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Mahdiyeh Sadat Moosavi

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**ÉCOLE DOCTORALE SCIENCES DES MÉTIERS DE L'INGÉNIEUR**  
**[LISPEN, Institut Arts et Métiers de Chalon - Campus de Cluny]**

# THÈSE

présentée par : **Mahdiyeh Sadat Moosavi**  
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Spécialité : **Informatique-Réalité Virtuelle**

**Individualized Model of Interaction by Analyzing the Sense  
of Presence for The Optimization of Virtual Immersion**

**THÈSE dirigée par :**

M. Frédéric Merienne

**et co-encadrée par :**

M. Christophe Guillet

**Jury**

**M. Peter Ford**

**Dominey**

**M. David Rudrauf**

**M. Franck Gechter**

**M. Thierry Pozzo**

**M. Christophe  
Guillet**

**M. Frédéric  
Mérienne**

Directeur de recherche  
à l'INSERM

Professeur, Université  
de Paris Saclay

Professeur, Université  
de technologie de  
Belfort Montbéliard

Professeur, Université  
de Bourgogne  
Maître de Conférences,  
Université de  
Bourgogne

Professeur, École  
nationale supérieure  
d'arts et métiers

président  
Examineur  
Rapporteur

Rapporteur

Examineur

Examineur

Examineur

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I wanna thank me for always being a giver

And tryna give more than I recieve

I wanna thank me for tryna do more right than wrong

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## Résumé :

Cette thèse entreprend une exploration approfondie du "Sens de Présence" (SoP) dans le cadre de la Réalité Virtuelle (RV), un élément vital qui façonne significativement l'expérience de l'utilisateur. Reconnaisant le SoP comme le sentiment subjectif d' « être là » dans un environnement virtuel, les travaux proposent une compréhension complète de ces subtilités, y compris les rôles significatifs des caractéristiques individuelles et des facteurs environnementaux.

Une méthodologie spécifique au contexte pour mesurer le SoP est proposée, qui prend en compte les facteurs individuels et spécifiques à la tâche souvent négligés, permettant ainsi une mesure plus personnalisée et précise. L'accent est mis sur la 'présence personnelle', qui malgré sa nature subjective, est identifiée comme un aspect crucial du SoP.

Dans une approche innovante, la recherche introduit des interventions métaphoriques adaptées au contexte de la RV comme un moyen d'améliorer le SoP. Ces interventions visent à augmenter significativement l'immersion et l'engagement, enrichissant l'expérience RV de l'utilisateur tout en reconnaissant l'importance des différences individuelles.

Les résultats de l'étude sont validés empiriquement à travers une série d'études utilisateurs et de mises en œuvre pratiques, jetant une base solide pour les recherches futures et les applications pratiques en RV. Ces travaux apportent des contributions substantielles à la compréhension, la mesure et l'amélioration du SoP, mettant en évidence le potentiel des résultats pour influencer un large éventail d'applications telles que l'éducation, la santé, et le divertissement.

Malgré les éventuelles limitations découlant de la nature subjective du SoP et des variations individuelles, cette thèse offre une perspective nouvelle et contextuellement pertinente sur le SoP, sa mesure, et les stratégies d'amélioration, traçant la voie pour de nouvelles avancées dans le domaine de la RV.

***Mots-clés: Réalité Virtuelle, immersion et sens de présence, Approche Spécifique au Contexte, Interventions Métaphoriques, Différences Individuelles.***

# Abstract:

This dissertation undertakes an in-depth exploration of the "Sense of Presence" (SoP) within Virtual Reality (VR), a vital element that significantly shapes the user experience. Recognizing SoP as the subjective feeling of 'being there' within a virtual environment, the study provides a comprehensive understanding of its intricacies, including the significant roles of individual characteristics and environmental factors.

A context-specific methodology for measuring SoP is proposed that takes into account the often-overlooked individual and task-specific factors, thereby enabling a more personalized and precise measurement. The focus is placed on 'personal presence,' which despite its subjective nature, is identified as a crucial aspect of SoP.

The research introduces metaphoric interventions tailored to the VR context to enhance SoP. These interventions aim to significantly augment immersion and engagement, enriching the user's VR experience while also recognizing the importance of individual differences.

The findings from the study are empirically validated through a series of user studies and practical implementations, laying a robust foundation for future research and practical applications in VR. The research provides substantial contributions to the understanding, measurement, and enhancement of SoP, highlighting the potential of the findings to influence a wide array of applications such as education, healthcare, and entertainment.

Despite potential limitations arising from the subjective nature of SoP and individual variances, this work provides a contextually relevant perspective on SoP, its measurement, and enhancement strategies, setting a course for further advancements in the field of VR.

***Keywords: Virtual Reality, immersion and sense of presence, Context-specific Approach, Metaphoric Interventions, Individual Differences***

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# Chapter 1 Introduction

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Through the ages, humans have always dreamed of seizing and mirroring reality. Artists have expressed this desire in a variety of ways - in literature, painting, sculpture, theatre, and opera. The representation of people has gotten more popular in recent decades thanks to photography, film, and television. With the rapid progress in computational power, interactive computer graphics, immersive displays, and digital transmission, we're able to simulate reality with such fidelity that it's hard to tell what's real and what's not.

No matter how advanced our representational technologies get, their true worth is intrinsically tied to their users' expectations, engagements, and reactions. Like the Picturephone in the 1970s, technology has failed because it didn't meet user needs or didn't add value to their experiences. Measurement of these experiences and responses isn't just important, it's essential.

