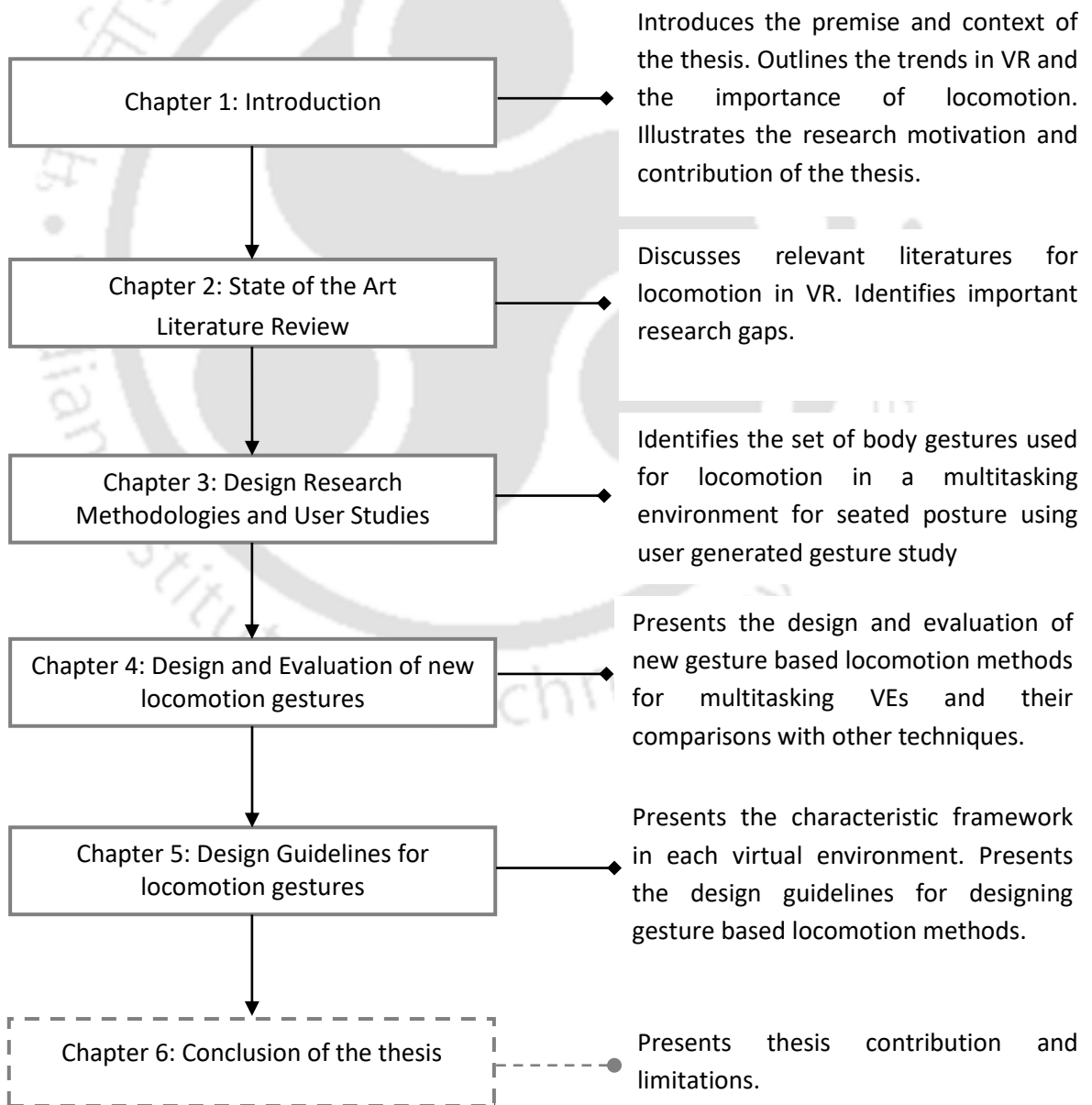
The locomotion techniques that produce continuous movement in VE help the user to have a continuous optic flow and self-motion perception as compared to the discontinuous movement techniques. The continuous movement helps in spatiotemporal continuity, which increases the presence. In the studies, the *pointing* and the *mirror leaning* gesture produced continuous movement and thereby had a better presence in their respective environments when compared with the other techniques. With *teleportation*, the movement is discontinuous, and because of this spatiotemporal discontinuity, it produces breaks in the presence. Hence VR applications that require more presence in their user experience could incorporate a continuous locomotion technique for better immersion.

### 5.3 Summary

Overall this chapter presented the characteristic framework for the three VEs. This characteristic framework presents the gesture's overall performance in each functional and non-functional requirement for the different scenarios. Further, we discussed the design guidelines formulated from the three experimental studies performed during the research. Although these guidelines are made for gestural locomotion techniques, they can also be extended for other types of locomotion techniques. We believe these guidelines would help the designers build better gestural locomotion techniques for VR applications.

#### A quick recap of previous chapters:

The visual summary of the chapters covered so far is provided as follows:



## CHAPTER 6 – CONCLUSION AND FUTURE WORK

### 6.1 Conclusion

This thesis investigates the design and evaluation of user-centric locomotion gestures in HMD-VR interfaces for a seated position in a multitasking environment. The study compared the three newly designed controller-less locomotion gestures to gestures found in the literature for virtual travel and determined their suitability for use in various VEs based on their characteristics. This chapter highlights the research's key contributions, limitations, and future research directions for gestural locomotion techniques.

The thesis started with an aim to identify user-centric gestures for locomotion in a multitasking environment in a seated position (i) when both hands are free, (ii) when one hand is engaged in the selection of a virtual object, (iii) when both hands are engaged in the selection of virtual objects using a gesture elicitation study. The literature study portrayed several techniques that perform locomotion in VR. The most natural locomotion, real walking, has the disadvantage of tracker coverage and requires a significant unhindered physical space to traverse large VEs. The controller-based (ALT) techniques are unnatural and result in VR sickness. Although the teleportation technique lessens motion sickness, it results in spatial disorientation. The redirected techniques are similar real walking provide better spatial understanding but still require a minimum tracking space of (12m x 44m). The repositioning systems have huge mechanical setups and are unsuitable for home environments.

The literature identifies proxy gestural techniques as one of the most promising approaches to locomotion in a VE. They mimic a part of the walking gait cycle. Several empirical studies showed that these gestural techniques provided better presence and spatial orientation than the controller-based locomotion techniques. However, these studies evaluated the gestures by performing sole locomotion tasks. The literature revealed a research gap demanding the investigation of the gestural techniques in real-time multitasking applications that require the user to perform locomotion and selection and manipulation tasks, such as in virtual supermarkets, games, and industrial training.

Furthermore, as user-defined gestures are easier to learn and remember than pre-defined gestures, it also demands identifying gestures for various scenarios using user-generated gesture elicitation methodology. In addition, studying gestures for seated positions is essential because they help to

mitigate physical fatigue when gestures are performed in a standing position for a longer duration. Moreover, the gestures can be adapted to different user groups, such as the elderly and physically disabled, to explore the VE. Based on the research gap identified we investigated the following research questions in this thesis.

**RQ1-** *What are the user-centric gestures that are natural for locomotion in a VE when both hands are free in a seated position?*

**RQ2** - *What are the user-centric gestures that are natural for locomotion in a multitasking VE when one hand is engaged in another interaction, such as selecting or manipulating a virtual object in a seated position?*

**RQ3** – *What are the user-centric gestures that are natural for locomotion in a multitasking VE when both hands are engaged in other interactions, such as selecting or manipulating two virtual objects in a seated position?*

**RQ4** – *How do the newly designed gesture-based locomotion techniques impact the task completion time, collisions, intuitiveness, comfort, ease of use, perceived workload, motion sickness, spatial knowledge, and presence compared to existing locomotion techniques in a seated position?*

Overall a systematic literature review helped us to build a broader theme of this research a) to identify the user-centric gestures for locomotion in a multitasking environment in a seated position, b) to design and evaluate new gestural locomotion techniques in comparison with the gestures in literature for the different functional and non-functional requirements. We performed a series of five experiments to accomplish the research objectives. From the results obtained, we proposed design guidelines and recommendations for efficient and effective gesture-based locomotion techniques for travel in a seated position for multitasking VEs.

We performed a series of five experiments during the research. The first study experiment (Study 1) aimed to identify suitable body gestures for virtual travel in three different environments using the gesture elicitation method. The first environment (VE1) consists of only virtual locomotion. In the second environment (VE2), the user performed virtual locomotion while one hand engaged in selecting a virtual object. In the third environment (VE3), the user performed virtual locomotion with both hands engaged in selecting virtual objects. The experiment conceptualized two computational functions – walking and running while moving in the VE. Forty university students performed the gestures of their

choice for walking and running functionalities in three VEs. The collection of user-performed gestures was filtered based on the frequency of gestures performed for each computational function, logical mapping of the gestures to the functions, semantic representation of the gestures, and to reduce false positives. This helped us to identify the different user-centric gesture sets for each environment.

The second study experiment (Study2) aimed to evaluate the top three gestures from Study1 for appropriateness, ease of use, effort, and user preference. The top three gestures for VE1 were "*Calling gesture*" – Cyclic movement of the right hand as calling someone, "*Bike riding gesture* with both hands," and "*Torso leaning*." The top three gestures for VE2 were "*Calling gesture*," "*Torso Leaning*," and "*Deictic Pointing*." The top three gestures for VE3 were "*WIP – Walk in Place*," "*Tapping* - Tapping the legs alternatively with heels on the ground," and "*Torso Leaning*" gestures. The gestures from Study 1 were divided into upper- and lower-body gestures. Further, we analyzed the gestures based on their geometric features, such as hand usage and gesture forms. As the level of multitasking evolved from completing solely locomotion tasks to conducting locomotion combined with multitasking using both hands, users chose the '*static pose*' and '*static pose and path*' gestures over the '*dynamic pose*' and '*dynamic pose and path*' gestures. We strongly believe that the classification outcomes will allow future designers and developers to determine the proper gesture categories for task-related virtual travel in a seated position in multitasking circumstances. From the results of Study 2, three novel locomotion gestures were designed and implemented for virtual travel. These gestures were intended to be used for natural locomotion while the user is seated in three different VEs. We used objective measures for calculating task completion time and collisions of the newly designed gestures and subjective measures for investigating intuitiveness, comfort, ease of use, simulation sickness, presence, perceived workload, spatial knowledge and user preference to evaluate the newly designed gestures (*Calling, Deictic Pointing, and Mirror Leaning*) with the gestures in literature (*tapping and teleportation*).

The aim of the third study experiment (Study 3) was to design and implement the *Calling gesture* for virtual locomotion in VE1 when both hands are free. The *Calling gesture, Tapping, and Teleportation* gesture was compared for three different search tasks in a virtual supermarket. The *teleportation* gesture was found to be suitable for VEs with only virtual locomotion and when the target object's location was known ahead of time. The aim of the fourth study experiment (Study 4) was to design and compare the *deictic pointing* gesture with the *tapping and teleportation* gesture. The *Deictic Pointing* gesture was suitable for virtual locomotion when one hand selects and manipulates a virtual object. This gesture enabled users to travel even short distances, precisely controlling their position in VE. The aim

of the fifth study experiment (Study 5) was to design and compare the *Mirror Leaning* gesture with the *tapping* and *teleportation* gesture. The *mirror-leaning* gesture was found to be most suitable for locomotion when both hands of the user were engaged in the selection and manipulation of the virtual object. Users preferred this gesture because of its high presence and low motion sickness while traveling in the VE.

We further presented a systematic characteristic framework of gestural locomotion technique over the functional and non-functional requirements based on the comparative study results. We believe this would aid in determining the most effective technique for movement in a VE based on one's objectives, desired user experiences, application environment, or specific user preferences. Further, we recommended the design guidelines for creating gesture-based locomotion techniques from the three comparative studies. This, in our opinion, would considerably help interaction designers to design locomotion gestures appropriate for the application setting.

## 6.2 Limitations of the research

Finally, there were certain limitations to the current research. According to Nielsen (2004), interactional gestures have different meanings based on the culture. For example, a gesture such as a ring formed by the thumb and index finger denotes "O.K." in western culture but denotes money in Japan. Cassell (1998) states that some gestures, such as emblems and metamorphic gestures are culturally dependent, while other types are mostly universal. All our participants for the five experimental studies were from India. They suggested gestures for natural locomotion in different scenarios. Computer users from diverse countries or cultures may suggest different sets of task gestures and subjective ratings along the categories we tested. Therefore, increasing the number of participants and including them from different cultures can account for better generalization and cultural coverage of the gestures.

Another limitation is that our participants were university students with a mean age of 25 years and those with prior experience with VR applications. The gesture set proposed in this research may change when users of different age groups, such as elderly users and no prior VR experience users, are considered. We evaluated the gestures using young participants with VR experience, and the results cannot be generalized for users of all age groups and experience levels.

Our goal was to empirically investigate how newly designed controller-less locomotion techniques perform in a real-time VR application such as a supermarket. To achieve this objective, we considered the inside-out tracking system of the HMD, as it is suitable for this purpose since the HCI community also

widely uses it. However, the results achieved are conditioned by the characteristics of the sensor in the headset and by the positioning of the hand in front of the HMD while performing the gesture. While the apparatus used does not require any additional interface to be attached for recognition of the gesture, we acknowledge that future research is needed to evaluate the performance of the gestures when more accurate tracking systems are used.

### **6.3 Contributions of the research**

Overall, this research work laid out four significant contributions, which were reported at the beginning of the thesis. Following are the contributions reiterated.

- 1) A set of user-centric gestures for locomotion in a VE (i) when both hands are free from multitasking (ii) when one hand is engaged in another interaction, such as the selection or manipulation of a virtual object (iii) when both hands are engaged in another interaction, such as selection or manipulation of virtual objects.
- 2) Classification of the locomotion gestures based on the body parts and their geometric features, such as hand usage and gesture forms.
- 3) Design and implementation of new locomotion gestures for three multitasking scenarios. A detailed evaluation of the new gestures (*Calling*, *Deictic Pointing*, and *Mirror Leaning*) compared with the gestures in literature (*tapping* and *teleportation*) for their performance, intuitiveness, comfort, ease of use, presence, spatial knowledge, and simulation sickness for different travel tasks common in VR applications.
- 4) A set of design guidelines for researchers and interaction designers to design locomotion techniques to travel in a seated position.

### **6.4 Scope of Future Research**

The quantitative findings identified through the comparative study of newly designed gestures and gestures in literature helped to devise the characteristic framework for the functional and non-functional requirements of the locomotion technique. This has been proposed on the basis of users performing different search tasks in a virtual supermarket. The following section elaborates on the new proposals for future research.

We evaluated the locomotion techniques for three different tasks: moving in a straight-line path, moving in a directed path, and moving in an undirected path. Since it allowed us to establish the study's objective—indirectly defining the complexity of applying the techniques—we discovered that utilizing these three tasks was suitable. The idea that a strategy should be as simple as possible to execute this kind of activity without traveling error and with the fewest possible collisions served as the basis for selecting this task. However, these locomotion gestures can be evaluated for movement in different terrain, moving in paths with obstacles (people, objects, etc.), or evasion tasks where the user has to dodge a series of moving objects (such as bullets).

Further, we have compared gestures that produce both continuous (*Deictic Pointing, Mirror Leaning*) and non-continuous movement (*teleportation, tapping*). For comparison, other seated-based techniques like *trigger-walking, point-tugging, arm-cycling*, and *'point and teleport'* using controllers, among others, can be considered. Studying the performance of controller-based gestures and controller-less gestures in a seated position in multitasking scenarios might be intriguing. Similarly comparing the newly designed controller-less gestures and automatic locomotion techniques (ALTs) for the different tasks would also be interesting.

We used a gesture elicitation study to design the gestures for locomotion, primarily for walking and running functions. We propose to use the same methodology followed in the research for developing gestures for other functionalities such as jumping, swimming, climbing, and flying and evaluate their performance with the controller-based locomotion. This also opens the scope of future research investigating gesture memorability and recall, mainly when different gestures are used for different functions in the VR application.

Further, in this research, we have investigated the newly designed locomotion techniques for search tasks in a virtual supermarket. The future scope would be to apply the newly designed locomotion methods for various other VR applications such as time-critical applications, virtual walkthroughs, exer games, and thematic games. A detailed analysis of the gesture performances in different applications would strengthen the findings and eventually help build a comprehensive characteristic framework for the different locomotion techniques. We believe this would help future researchers and designers select the appropriate gesture for locomotion based on the type VR application.

## REFERENCES

### A

1. Akers, D. (2006, April). Wizard of oz for participatory design: inventing a gestural interface for 3d selection of neural pathway estimates. In CHI'06 Extended Abstracts on Human Factors in Computing Systems (pp. 454-459).
2. Arns, L. L. (2002). A new taxonomy for locomotion in virtual environments. Iowa State University.
3. Arora, R., Kazi, R. H., Kaufman, D. M., Li, W., & Singh, K. (2019, October). Magicalhands: Mid-air hand gestures for animating in vr. In Proceedings of the 32nd annual ACM symposium on user interface software and technology (pp. 463-477).
4. Awada, M., Zhu, R., Becerik-Gerber, B., Lucas, G., & Southers, E. (2021). An integrated emotional and physiological assessment for VR-based active shooter incident experiments. *Advanced Engineering Informatics*, 47, 101227.

### B

5. Bakker, N. H., Passenier, P. O., & Werkhoven, P. J. (2003). Effects of head-slaved navigation and the use of teleports on spatial orientation in virtual environments. *Human factors*, 45(1), 160-169.
6. Bargas-Avila, J. A., & Hornbæk, K. (2011, May). Old wine in new bottles or novel challenges: a critical analysis of empirical studies of user experience. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 2689-2698).
7. Bell, H. H., & Waag, W. L. (1998). Evaluating the effectiveness of flight simulators for training combat skills: A review. *The international journal of aviation psychology*, 8(3), 223-242.
8. Bhandari, J., Tregillus, S., & Folmer, E. (2017, November). Legomotion: Scalable walking-based virtual locomotion. In Proceedings of the 23rd ACM symposium on virtual reality software and technology (pp. 1-8).
9. Bhandari, J., MacNeilage, P. R., & Folmer, E. (2018, May). Teleportation without Spatial Disorientation Using Optical Flow Cues. In *Graphics interface* (pp. 162-167).

10. Billinghurst, M., & Weghorst, S. (1995, March). The use of sketch maps to measure cognitive maps of virtual environments. In Proceedings Virtual Reality Annual International Symposium'95 (pp. 40-47). IEEE.
11. Brooks, F. P. (1999). What's real about virtual reality?. IEEE Computer graphics and applications, 19(6), 16-27.
12. Brouet, R., Blanch, R., & Cani, M. P. (2013). Understanding hand degrees of freedom and natural gestures for 3D interaction on tabletop. In Human-Computer Interaction–INTERACT 2013: 14th IFIP TC 13 International Conference, Cape Town, South Africa, September 2-6, 2013, Proceedings, Part I 14 (pp. 297-314). Springer Berlin Heidelberg.
13. Bruder, G., Steinicke, F., & Hinrichs, K. H. (2009, March). Arch-explore: A natural user interface for immersive architectural walkthroughs. In 2009 IEEE Symposium on 3D User Interfaces (pp. 75-82). IEEE.
14. Bruns, C. R., & Chamberlain, B. C. (2019). The influence of landmarks and urban form on cognitive maps using virtual reality. Landscape and Urban Planning, 189, 296-306.
15. Boletsis, C., & Chasanidou, D. (2022). A Typology of Virtual Reality Locomotion Techniques. Multimodal Technologies and Interaction, 6(9), 72.
16. Boletsis, C., & Cedergren, J. E. (2019). VR locomotion in the new era of virtual reality: an empirical comparison of prevalent techniques. Advances in Human-Computer Interaction, 2019.
17. Bonato, F., Bubka, A., Palmisano, S., Phillip, D., & Moreno, G. (2008). Vection change exacerbates simulator sickness in virtual environments. Presence: Teleoperators and Virtual Environments, 17(3), 283-292.
18. Bowman, D. A., Chen, J., Wingrave, C. A., Lucas, J., Ray, A., Polys, N. F., ... & Ni, T. (2006). New directions in 3d user interfaces. International Journal of Virtual Reality, 5(2), 3-14.
19. Bowman, D., Kruijff, E., LaViola Jr, J. J., & Poupyrev, I. P. (2004). 3D User interfaces: theory and practice, CourseSmartTextbook. Addison-Wesley.
20. Bowman, D. A., Koller, D., & Hodges, L. F. (1998). A methodology for the evaluation of travel techniques for immersive virtual environments. Virtual reality, 3(2), 120-131.
21. Bowman, D. A., Koller, D., & Hodges, L. F. (1997, March). Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality (pp. 45-52). IEEE.

22. Bozgeyikli, E., Raij, A., Katkooori, S., & Dubey, R. (2016, October). Point & teleport locomotion technique for virtual reality. In Proceedings of the 2016 annual symposium on computer-human interaction in play (pp. 205-216).
23. Bozgeyikli, E., Raij, A., Katkooori, S., & Dubey, R. (2016, October). Locomotion in virtual reality for individuals with autism spectrum disorder. In Proceedings of the 2016 Symposium on Spatial User Interaction (pp. 33-42).
24. Bozgeyikli, E., Raij, A., Katkooori, S., & Dubey, R. (2019). Locomotion in virtual reality for room scale tracked areas. *International Journal of Human-Computer Studies*, 122, 38-49.
25. Bozkir, E., Geisler, D., & Kasneci, E. (2019, September). Assessment of driver attention during a safety critical situation in VR to generate VR-based training. In ACM Symposium on Applied Perception 2019 (pp. 1-5).
26. Buckwald, M., & Holz, D. (2010). The leap motion 3d controller.
27. Buttussi, F., & Chittaro, L. (2019). Locomotion in place in virtual reality: A comparative evaluation of joystick, teleport, and leaning. *IEEE transactions on visualization and computer graphics*, 27(1), 125-136.

## C

28. Caggianese, G., Capece, N., Erra, U., Gallo, L., & Rinaldi, M. (2020). Freehand-steering locomotion techniques for immersive virtual environments: A comparative evaluation. *International Journal of Human-Computer Interaction*, 36(18), 1734-1755.
29. Cannavò, A., Calandra, D., Praticò, F. G., Gatteschi, V., & Lamberti, F. (2020). An evaluation testbed for locomotion in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 27(3), 1871-1889.
30. Cardoso, J. (2017). Gesture-Based Locomotion in Immersive VR Worlds with the Leap Motion Controller.
31. Cassell, Justine. "A framework for gesture generation and interpretation." *Computer vision in human-machine interaction* (1998): 191-215.
32. Chen, H., & Fuchs, H. (2017, June). Supporting free walking in a large virtual environment: imperceptible redirected walking with an immersive distractor. In Proceedings of the Computer Graphics International Conference (pp. 1-6).

33. Cliburn, D., Rilea, S., Parsons, D., Surya, P., & Semler, J. (2009, December). The effects of teleportation on recollection of the structure of a virtual world. In Proceedings of the 15th Joint virtual reality Eurographics conference on Virtual Environments (pp. 117-120).
34. Coomer, N., Bullard, S., Clinton, W., & Williams-Sanders, B. (2018, August). Evaluating the effects of four VR locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In Proceedings of the 15th ACM symposium on applied perception (pp. 1-8).
35. Ciger, J., Gutierrez, M., Vexo, F., & Thalmann, D. (2003, April). The magic wand. In Proceedings of the 19th spring conference on Computer graphics (pp. 119-124).
36. Chance, S. S., Gaunet, F., Beall, A. C., & Loomis, J. M. (1998). Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence*, 7(2), 168-178.
37. Chou, Y. H., Wagenaar, R. C., Saltzman, E., Giphart, J. E., Young, D., Davidsdottir, R., & Cronin-Golomb, A. (2009). Effects of optic flow speed and lateral flow asymmetry on locomotion in younger and older adults: a virtual reality study. *Journals of Gerontology: Series B*, 64(2), 222-231.

## D

38. Davis, S., Nesbitt, K., & Nalivaiko, E. (2014, December). A systematic review of cybersickness. In Proceedings of the 2014 conference on interactive entertainment (pp. 1-9).
39. Dean, G. A. (1965). An analysis of the energy expenditure in level and grade walking. *Ergonomics*, 8(1), 31-47.

## E

40. Eike Langbehn, Paul Lubos, Gerd Bruder, and Frank Steinicke. Bending the Curve: Sensitivity to Bending of Curved Paths and Application in Room-Scale VR. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1349–1358, 4 2017.
41. Ellis, S. R. (1994). What are virtual environments?. *IEEE Computer Graphics and Applications*, 14(1), 17-22.
42. Engel, D., Curio, C., Tcheang, L., Mohler, B., & Bülthoff, H. H. (2008, October). A psychophysically calibrated controller for navigating through large environments in a limited free-walking space.

In Proceedings of the 2008 ACM symposium on Virtual reality software and technology (pp. 157-164).

## F

43. Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 24(1), 227.
44. Feasel, J., Whitton, M. C., Kassler, L., Brooks, F. P., & Lewek, M. D. (2011). The integrated virtual environment rehabilitation treadmill system. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 19(3), 290-297.
45. Feasel, J., Whitton, M. C., & Wendt, J. D. (2008, March). LLCM-WIP: Low-latency, continuous-motion walking-in-place. In 2008 IEEE symposium on 3D user interfaces (pp. 97-104). IEEE.
46. Fels, S., Kinoshita, Y., Chen, T. P. G., Takama, Y., Yohanan, S., Gadd, A., ... & Funahashi, K. (2005). Swimming across the Pacific: a VR swimming interface. *IEEE Computer Graphics and Applications*, 25(1), 24-31.
47. Fernandes, K. J., Raja, V., & Eyre, J. (2003). Cybersphere: the fully immersive spherical projection system. *Communications of the ACM*, 46(9), 141-146.
48. Ferracani, A., Pezzatini, D., Bianchini, J., Biscini, G., & Del Bimbo, A. (2016, October). Locomotion by natural gestures for immersive virtual environments. In Proceedings of the 1st international workshop on multimedia alternate realities (pp. 21-24).
49. Fiore, L. P., Coben, E., Merritt, S., Liu, P., & Interrante, V. (2013, December). Towards Enabling More Effective Locomotion in VR Using a Wheelchair-based Motion Platform. In EGVE/EuroVR (pp. 83-90).
50. Freina, L., & Ott, M. (2015, April). A literature review on immersive virtual reality in education: state of the art and perspectives. In The international scientific conference elearning and software for education (Vol. 1, No. 133, pp. 10-1007).

## G

51. Gao, B., Mai, Z., Tu, H., & Duh, H. B. L. (2021, March). Evaluation of Body-centric Locomotion with Different Transfer Functions in Virtual Reality. In 2021 IEEE Virtual Reality and 3D User Interfaces (VR) (pp. 493-500). IEEE.

52. Griffin, N. N., Liu, J., & Folmer, E. (2018, October). Evaluation of handsbusy vs handsfree virtual locomotion. In Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play (pp. 211-219).

## H

53. Harris, A., Nguyen, K., Wilson, P. T., Jackoski, M., & Williams, B. (2014, November). Human joystick: Wii-leaning to translate in large virtual environments. In Proceedings of the 13th ACM SIGGRAPH international conference on virtual-reality continuum and its applications in industry (pp. 231-234).
54. Harris, L. R., Jenkin, M. R., Zikovitz, D., Redlick, F., Jaekl, P., Jasiobedzka, U. T., ... & Allison, R. S. (2002). Simulating self-motion I: Cues for the perception of motion. *Virtual Reality*, 6(2), 75.
55. Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology* (Vol. 52, pp. 139-183). North-Holland.
56. Hashemian, A., Lotfaliei, M., Adhikari, A., Kruijff, E., & Riecke, B. (2020). HeadJoystick: Improving Flying in VR using a Novel Leaning-Based Interface. *IEEE Transactions on Visualization and Computer Graphics*.
57. Henze, N., Löcken, A., Boll, S., Hesselmann, T., & Pielot, M. (2010, December). Free-hand gestures for music playback: deriving gestures with a user-centred process. In Proceedings of the 9th international conference on Mobile and Ubiquitous Multimedia (pp. 1-10).
58. Hettinger, L. J. (2002). Illusory self-motion in virtual environments. In *Handbook of virtual environments* (pp. 511-532). CRC Press.
59. Hollerbach, J. M., Xu, Y., Christensen, R. R., & Jacobsen, S. C. (2000, November). Design specifications for the second generation Sarcos Treadport locomotion interface. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 26652, pp. 1293-1298). American Society of Mechanical Engineers.

## I

60. IDC (2020). "VR Headset Market Expected to Grow Despite Short-Term Decline", According to IDC (2020) <<https://www.businesswire.com/news/home/20200916005157/en/VR-Headset-Market-Expected-to-Grow-Despite-Short-Term-Decline-According-to-IDC>>.

61. Ijspeert, A. (2002). Locomotion, vertebrate. *The handbook of brain theory and neural networks*, 649-654.
62. Interrante, V., Ries, B., & Anderson, L. (2007, March). Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *2007 IEEE Symposium on 3D User interfaces*. IEEE.
63. Iwata, H., Yano, H., & Tomiyoshi, M. (2007). String walker. In *ACM SIGGRAPH 2007 emerging technologies* (pp. 20-es).
64. Iwata, H., Yano, H., & Nakaizumi, F. (2001, March). Gait master: A versatile locomotion interface for uneven virtual terrain. In *Proceedings IEEE Virtual Reality 2001* (pp. 131-137). IEEE.

## J

65. Jahani, H., & Kavakli, M. (2018). Exploring a user-defined gesture vocabulary for descriptive mid-air interactions. *Cognition, Technology & Work*, 20(1), 11-22.

## K

66. Kang, H. J., Shin, J. H., & Ponto, K. (2020, March). A comparative analysis of 3d user interaction: How to move virtual objects in mixed reality. In *2020 IEEE conference on virtual reality and 3D user interfaces (VR)* (pp. 275-284). IEEE.
67. Ke, P., & Zhu, K. (2021, March). Larger step faster speed: investigating gesture-amplitude-based locomotion in place with different virtual walking speed in virtual reality. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)* (pp. 438-447). IEEE.
68. Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3), 203-220.
69. Khundam, C., & Nöel, F. (2021). A study of physical fitness and enjoyment on virtual running for exergames. *International Journal of Computer Games Technology*, 2021.
70. Khundam, C. (2021). A Study on Usability and Motion Sickness of Locomotion Techniques for Virtual Reality. *ECTI Transactions on Computer and Information Technology (ECTI-CIT)*, 15(3), 347-361.
71. Kim, W., & Xiong, S. (2021). User-defined walking-in-place gestures for VR locomotion. *International Journal of Human-Computer Studies*, 152, 102648. Kim, W., & Xiong, S. (2021).

User-defined walking-in-place gestures for VR locomotion. *International Journal of Human-Computer Studies*, 152, 102648.

72. Kim, Y. M., Lee, Y., Rhiu, I., & Yun, M. H. (2021). Evaluation of locomotion methods in virtual reality navigation environments: An involuntary position shift and task performance. *International Journal of Human-Computer Studies*, 155, 102691.
73. Kim, J. S., Gračanin, D., Matković, K., & Quek, F. (2010, June). The effects of finger-walking in place (FWIP) for spatial knowledge acquisition in virtual environments. In *International Symposium on Smart Graphics* (pp. 56-67). Springer, Berlin, Heidelberg.
74. Kitson, A., Hashemian, A. M., Stepanova, E. R., Kruijff, E., & Riecke, B. E. (2017, March). Comparing leaning-based motion cueing interfaces for virtual reality locomotion. In *2017 IEEE Symposium on 3d user interfaces (3DUI)* (pp. 73-82). IEEE.
75. Kruijff, E., Marquardt, A., Trepkowski, C., Lindeman, R. W., Hinkenjann, A., Maiero, J., & Riecke, B. E. (2016, October). On your feet! Enhancingvection in leaning-based interfaces through multisensory stimuli. In *Proceedings of the 2016 Symposium on Spatial User Interaction* (pp. 149-158).
76. Kruijff, E., Riecke, B., Trepkowski, C., & Kitson, A. (2015, August). Upper body leaning can affect forward self-motion perception in virtual environments. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction* (pp. 103-112).
77. Koonce, J. M., & Bramble Jr, W. J. (1998). Personal computer-based flight training devices. *The international journal of aviation psychology*, 8(3), 277-292.

## L

78. Langbehn, E., Lubos, P., Bruder, G., & Steinicke, F. (2017). Bending the curve: Sensitivity to bending of curved paths and application in room-scale vr. *IEEE transactions on visualization and computer graphics*, 23(4), 1389-1398.
79. LaViola Jr, J. J., Feliz, D. A., Keefe, D. F., & Zeleznik, R. C. (2001, March). Hands-free multi-scale navigation in virtual environments. In *Proceedings of the 2001 symposium on Interactive 3D graphics* (pp. 9-15).
80. LaViola Jr, J. J. (2000). A discussion of cybersickness in virtual environments. *ACM Sigchi Bulletin*, 32(1), 47-56.
81. Lee, D. Y., Cho, Y. H., Min, D. H., & Lee, I. K. (2020, March). Optimal planning for redirected walking based on reinforcement learning in multi-user environment with irregularly shaped

physical space. In 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (pp. 155-163). IEEE.

82. Liu, S., Lee, G., Li, Y., Piumsomboon, T., & Ens, B. (2021, December). Force-Based Foot Gesture Navigation in Virtual Reality. In Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology (pp. 1-3).

## M

83. Marchal, M., Cirio, G., Visell, Y., Fontana, F., Serafin, S., Cooperstock, J., & Lécuyer, A. (2013). Multimodal rendering of walking over virtual grounds. *Human Walking in Virtual Environments: Perception, Technology, and Applications*, 263-295.
84. Martindale, J. (2016). Digital trends: How should we move around in VR? nobody has figured it out yet.
85. McCullough, M., Xu, H., Michelson, J., Jackoski, M., Pease, W., Cobb, W., ... & Williams, B. (2015, September). Myo arm: swinging to explore a VE. In Proceedings of the ACM SIGGRAPH Symposium on Applied Perception (pp. 107-113).
86. McGrath, J. L., Taekman, J. M., Dev, P., Danforth, D. R., Mohan, D., Kman, N., ... & Won, K. (2018). Using virtual reality simulation environments to assess competence for emergency medicine learners. *Academic Emergency Medicine*, 25(2), 186-195.
87. McMahan, R. P., Lai, C., & Pal, S. K. (2016, July). Interaction fidelity: the uncanny valley of virtual reality interactions. In International conference on virtual, Augmented and Mixed Reality (pp. 59-70). Springer, Cham.
88. Medina, E., Fruland, R., & Weghorst, S. (2008, September). Virtosphere: Walking in a human size VR "hamster ball". In Proceedings of the Human Factors and Ergonomics Society Annual Meeting (Vol. 52, No. 27, pp. 2102-2106). Sage CA: Los Angeles, CA: SAGE Publications.
89. Merhi, O., Faugloire, E., Flanagan, M., & Stoffregen, T. A. (2007). Motion sickness, console video games, and head-mounted displays. *Human factors*, 49(5), 920-934.
90. Mine, M. R. (1995). Virtual environment interaction techniques. UNC Chapel Hill CS Dept.
91. Mousas, C., Kao, D., Koiliyas, A., & Rekabdar, B. (2021). Evaluating virtual reality locomotion interfaces on collision avoidance task with a virtual character. *The Visual Computer*, 37(9), 2823-2839.

92. Multon, F., & Olivier, A. H. (2013). Biomechanics of walking in real world: naturalness we wish to reach in virtual reality. In *Human walking in virtual environments* (pp. 55-77). Springer, New York, NY.

## N

93. Nabiyouni, M., Saktheeswaran, A., Bowman, D. A., & Karanth, A. (2015, March). Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)* (pp. 3-10). IEEE.
94. Nacenta, M. A., Kamber, Y., Qiang, Y., & Kristensson, P. O. (2013, April). Memorability of pre-designed and user-defined gesture sets. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 1099-1108).
95. Neumann, W. P., Wells, R. P., Norman, R. W., Frank, J., Shannon, H., Kerr, M. S., & OUBPS Working Group. (2001). A posture and load sampling approach to determining low-back pain risk in occupational settings. *International Journal of Industrial Ergonomics*, 27(2), 65-77.
96. Nguyen-Vo, T., Riecke, B. E., Stuerzlinger, W., Pham, D. M., & Kruijff, E. (2019). Naviboard and navichair: Limited translation combined with full rotation for efficient virtual locomotion. *IEEE transactions on visualization and computer graphics*, 27(1), 165-177.
97. Nielsen, Michael, et al. "A procedure for developing intuitive and ergonomic gesture interfaces for HCI." *Gesture-Based Communication in Human-Computer Interaction: 5th International Gesture Workshop, GW 2003, Genova, Italy, April 15-17, 2003, Selected Revised Papers 5*. Springer Berlin Heidelberg, 2004.
98. Nilsson, N. C., Serafin, S., Steinicke, F., & Nordahl, R. (2018). Natural walking in virtual reality: A review. *Computers in Entertainment (CIE)*, 16(2), 1-22.
99. Nilsson, N. C., Peck, T., Bruder, G., Hodgson, E., Serafin, S., Whitton, M., ... & Rosenberg, E. S. (2018). 15 years of research on redirected walking in immersive virtual environments. *IEEE computer graphics and applications*, 38(2), 44-56.
100. Nilsson, N. C., Serafin, S., & Nordahl, R. (2016, July). Walking in place through virtual worlds. In *International Conference on Human-Computer Interaction* (pp. 37-48). Springer, Cham.
101. Nilsson, N. C., Serafin, S., & Nordahl, R. (2014). Establishing the range of perceptually natural visual walking speeds for virtual walking-in-place locomotion. *IEEE transactions on visualization and computer graphics*, 20(4), 569-578.

102. Nilsson, N. C., Serafin, S., & Nordahl, R. (2014, November). The influence of step frequency on the range of perceptually natural visual walking speeds during walking-in-place and treadmill locomotion. In Proceedings of the 20th ACM symposium on virtual reality software and technology (pp. 187-190).
103. Nilsson, N. C., Serafin, S., Laursen, M. H., Pedersen, K. S., Sikström, E., & Nordahl, R. (2013, March). Tapping-in-place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input. In 2013 IEEE symposium on 3D user interfaces (3DUI) (pp. 31-38). IEEE.
104. Nilsson, N. C., Serafin, S., & Nordahl, R. (2013). The perceived naturalness of virtual locomotion methods devoid of explicit leg movements. In Proceedings of Motion on Games (pp. 155-164).
105. Nielsen, M., Störring, M., Moeslund, T. B., & Granum, E. (2003, April). A procedure for developing intuitive and ergonomic gesture interfaces for HCI. In International gesture workshop (pp. 409-420). Springer, Berlin, Heidelberg.
106. Nitzsche, N., Hanebeck, U. D., & Schmidt, G. (2004). Motion compression for telepresent walking in large target environments. *Presence: Teleoperators & Virtual Environments*, 13(1), 44-60.
107. Noma, H., & Miyasato, T. (1998, November). Design for locomotion interface in a large scale virtual environment ATLAS: ATR locomotion interface for active self motion. In ASME International Mechanical Engineering Congress and Exposition (Vol. 15861, pp. 111-118). American Society of Mechanical Engineers.
108. Nordahl, R., Serafin, S., Turchet, L., & Nilsson, N. C. (2011). A multimodal architecture for simulating natural interactive walking in virtual environments. *PsychNology Journal*, 9(3), 245-268.
- O**
109. Otaran, A., & Farkhatdinov, I. (2021). Haptic ankle platform for interactive walking in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*.

**P**

110. Pai, Y. S., Chen, Z., Chan, L., Isogai, M., Kimata, H., & Kunze, K. (2018, September). Pinchmove: improved accuracy of user mobility for near-field navigation in virtual environments. In Proceedings of the 20th international conference on human-computer interaction with mobile devices and services (pp. 1-11).
111. Pai, Y. S., & Kunze, K. (2017, November). Armswing: Using arm swings for accessible and immersive navigation in ar/vr spaces. In Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia (pp. 189-198).
112. Paris, R., Joshi, M., He, Q., Narasimham, G., McNamara, T. P., & Bodenheimer, B. (2017, September). Acquisition of survey knowledge using walking in place and resetting methods in immersive virtual environments. In Proceedings of the ACM Symposium on Applied Perception (pp. 1-8).
113. Peck, T. C., Fuchs, H., & Whitton, M. C. (2010, March). Improved redirection with distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments. In 2010 IEEE Virtual Reality Conference (VR) (pp. 35-38). IEEE.
114. Peck, T. C., Fuchs, H., & Whitton, M. C. (2011). The design and evaluation of a large-scale real-walking locomotion interface. *IEEE transactions on visualization and computer graphics*, 18(7), 1053-1067.
115. Perkins Coie (2020). "2020 AUGMENTED AND VIRTUAL REALITY SURVEY REPORT", <https://www.perkinscoie.com/images/content/2/3/v4/231654/2020-AR-VR-Survey-v3.pdf>
116. Peskin, M., Wyka, K., Cukor, J., Olden, M., Altemus, M., Lee, F. S., & Difede, J. (2019). The relationship between posttraumatic and depressive symptoms during virtual reality exposure therapy with a cognitive enhancer. *Journal of anxiety disorders*, 61, 82-88.
117. Pfeuffer, K., Mayer, B., Mardanbegi, D., & Gellersen, H. (2017, October). Gaze+ pinch interaction in virtual reality. In Proceedings of the 5th symposium on spatial user interaction (pp. 99-108).
118. Piumsomboon, T., Clark, A., Billingham, M., & Cockburn, A. (2013, September). User-defined gestures for augmented reality. In IFIP Conference on Human-Computer Interaction (pp. 282-299). Springer, Berlin, Heidelberg.
119. Presson, C. C., & Montello, D. R. (1994). Updating after rotational and translational body movements: Coordinate structure of perspective space. *Perception*, 23(12), 1447-1455.
120. Prithul, A., & Berhe, I. (2021). Embodied Third-Person Virtual Locomotion using a Single Depth Camera. *Proceedings of Graphics Interface 2021*.

## R

121. Razzaque, S. (2005). Redirected walking. The University of North Carolina at Chapel Hill.
122. Razzaque, S., Swapp, D., Slater, M., Whitton, M. C., & Steed, A. (2002, May). Redirected walking in place. In EGVE (Vol. 2, pp. 123-130).
123. Riecke, B. E., & Zielasko, D. (2021, March). Continuous vs. Discontinuous (Teleport) Locomotion in VR: How Implications can Provide both Benefits and Disadvantages. In 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW) (pp. 373-374). IEEE.
124. Roston, G. P., & Peurach, T. (1997, April). A whole body kinesthetic display device for virtual reality applications. In Proceedings of International Conference on Robotics and Automation (Vol. 4, pp. 3006-3011). IEEE.
125. Ruddle, R. A., & Lessels, S. (2006). For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological science*, 17(6), 460-465.
126. Ruiz, J., Li, Y., & Lank, E. (2011, May). User-defined motion gestures for mobile interaction. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 197-206).

## S

127. Sarupuri, B., Hoermann, S., Steinicke, F., & Lindeman, R. W. (2017, October). Triggerwalking: a biomechanically-inspired locomotion user interface for efficient realistic virtual walking. In Proceedings of the 5th symposium on spatial user interaction (pp. 138-147).
128. Schäfer, A., Reis, G., & Stricker, D. (2021). Controlling teleportation-based locomotion in virtual reality with hand gestures: a comparative evaluation of two-handed and one-handed techniques. *Electronics*, 10(6), 715.
129. Sherman, W. R., & Craig, A. B. (2003). *Understanding virtual reality*. San Francisco, CA: Morgan Kaufman.
130. Slater, M., Steed, A., & Usoh, M. (1995). The virtual treadmill: A naturalistic metaphor for navigation in immersive virtual environments. In *Virtual environments' 95* (pp. 135-148). Springer, Vienna.

131. Slater, M., Usoh, M., & Steed, A. (1995). Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 2(3), 201-219.
132. Slater, M., & Usoh, M. (1994). Body centred interaction in immersive virtual environments. *Artificial life and virtual reality*, 1(1994), 125-148.
133. Slater, M., Usoh, M., & Steed, A. (1994). Steps and ladders in virtual reality. In *Virtual Reality Software And Technology* (pp. 45-54).
134. Slater, M., Usoh, M., & Steed, A. (1994). Depth of presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, 3(2), 130-144.
135. Souman, J. L., Giordano, P. R., Schwaiger, M., Frissen, I., Thümmel, T., Ulbrich, H., ... & Ernst, M. O. (2011). CyberWalk: Enabling unconstrained omnidirectional walking through virtual environments. *ACM Transactions on Applied Perception (TAP)*, 8(4), 1-22.
136. Steinicke, F., Bruder, G., Hinrichs, K., & Steed, A. (2009, August). Presence-enhancing real walking user interface for first-person video games. In *Proceedings of the 2009 ACM SIGGRAPH Symposium on Video Games* (pp. 111-118).
137. Stephen, R. E. (1994). What are virtual environments. *IEEE Computer Graphics and Applications*, 1, 17-22.
138. Stoakley, R., Conway, M. J., & Pausch, R. (1995, May). Virtual reality on a WIM: interactive worlds in miniature. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 265-272).
139. Stoev, S. L., Schmalstieg, D., & Straßer, W. (2001). Two-handed through-the-lens-techniques for navigation in virtual environments. In *Immersive Projection Technology and Virtual Environments 2001* (pp. 51-60). Springer, Vienna.
140. Strauss, R. R., Ramanujan, R., Becker, A., & Peck, T. C. (2020). A steering algorithm for redirected walking using reinforcement learning. *IEEE transactions on visualization and computer graphics*, 26(5), 1955-1963.
141. Suma, E. A., Lipps, Z., Finkelstein, S., Krum, D. M., & Bolas, M. (2012). Impossible spaces: Maximizing natural walking in virtual environments with self-overlapping architecture. *IEEE Transactions on Visualization and Computer Graphics*, 18(4), 555-564.
142. Suma, E. A., Clark, S., Krum, D., Finkelstein, S., Bolas, M., & Warte, Z. (2011, March). Leveraging change blindness for redirection in virtual environments. In *2011 IEEE Virtual Reality Conference* (pp. 159-166). IEEE.

## T

143. Tregillus, S., Al Zayer, M., & Folmer, E. (2017, May). Handsfree omnidirectional VR navigation using head tilt. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (pp. 4063-4068).
144. Tregillus, S., & Folmer, E. (2016, May). Vr-step: Walking-in-place using inertial sensing for hands free navigation in mobile vr environments. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (pp. 1250-1255).
145. Trinon, H. (2019). Immersive technologies for virtual reality-case study: Flight simulator for pilot training.

## U

146. Usoh, M., Arthur, K., Whitton, M. C., Bastos, R., Steed, A., Slater, M., & Brooks Jr, F. P. (1999, July). Walking> walking-in-place> flying, in virtual environments. In Proceedings of the 26th annual conference on Computer graphics and interactive techniques (pp. 359-364).

## V

147. Valuates, <https://reports.valuates.com/market-reports/ALLI-Auto-4H304/augmented-and-virtual-reality>
148. Väljamäe, A. (2009). Auditorily-induced illusory self-motion: A review. Brain research reviews, 61(2), 240-255.
149. Vasylevska, K., & Kaufmann, H. (2017, March). Towards efficient spatial compression in self-overlapping virtual environments. In 2017 IEEE Symposium on 3D User Interfaces (3DUI) (pp. 12-21). IEEE.
150. Vasylevska, K., Kaufmann, H., Bolas, M., & Suma, E. A. (2013, March). Flexible spaces: Dynamic layout generation for infinite walking in virtual environments. In 2013 IEEE Symposium on 3D User Interfaces (3DUI) (pp. 39-42). IEEE.
151. Vatavu, R. D. (2012, July). User-defined gestures for free-hand TV control. In Proceedings of the 10th European conference on Interactive tv and video (pp. 45-48).
152. Vermeeren, A. P., Law, E. L. C., Roto, V., Obrist, M., Hoonhout, J., & Väänänen-Vainio-Mattila, K. (2010, October). User experience evaluation methods: current state and

development needs. In Proceedings of the 6th Nordic conference on human-computer interaction: Extending boundaries (pp. 521-530).

153. von Willich, J., Schön, D., Günther, S., Müller, F., Mühlhäuser, M., & Funk, M. (2019, May). VRChairRacer: Using an Office Chair Backrest as a Locomotion Technique for VR Racing Games. In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-4).

## W

154. Waller, D., & Hodgson, E. (2013). Sensory contributions to spatial knowledge of real and virtual environments. Human walking in virtual environments: Perception, technology, and applications, 3-26.
155. Wang, J., & Lindeman, R. W. (2012, March). Comparing isometric and elastic surfboard interfaces for leaning-based travel in 3D virtual environments. In 2012 IEEE Symposium on 3D User Interfaces (3DUI) (pp. 31-38). IEEE.
156. Whitton, M. C., & Razaque, S. (2008). Locomotion Interfaces. HCI Beyond the GUI. 107–146.
157. Whitton, M. C., Cohn, J. V., Feasel, J., Zimmons, P., Razaque, S., Poulton, S. J., ... & Brooks, F. P. (2005, March). Comparing VE locomotion interfaces. In IEEE Proceedings. VR 2005. Virtual Reality, 2005. (pp. 123-130). IEEE.
158. Williams, B., Bailey, S., Narasimham, G., Li, M., & Bodenheimer, B. (2011). Evaluation of walking in place on a wii balance board to explore a virtual environment. ACM Transactions on Applied Perception (TAP), 8(3), 1-14.
159. Williams, B., Narasimham, G., Rump, B., McNamara, T. P., Carr, T. H., Rieser, J., & Bodenheimer, B. (2007, July). Exploring large virtual environments with an HMD when physical space is limited. In Proceedings of the 4th symposium on Applied perception in graphics and visualization (pp. 41-48).
160. Wilson, P. T., Kalescky, W., MacLaughlin, A., & Williams, B. (2016, December). VR locomotion: walking> walking in place> arm swinging. In Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry-Volume 1 (pp. 243-249).

161. Wobbrock, J. O., Morris, M. R., & Wilson, A. D. (2009, April). User-defined gestures for surface computing. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 1083-1092).

## X

162. Xing, X., & Saunders, J. A. (2021). Different generalization of fast and slow visuomotor adaptation across locomotion and pointing tasks. *Experimental Brain Research*, 239(9), 2859-2871.
163. Xu, M., Murcia-López, M., & Steed, A. (2017, March). Object location memory error in virtual and real environments. In 2017 IEEE Virtual Reality (VR) (pp. 315-316). IEEE.

## Z

164. Zambaka, C., Babu, S., Xiao, D., Ulinski, A., Hodges, L. F., & Lok, B. (2004, March). Effects of travel technique on cognition in virtual environments. In *IEEE Virtual Reality 2004* (pp. 149-286). IEEE.
165. Zhang, F., Chu, S., Pan, R., Ji, N., & Xi, L. (2017, May). Double hand-gesture interaction for walk-through in VR environment. In 2017 IEEE/ACIS 16th International Conference on Computer and Information Science (ICIS) (pp. 539-544). IEEE.
166. Zielasko, D., & Riecke, B. E. (2021). To sit or not to sit in vr: Analyzing influences and (dis) advantages of posture and embodied interaction. *Computers*, 10(6), 73.

## APPENDIX A

### User Study 1 – Investigating suitable locomotion gestures for different multitasking environments

#### Introduction to this Questionnaire

Thank you very much for agreeing to take part in this important study of “ Gesture Elicitation User Study for Locomotion in VR “.

This short questionnaire is a part of research work being conducted for gesture elicitation for the locomotion functionality in HMD based VR at EILAB at Department of Design, IIT Guwahati. The aim of this research is to elucidate the gestures for locomotion activity in a HMD based VR in a multitasking environment.

You can perform gestures of your choice which you think most natural, intuitive, and best represents the virtual travel task for the particular scenario.

We have a training module for the users who are new to VR. They can explore the environment and have some hands-on experience of locomotion in HMD based VR.

This experiment will take 50-60 minutes to complete. All personal information provided by you in this questionnaire will be kept confidential and we assure you that the participants will be kept non-traceable and anonymous. The names of the participants have only been taken for the follow-up interview if required.

Once again thank you for participating in this research study and giving us your precious time.

For submissions or inquiry please contact

Priya Vinod

PhD Research Scholar,

EI LAB,

Department of Design, IIT Guwahati.

Email Id – priyaganapathy@gmail.com

Phone - 9365278248

General Information about the participant

1. Full Name: \_\_\_\_\_

2. Age: \_\_\_\_\_

3. Gender:  Male  Female

4. Name of the Degree Course and the Institution you're enrolled in:

\_\_\_\_\_

5. Have you ever heard or read about the term Virtual Reality?

Yes  No

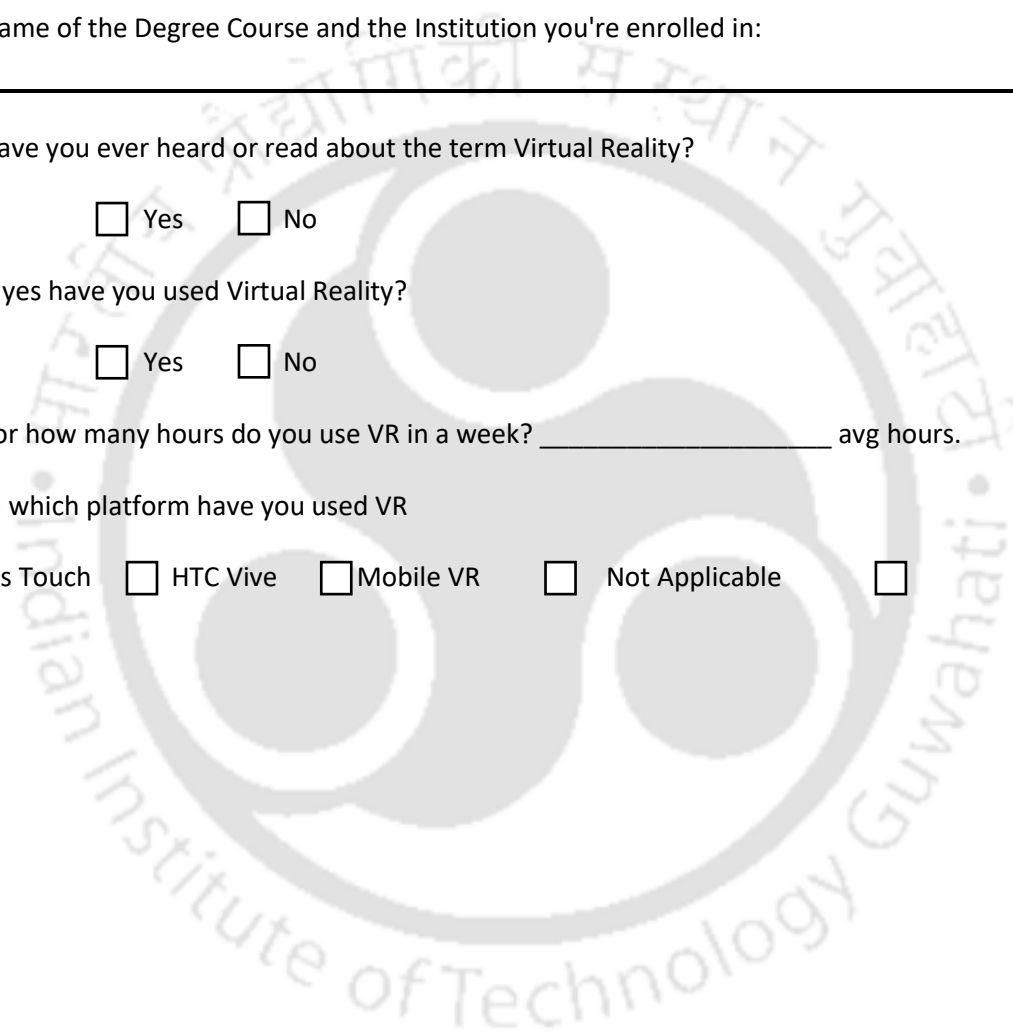
6. If yes have you used Virtual Reality?

Yes  No

7. For how many hours do you use VR in a week? \_\_\_\_\_ avg hours.

8. In which platform have you used VR

Oculus Touch  HTC Vive  Mobile VR  Not Applicable



**VE 1 – Virtual Locomotion without selection or manipulation**

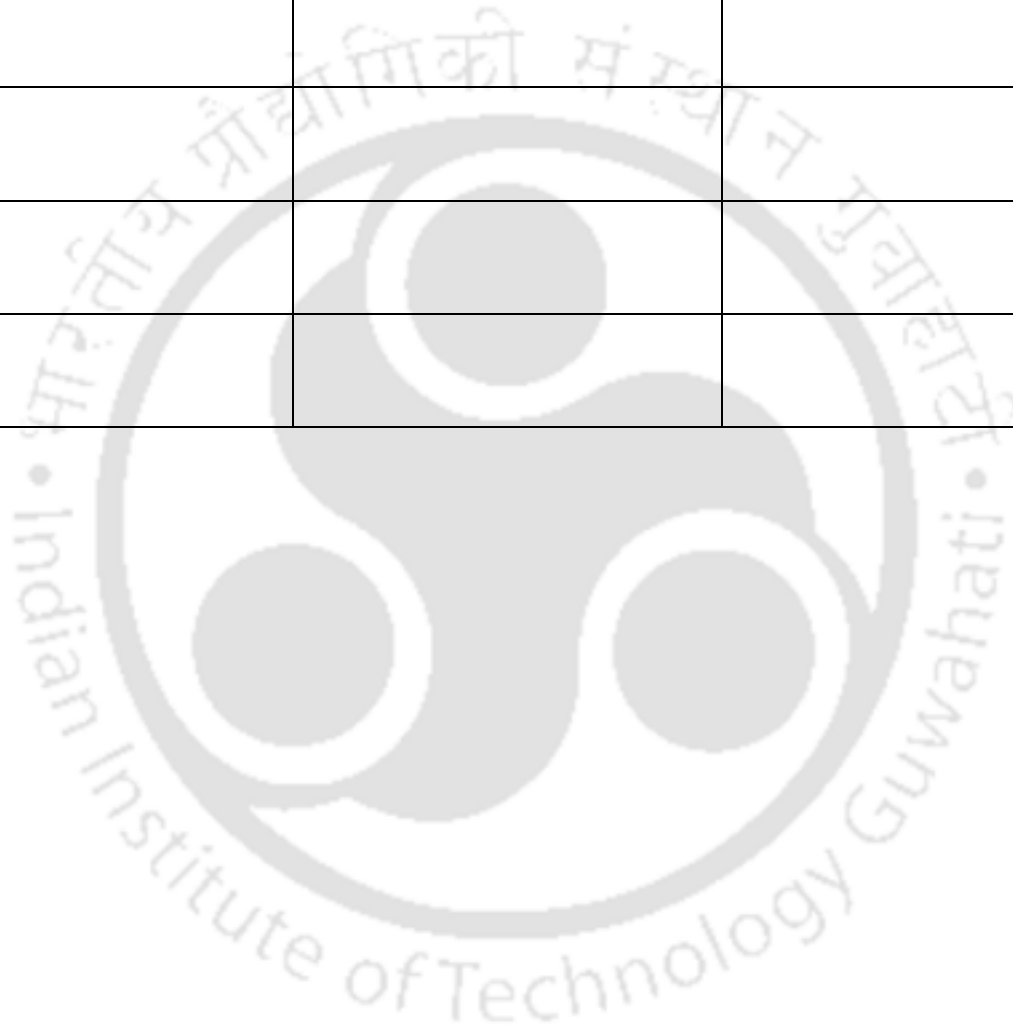
<b><u>Gesture for Walking</u></b>	<b><u>Gesture for Running</u></b>	<b><u>Preference</u></b>

**VE 2 – Virtual Locomotion along with one selection or manipulation of a virtual object**

<b><u>Gesture for Walking</u></b>	<b><u>Gesture for Running</u></b>	<b><u>Preference</u></b>

**VE 3 – Virtual Locomotion along with two selection and manipulation of two virtual objects**

<b><u>Gesture for Walking</u></b>	<b><u>Gesture for Running</u></b>	<b><u>Preference</u></b>



## APPENDIX B

### **User Study 2 – Evaluating the proposed locomotion gestures for the different multitasking environments**

#### **Introduction to this Questionnaire**

Thank you very much for agreeing to take part in this important study of “Evaluating the proposed locomotion gestures for the different multitasking environments “.

This short questionnaire is a part of research work being conducted for gesture elicitation for the locomotion functionality in HMD based VR at EILAB at Department of Design, IIT Guwahati. The aim of this research is to evaluate the gestures for locomotion in different environments.

This questionnaire will help us in identifying the most preferred gesture based on the effort, match, preference and ease of use from the set of user-defined gestures which was obtained from the first study.

We have a training module for the users who are new to VR. They can explore the environment and have some hands-on experience of locomotion in HMD based VR.

This experiment will take 30-40 minutes to complete. All personal information provided by you in this questionnaire will be kept confidential and we assure you that the participants will be kept non-traceable and anonymous. The names of the participants have only been taken for the follow-up interview if required.

Once again thank you for participating in this research study and giving us your precious time.

For submissions or inquiry please contact

Priya Vinod

PhD Research Scholar,

EI LAB,

Department of Design, IIT Guwahati.

Email Id – priyaganapathy@gmail.com

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General Information about the participant

1. Full Name: \_\_\_\_\_

2. Age: \_\_\_\_\_

3. Gender:  Male  Female

4. Name of the Degree Course and the Institution you're enrolled in:

\_\_\_\_\_

5. Have you ever heard or read about the term Virtual Reality?

Yes  No

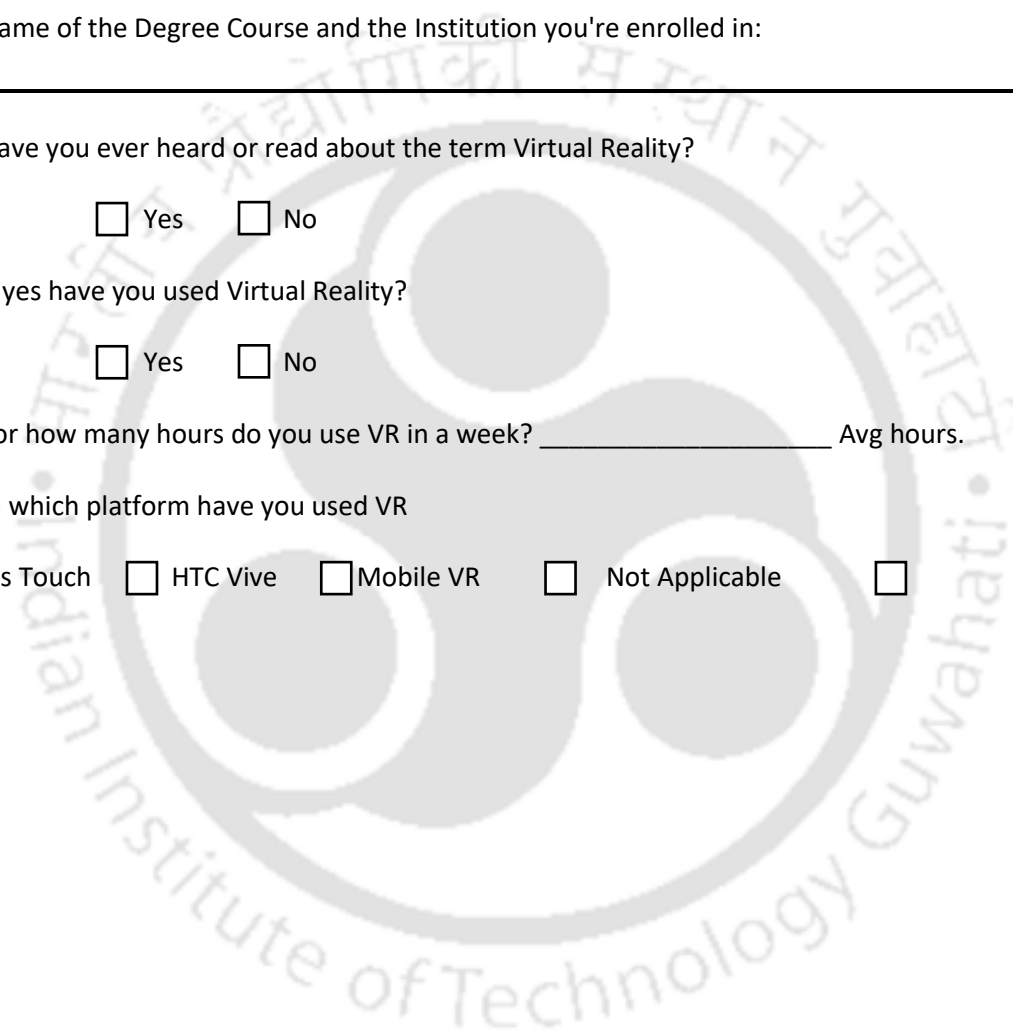
6. If yes have you used Virtual Reality?

Yes  No

7. For how many hours do you use VR in a week? \_\_\_\_\_ Avg hours.

8. In which platform have you used VR

Oculus Touch  HTC Vive  Mobile VR  Not Applicable



**VE 1 – Virtual Locomotion without selection or manipulation**

**a) Gesture 1 – Calling Gesture**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**b) Gesture 2 – Leaning**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**c) Gesture 3 – Bike Riding**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**(iv) Effort Ranking**----Ranking based on the gesture that requires the least amount of effort (1 being least effort and 3 being more effort)

**Gesture 1 -**

**Gesture 2 -**

**Gesture 3 -**

**(v) User Preference Ranking**----Overall User Preference (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> preference)

**Gesture 1 -**

**Gesture 2 -**

**Gesture 3 -**

**Comment if any**

**VE 2 – Virtual Locomotion along with one selection or manipulation of a virtual object**

**a) Gesture 1 – Calling Gesture**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**b) Gesture 2 – Leaning**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**c) Gesture 3 - Pointing**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**(iv) Effort Ranking**----Ranking based on the gesture that requires the least amount of effort (1 being least effort and 3 being more effort)

**Gesture 1 -**

**Gesture 2 -**

**Gesture 3 -**

**(v) User Preference Ranking**---Overall User Preference (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> preference)

**Gesture 1 -**

**Gesture 2 -**

**Gesture 3 -**

**Comment if any**

**VE 3 – Virtual Locomotion along with two selection and manipulation of two virtual objects**

**a) Gesture 1 – WIP**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**b) Gesture 2 – Tapping**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**c) Gesture 3 – Leaning**

Please rate (i.e. put a tick mark (✓) in the box) agreement or disagreement with the following statement.

**(i) Matching**

I found the gesture is a good match for the intended purpose

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(ii) Ease of Use**

I found the gesture easy to perform

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**(iii) Effort (1 is Easy and 5 is difficult)**

The amount of effort required to perform the task using this gesture along with selection and manipulation

<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
1	2	3	4	5

**(iv) Effort Ranking**----Ranking based on the gesture that requires the least amount of effort (1 being least effort and 3 being more effort)

**Gesture 1 -**

**Gesture 2 -**

**Gesture 3 -**

**(v) User Preference Ranking**---Overall User Preference (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> preference)

**Gesture 1 -**

**Gesture 2 -**

**Gesture 3 -**

**Comment if any**

## APPENDIX C

### User Study 3 – Comparing Calling, Tapping and Teleportation locomotion technique for virtual travel with no multitasking

#### Introduction to this Questionnaire

Thank you very much for agreeing to take part in this important study of “Comparing gesture based locomotion technique for virtual travel with no multitasking”.

This questionnaire is a part of research work being conducted for “Design and Evaluation of User-Centric Gestures for Locomotion in HMD-VR Interfaces for a Seated Position”. The aim of this research is to evaluate the three techniques for locomotion in a HMD based VR in a multitasking environment.

We have a training module for the users who are new to VR. They can explore the environment and have some hands-on experience of locomotion in HMD based VR.

This experiment will take 50-60 minutes to complete. All personal information provided by you in this questionnaire will be kept confidential and we assure you that the participants will be kept non-traceable and anonymous. The names of the participants have only been taken for the follow-up interview if required.

Once again thank you for participating in this research study and giving us your precious time.

For submissions or inquiry please contact

Priya Vinod

PhD Research Scholar,

EI LAB,

Department of Design, IIT Guwahati.

Email Id – priyaganapathy@gmail.com

Phone - 9365278248

General Information about the participant

1. Full Name: \_\_\_\_\_

2. Age: \_\_\_\_\_

3. Gender:  Male  Female

4. Name of the Degree Course and the Institution you're enrolled in:

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5. Do you play games in gadgets (mobile, PS4, Xbox)?

Yes  No

6. For how many hours do you play in gadgets for a week? \_\_\_\_\_ avg hours.

7. Have you ever heard or read about the term Virtual Reality?

Yes  No

8. If yes have you used Virtual Reality?

Yes  No

9. For how many hours do you use VR in a week? \_\_\_\_\_ Avg hours.

10. If you are using VR, then what kind of applications do you work with \_\_\_\_\_

11. In which platform have you used VR

Oculus Touch  HTC Vive  Mobile VR  Not Applicable

**Degree of intuitiveness:** The technique used to perform the walking task was found to be natural.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Degree of Comfort** - I felt the technique to be comfortable to use for long period of time.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Ease of use**– I felt the technique was easy to perform for completing the given task.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Physical Effort –NASA TLX – 7 point Likert scale or general question**

1) *Mental Demand* - How mentally demanding was the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

2) *Physical Demand* - How physically demanding was the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

3) *Temporal Demand* - How hurried or rushed was the pace of the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

4) *Performance* - How successful were you in accomplishing what you were asked to do?

Perfect	Better	Good	Neutral	Bad	Worse	Failure

5) *Effort* - How hard did you have to work to accomplish your level of performance?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

6) *Frustration* - How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

**Task Performance –**

	Straight Line Path	Directed Path	Undirected Path
Total Time			
Object 1			
Object 2			
Object 3			
Object 4			
Object 5			
Object 6			

**Spatial Knowledge**

a) Which objects were seen between apples and biscuits?

\_\_\_\_\_

b) Which vegetable was seen near the banana?

\_\_\_\_\_

c) Opposite to Coco-Cola shelf the object kept was?

(i) Banana (ii) Coffee (iii) Wafers (iv) Cornflakes

d) In which shelf was the chocolate syrup bottle kept?

(i) Lower shelf (ii) middle shelf (iii) upper shelf

e) Name any one advertisement that was placed near the entrance of the supermarket

\_\_\_\_\_

**Presence**

<p>1 How dizzy, sick or nauseous did you feel resulting from the experience, if at all?</p> <p><b><i>I felt sick or dizzy or nauseous during or as a result of the experience...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much so</p>
<p>2 Please rate <i>your sense of being in the supermarket using the technique</i>, on the following scale from 1 to 7, where 7 represent your <i>normal experience of being in a place</i>.</p> <p><b><i>I had a sense of being there in the supermarket...</i></b></p> <p>at no time 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all the time</p>
<p>3 To what extent were there times during the experience when the supermarket was the reality for you?</p> <p><b><i>There were times during the experience when supermarket was the reality for me...</i></b></p> <p>at no time 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all the time</p>
<p>4 When you think back about your experience, do you think of the supermarket more as <i>images that you saw</i>, or more as <i>somewhere that you visited</i>?</p> <p><b><i>The supermarket seemed to be more like...</i></b></p> <p>images that I saw 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> somewhere I visited</p>
<p>5 During experiment, how realistic was the experience while moving in the supermarket using this technique?</p> <p><b><i>The movement was real...</i></b></p> <p>never 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all time</p>
<p>6 Overall, how much did you enjoy your experience?</p>

***I enjoyed the experience .....***

not at all 1  2  3  4  5  6  7  very much so

7 During the time of the experience, did you often think to yourself that you were walking in the supermarket while interacting or moving?

***During the experience I was thinking that I was really walking ...***

most of the time 1  2  3  4  5  6  7  rarely

8 During the course of the experience, how much were you aware of the real world surrounding?

***During the course of the experience I was aware of the real world surrounding ...***

not at all 1  2  3  4  5  6  7  very much

9 How much did you behave within the VR supermarket as if the situation were real?

***I responded as if the situation were real ...***

not at all 1  2  3  4  5  6  7  very much

10 How realistic was the grabbing of objects seemed to you for selection in the supermarket ?

***I felt it was real ...***

not at all 1  2  3  4  5  6  7  very much

11 How difficult was it to move in the turnings in the supermarket using this technique?

***The movement in the turnings was easy...***

not at all 1  2  3  4  5  6  7  very much

12 How much did you have physical responses (such as change in heart rate, startled, sweating, etc.) when collided with the shopping items as if they were real?

***My physical responses to while colliding with the shopping items as if they were real....***

not at all 1  2  3  4  5  6  7  very much

<p>13 How easy was it to stop while moving using the technique?</p> <p><b><i>I immediately stopped when I stopped performing the technique</i></b></p> <p>Not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>14 How much did you want to leave the supermarket before completion?</p> <p><b><i>I wanted to leave...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>15 How easy it was to grab the items from the shelf using this locomotion technique?</p> <p><b><i>It was easy to grab the items in this technique...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>16 How easy was it to navigate in the supermarket using this technique?</p> <p><b><i>It was easy to navigate using this technique...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>17 How easy was it to look for the items placed in different heights using this technique?</p> <p><b><i>It was easy to look for the items at different heights using this technique</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>18 How easy was it to avoid colliding with the shopping carts and items using this technique?</p> <p><b><i>It was easy to avoid collision with carts and items using this technique...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>

## Simulator Sickness Questionnaire

Circle how much each symptom below is affecting you **right now**.

1	General Discomfort	None	Slight	Moderate	Severe
2	Fatigue	None	Slight	Moderate	Severe
3	Headache	None	Slight	Moderate	Severe
4	Eye Strain	None	Slight	Moderate	Severe
5	Difficulty Focusing	None	Slight	Moderate	Severe
6	Salivation Increasing	None	Slight	Moderate	Severe
7	Sweating	None	Slight	Moderate	Severe
8	Nausea	None	Slight	Moderate	Severe
9	Difficulty Concentrating	None	Slight	Moderate	Severe
10	Fullness of Head	None	Slight	Moderate	Severe
11	Blurred Vision	None	Slight	Moderate	Severe
12	Dizziness with Eyes Open	None	Slight	Moderate	Severe
13	Dizziness with Eyes Closed	None	Slight	Moderate	Severe
14	Vertigo*	None	Slight	Moderate	Severe
15	Stomach Awareness**	None	Slight	Moderate	Severe
16	Burping	None	Slight	Moderate	Severe

\* Vertigo is experienced as loss of orientation with respect to vertical upright.

\*\* Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

**USER PREFERENCE QUESTIONNAIRE**

1.	Which locomotion technique you prefer for moving in the supermarket?	<input type="checkbox"/> Calling	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
2.	Which locomotion technique you prefer for easily looking at items in the supermarket?	<input type="checkbox"/> Calling	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
3.	Which locomotion technique you prefer for grabbing the items in the supermarket?	<input type="checkbox"/> Calling	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
4.	Which locomotion technique was most comfortable for the performed activity?	<input type="checkbox"/> Calling	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
5.	Which locomotion technique required less effort to perform the activity?	<input type="checkbox"/> Calling	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
6.	Can you rate the preference of the three locomotion technique from 1-3 (with 1-most preferred to 3 –least preferred)	a) Calling - _____ b) Tapping - _____ c) Teleportation - _____		

7. Can you please provide the reason for preferring the above locomotion technique?

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## APPENDIX D

### **User Study 4 – Comparing Deictic Pointing, Tapping and Teleportation locomotion technique for virtual travel with one hand engaged in selection and manipulation of one virtual object.**

#### **Introduction to this Questionnaire**

Thank you very much for agreeing to take part in this important study of “Comparing gesture based locomotion technique for virtual travel when one hand is engaged in multitasking”.

This questionnaire is a part of research work being conducted for “Design and Evaluation of User-Centric Gestures for Locomotion in HMD-VR Interfaces for a Seated Position”. The aim of this research is to evaluate the three techniques for locomotion in a HMD based VR in a multitasking environment.

We have a training module for the users who are new to VR. They can explore the environment and have some hands-on experience of locomotion in HMD based VR.

This experiment will take 50-60 minutes to complete. All personal information provided by you in this questionnaire will be kept confidential and we assure you that the participants will be kept non-traceable and anonymous. The names of the participants have only been taken for the follow-up interview if required.

Once again thank you for participating in this research study and giving us your precious time.

For submissions or inquiry please contact

Priya Vinod

PhD Research Scholar,

EI LAB,

Department of Design, IIT Guwahati.

Email Id – priyaganapathy@gmail.com

Phone - 9365278248

General Information about the participant

1. Full Name: \_\_\_\_\_
2. Age: \_\_\_\_\_
3. Gender:  Male  Female
4. Name of the Degree Course and the Institution you're enrolled in:  
\_\_\_\_\_
5. Do you play games in gadgets (mobile, PS4, Xbox)?  
 Yes  No
6. For how many hours do you play in gadgets for a week? \_\_\_\_\_ Avg hours.
7. Have you ever heard or read about the term Virtual Reality?  
 Yes  No
8. If yes have you used Virtual Reality?  
 Yes  No
9. For how many hours do you use VR in a week? \_\_\_\_\_ avg hours.
10. If you are using VR, then what kind of applications do you work with \_\_\_\_\_
11. In which platform have you used VR  
Oculus Touch  HTC Vive  Mobile VR  Not Applicable

**Degree of intuitiveness:** The technique used to perform the walking task was found to be natural.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Degree of Comfort** - I felt the technique to be comfortable to use for long period of time.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Ease of use**– I felt the technique was easy to perform for completing the given task.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Physical Effort –NASA TLX – 7 point Likert scale or general question**

1) *Mental Demand* - How mentally demanding was the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

*Physical Demand* - How physically demanding was the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

2) *Temporal Demand* - How hurried or rushed was the pace of the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

3) *Performance* - How successful were you in accomplishing what you were asked to do?

Perfect	Better	Good	Neutral	Bad	Worse	Failure

4) *Effort* - How hard did you have to work to accomplish your level of performance?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

5) *Frustration* - How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

**Task Performance –**

	Straight Line Path	Directed Path	Undirected Path
Total Time			
Object 1			
Object 2			
Object 3			
Object 4			
Object 5			
Object 6			

**Spatial Knowledge**

a) Which objects were seen between cereals and biscuits?

\_\_\_\_\_

b) Which vegetable was seen near the apples?

\_\_\_\_\_

c) Opposite to cereal shelf the object kept was?

(ii) Banana (ii) Coffee (iii) Wafers (iv) Cornflakes

d) In which shelf was the Coco-cola bottle kept?

(ii) Lower shelf (ii) middle shelf (iii) upper shelf

e) Name any one advertisement that was placed near the freezer of the supermarket

\_\_\_\_\_

Presence

<p>1 How dizzy, sick or nauseous did you feel resulting from the experience, if at all?</p> <p><b><i>I felt sick or dizzy or nauseous during or as a result of the experience...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much so</p>
<p>2 Please rate <i>your sense of being in the supermarket using the technique</i>, on the following scale from 1 to 7, where 7 represent your <i>normal experience of being in a place</i>.</p> <p><b><i>I had a sense of being there in the supermarket...</i></b></p> <p>at no time 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all the time</p>
<p>3 To what extent were there times during the experience when the supermarket was the reality for you?</p> <p><b><i>There were times during the experience when supermarket was the reality for me...</i></b></p> <p>at no time 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all the time</p>
<p>4 When you think back about your experience, do you think of the supermarket more as <i>images that you saw</i>, or more as <i>somewhere that you visited</i>?</p> <p><b><i>The supermarket seemed to be more like...</i></b></p> <p>images that I saw 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> somewhere I visited</p>
<p>5 During experiment, how realistic was the experience while moving in the supermarket using this technique?</p> <p><b><i>The movement was real...</i></b></p> <p>never 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all time</p>
<p>6 Overall, how much did you enjoy your experience?</p> <p><b><i>I enjoyed the experience .....</i></b></p>

not at all 1  2  3  4  5  6  7  very much so

7 During the time of the experience, did you often think to yourself that you were walking in the supermarket while interacting or moving?

***During the experience I was thinking that I was really walking ...***

most of the time 1  2  3  4  5  6  7  rarely

8 During the course of the experience, how much were you aware of the real world surrounding?

***During the course of the experience I was aware of the real world surrounding ...***

not at all 1  2  3  4  5  6  7  very much

9 How much did you behave within the VR supermarket as if the situation were real?

***I responded as if the situation were real ...***

not at all 1  2  3  4  5  6  7  very much

10 How realistic was the grabbing of objects seemed to you for selection in the supermarket ?

***I felt it was real ...***

not at all 1  2  3  4  5  6  7  very much

11 How difficult was it to move in the turnings in the supermarket using this technique?

***The movement in the turnings was easy...***

not at all 1  2  3  4  5  6  7  very much

12 How much did you have physical responses (such as change in heart rate, startled, sweating, etc.) when collided with the shopping items as if they were real?

***My physical responses to while colliding with the shopping items as if they were real...***

not at all 1  2  3  4  5  6  7  very much

13 How easy was it to stop while moving using the technique?

<p><b><i>I immediately stopped when I stopped performing the technique</i></b></p> <p>Not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>14 How much did you want to leave the supermarket before completion?</p> <p><b><i>I wanted to leave...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>15 How easy it was to grab the items from the shelf using this locomotion technique?</p> <p><b><i>It was easy to grab the items in this technique...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>16 How easy was it to navigate in the supermarket using this technique?</p> <p><b><i>It was easy to navigate using this technique...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>17 How easy was it to look for the items placed in different heights using this technique?</p> <p><b><i>It was easy to look for the items at different heights using this technique</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>18 How easy was it to avoid colliding with the shopping carts and items using this technique?</p> <p><b><i>It was easy to avoid collision with carts and items using this technique...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>

# Simulator Sickness Questionnaire

Circle how much each symptom below is affecting you **right now**.

1	General Discomfort	None	Slight	Moderate	Severe
2	Fatigue	None	Slight	Moderate	Severe
3	Headache	None	Slight	Moderate	Severe
4	Eye Strain	None	Slight	Moderate	Severe
5	Difficulty Focusing	None	Slight	Moderate	Severe
6	Salivation Increasing	None	Slight	Moderate	Severe
7	Sweating	None	Slight	Moderate	Severe
8	Nausea	None	Slight	Moderate	Severe
9	Difficulty Concentrating	None	Slight	Moderate	Severe
10	Fullness of Head	None	Slight	Moderate	Severe
11	Blurred Vision	None	Slight	Moderate	Severe
12	Dizziness with Eyes Open	None	Slight	Moderate	Severe
13	Dizziness with Eyes Closed	None	Slight	Moderate	Severe
14	Vertigo*	None	Slight	Moderate	Severe
15	Stomach Awareness**	None	Slight	Moderate	Severe
16	Burping	None	Slight	Moderate	Severe

\* Vertigo is experienced as loss of orientation with respect to vertical upright.

\*\* Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

**USER PREFERENCE QUESTIONNAIRE**

1.	Which locomotion technique you prefer for moving in the supermarket?	<input type="checkbox"/> Deictic Pointing	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
2.	Which locomotion technique you prefer for easily looking at items in the supermarket?	<input type="checkbox"/> Deictic Pointing	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
3.	Which locomotion technique you prefer for grabbing the items in the supermarket?	<input type="checkbox"/> Deictic Pointing	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
4.	Which locomotion technique was most comfortable for the performed activity?	<input type="checkbox"/> Deictic Pointing	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
5.	Which locomotion technique required less effort to perform the activity?	<input type="checkbox"/> Deictic Pointing	<input type="checkbox"/> Tapping	<input type="checkbox"/> Teleportation
6.	Can you rate the preference of the three locomotion technique from 1-3 (with 1- most preferred to 3 –least preferred)	<p>a) Deictic Pointing- _____</p> <p>b) Tapping - _____</p> <p>c) Teleportation - _____</p>		

12. Can you please provide the reason for preferring the above locomotion technique?

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## APPENDIX E

**User Study 5 – Comparing Mirror Leaning, Tapping and Teleportation locomotion technique for virtual travel with both hands engaged in selection and manipulation of two virtual objects.**

### Introduction to this Questionnaire

Thank you very much for agreeing to take part in this important study of “Comparing gesture based locomotion technique for virtual travel when both hands are engaged “.

This questionnaire is a part of research work being conducted for “Design and Evaluation of User-Centric Gestures for Locomotion in HMD-VR Interfaces for a Seated Position”. The aim of this research is to evaluate the three techniques for locomotion in a HMD based VR in a multitasking environment.

We have a training module for the users who are new to VR. They can explore the environment and have some hands-on experience of locomotion in HMD based VR.

This experiment will take 50-60 minutes to complete. All personal information provided by you in this questionnaire will be kept confidential and we assure you that the participants will be kept non-traceable and anonymous. The names of the participants have only been taken for the follow-up interview if required.

Once again thank you for participating in this research study and giving us your precious time.

For submissions or inquiry please contact

Priya Vinod

PhD Research Scholar,

EI LAB,

Department of Design, IIT Guwahati.

Email Id – priyaganapathy@gmail.com

Phone - 9365278248

General Information about the participant

1. Full Name: \_\_\_\_\_

2. Age: \_\_\_\_\_

3. Gender:  Male  Female

4. Name of the Degree Course and the Institution you're enrolled in:

\_\_\_\_\_

5. Do you play games in gadgets (mobile, PS4, Xbox)?

Yes  No

6. For how many hours do you play in gadgets for a week? \_\_\_\_\_ avg hours.

7. Have you ever heard or read about the term Virtual Reality?

Yes  No

8. If yes have you used Virtual Reality?

Yes  No

9. For how many hours do you use VR in a week? \_\_\_\_\_ Avg hours.

10. If you are using VR, then what kind of applications do you work with \_\_\_\_\_

11. In which platform have you used VR

Oculus Touch  HTC Vive  Mobile VR  Not Applicable

**Degree of intuitiveness:** The technique used to perform the walking task was found to be natural.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Degree of Comfort** - I felt the technique to be comfortable to use for long period of time.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Ease of use**– I felt the technique was easy to perform for completing the given task.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

**Physical Effort –NASA TLX – 7 point Likert scale or general question**

1) *Mental Demand* - How mentally demanding was the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

2) *Physical Demand* - How physically demanding was the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

3) *Temporal Demand* - How hurried or rushed was the pace of the task?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

4) *Performance* - How successful were you in accomplishing what you were asked to do?

Perfect	Better	Good	Neutral	Bad	Worse	Failure

5) *Effort* - How hard did you have to work to accomplish your level of performance?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

6) *Frustration* - How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low	Low	Fairly Low	Neutral	Fairly High	High	Very High

**Task Performance –**

	Straight Line Path	Directed Path	Undirected Path
Total Time			
Object 1			
Object 2			
Object 3			
Object 4			
Object 5			
Object 6			

**Spatial Knowledge**

a) Which objects were seen between apples and pears?

\_\_\_\_\_

b) Which item was seen below the carrots?

\_\_\_\_\_

c) Opposite to chocolate Syrup shelf the object kept was?

(iii) Banana (ii) Coffee (iii) Wafers (iv) Cornflakes

d) In which shelf was the juice bottle kept?

(iii) Lower shelf (ii) middle shelf (iii) upper shelf

e) Name any one advertisement that was placed at the back wall of the supermarket

\_\_\_\_\_

Presence

<p>1 How dizzy, sick or nauseous did you feel resulting from the experience, if at all?</p> <p><b><i>I felt sick or dizzy or nauseous during or as a result of the experience...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much so</p>
<p>2 Please rate <i>your sense of being in the supermarket using the technique</i>, on the following scale from 1 to 7, where 7 represent your <i>normal experience of being in a place</i>.</p> <p><b><i>I had a sense of being there in the supermarket...</i></b></p> <p>at no time 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all the time</p>
<p>3 To what extent were there times during the experience when the supermarket was the reality for you?</p> <p><b><i>There were times during the experience when supermarket was the reality for me...</i></b></p> <p>at no time 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all the time</p>
<p>4 When you think back about your experience, do you think of the supermarket more as <i>images that you saw</i>, or more as <i>somewhere that you visited</i>?</p> <p><b><i>The supermarket seemed to be more like...</i></b></p> <p>images that I saw 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> somewhere I visited</p>
<p>5 During experiment, how realistic was the experience while moving in the supermarket using this technique?</p> <p><b><i>The movement was real...</i></b></p> <p>never 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> almost all time</p>
<p>6 Overall, how much did you enjoy your experience?</p> <p><b><i>I enjoyed the experience .....</i></b></p>

not at all 1  2  3  4  5  6  7  very much so

7 During the time of the experience, did you often think to yourself that you were walking in the supermarket while interacting or moving?

***During the experience I was thinking that I was really walking ...***

most of the time 1  2  3  4  5  6  7  rarely

8 During the course of the experience, how much were you aware of the real world surrounding?

***During the course of the experience I was aware of the real world surrounding ...***

not at all 1  2  3  4  5  6  7  very much

9 How much did you behave within the VR supermarket as if the situation were real?

***I responded as if the situation were real ...***

not at all 1  2  3  4  5  6  7  very much

10 How realistic was the grabbing of objects seemed to you for selection in the supermarket ?

***I felt it was real ...***

not at all 1  2  3  4  5  6  7  very much

11 How difficult was it to move in the turnings in the supermarket using this technique?

***The movement in the turnings was easy...***

not at all 1  2  3  4  5  6  7  very much

12 How much did you have physical responses (such as change in heart rate, startled, sweating, etc.) when collided with the shopping items as if they were real?

***My physical responses to while colliding with the shopping items as if they were real...***

not at all 1  2  3  4  5  6  7  very much

13 How easy was it to stop while moving using the technique?

<p><b><i>I immediately stopped when I stopped performing the technique</i></b></p> <p>Not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
<p>14 How much did you want to leave the supermarket before completion?</p> <p><b><i>I wanted to leave...</i></b></p> <p>not at all 1 <input type="radio"/> 2 <input type="radio"/> 3 <input type="radio"/> 4 <input type="radio"/> 5 <input type="radio"/> 6 <input type="radio"/> 7 <input type="radio"/> very much</p>
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8. Can you please provide the reason for preferring the above locomotion technique?

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## PUBLICATIONS

- 1) Ganapathi, P., & Sorathia, K. (2019). Elicitation study of body gestures for locomotion in HMD-VR interfaces in a sitting-position. International ACM SIGGRAPH Conference on Motion, Interaction, and Games (pp. 1-10).
- 2) Ganapathi, P., & Sorathia, K. (2022). Analysis of Body-Gestures Elucidated Through Elicitation Study for Natural Locomotion in Virtual Reality. In International Conference of the Indian Society of Ergonomics (pp. 1313-1326). Springer, Cham.
- 3) Ganapathi, P., & Sorathia, K. (2022). Virtual Reality Gesture Based Locomotion Technique – A Systematic Literature Review. In International Conference of the Indian Society of Ergonomics.
- 4) Ganapathi, P., & Sorathia, K. (2023). User Elicited Gesture Based Locomotion Techniques for Immersive Virtual Environments in a Seated Position: A Comparative Evaluation. *Accepted* in Frontiers in Virtual Reality Journal