On the one hand, it leads us towards design guidelines that make representational technologies easier to use. On the other hand, it makes it easier to develop reliable, valid, and robust psychological measurement methods. We can develop a comprehensive theoretical understanding and conduct empirical investigations of relevant constructs by exploring the mechanisms that drive user experiences and responses using these methodologies. As long as we stay focused on these two pillars, we'll be able to keep up with users' evolving needs.

In VR (Virtual Reality), the experiences are greatly shaped by the sense of "presence," which in turn governs pleasure, satisfaction, and benefits. As (Sheridan, 1992) puts it, presence is feeling physically present through computer-generated visual, auditory, or force displays. This psychological state happens when users forget that the media they perceive comes from technology, or even when they feel like it's an extension of their body (IJsselsteijn, 2004).

In the virtual realm, a potent sense of presence amplifies the user's feeling of immersion, enabling them to act like they would in the real world. Additionally, presence comes in three forms: personal, social, and environmental (Schuemie, et al., 2001). Personal presence pertains to the individual sense of "being there," while social and environmental presence encompass an individual's perception of the virtual environment - its inhabitants or the environment's reactivity.

A major focus of this research is the notion of personal presence, which is the most basic and universally applicable to all types of VR formats. Considering that presence is primarily a subjective experience, it has been a difficult concept to define and a difficult condition to measure.

During the past few decades, researchers have studied presence in depth, and they have discovered that it has many facets. As a self-reporting measurement tool for quantifying presence, (Schubert, et al., 1999) developed the Igroup Presence Questionnaire. (Sheridan, 1992) argues that presence is a subjective concept that cannot be easily defined or measured from a physiological perspective. Even though Sheridan does not dismiss objective measures of presence, he indicates that subjective reports are the most useful basic measure of presence (Sheridan, 1992) . Based on both individual differences and characteristics of VEs, we believe that the degree of presence experienced in a VE varies. A given VE's presence may be influenced by the individual's characteristics, traits, and abilities. As well as enhancing the feeling of presence, various characteristics of the VE may interfere with or detract from it as well. Considering these differences, presence measures should be designed in a manner that takes into consideration both the characteristics of the VE and their individual differences.

There has been significant progress in Virtual Reality (VR) technology, resulting in a significant paradigm shift in various fields, including education, healthcare, entertainment, and more. As the foundation of these applications, "sense of presence" (SoP) refers to the subjective experience of being present within a virtual environment. In spite of the fundamental role played by SoP in VR, research is still ongoing on how to measure and enhance it accurately. A novel method for measuring SoP in VR is presented in this thesis, as well as strategies that can be used to enhance it, with a particular focus on metaphoric interventions.

Research suggests that environmental factors and individual experiences have significant influences on perceived SoP, despite the concept that SoP is context-dependent not being universally acknowledged. We argue that a one-size-fits-all measurement approach to SoP could overlook critical nuances and subjective interpretations of the VR experience, which are often context-specific. This issue is addressed by proposing a methodology for measuring SoP objectively, grounded in the VR context.

Moreover, improving the SoP is essential for improving user engagement and overall effectiveness of VR applications. Unlike previous research, which focuses primarily on improving VR's technological aspects, our work suggests metaphoric interventions as a unique perspective. We hypothesize that these interventions, tailored to the VR context, can significantly augment SoP and create a more immersive and meaningful user experience.

## 1.1 Contributions

This thesis devoted to the exploration and advancement of the Sense of Presence (SoP) in Virtual Reality (VR), has as its central aim the development of novel conceptualizations, methodologies, and interventions for SoP, that will enhance the immersion of users in virtual environments. The scope of this work crosses several areas, including the theoretical underpinnings of SoP, its context-dependent nature, personalized experience, and an empirical validation of the developed approaches. Our proposals will help to fix current problems. We're going to introduce a series of research efforts, including theoretical development, user studies, and practical validation, to build a better, contextually apt SoP. In light of this, the thesis accomplishes multiple contributions concerning scientific and technical developments:

- ❖ In-depth literature review of SoP in VR, including its different types and impacts on user engagement and experience.
- ❖ Establishing a new method for assessing SoP, taking into account individual behaviors and task-specific sensations while addressing the deficiencies of existing measurements.
- ❖ We're developing metaphoric interventions to enhance SoP, a novel approach that prioritizes user engagement and immersive experiences over VR's technical facets.
- ❖ A rigorous examination of the role of individual differences in the SoP, highlighting the need for personalized VR experiences that cater to users' unique traits and abilities.
- ❖ An empirical validation of the proposed methods, providing a firm foundation for future researchers to apply, test, and further refine these approaches.
- ❖ Substantial foundational contributions to VR applications, by improving the comprehension, measurement, and enhancement of SoP, and potentially impacting a broad array of applications, such as education, healthcare, entertainment, and more.

## 1.2 Structure of the Thesis

An outline of the thesis structure is provided below, summarizing each chapter and its content:

**Chapter 2 - Literature Review:** In this chapter, we investigate a comprehensive literature review on the sense of immersion, presence, and methods to measure subjects' senses of presence in virtual reality. We analyze the current methodologies and their drawbacks, thereby setting the context for the novel approach we propose in the subsequent chapters.

**Chapter 3 - Methodology Proposal:** Based on individual behaviors, the task to perform in VR and the VR environment, we propose a new methodology for measuring and enhancing the sense of presence in VR. We use specific metaphors to enhance presence as part of this methodology.

**Chapter 4 - Experimental Studies:** This chapter describes how the proposed methodology was tested in a variety of VR contexts. Our methodology is evaluated using empirical evidence, which supports its effectiveness.

**Chapter 5 - Conclusions and Perspective:** The final chapter provides a summary of our overall conclusions and an outlook on the future work resulting from this thesis. We will discuss the potential extensions of the research, possible improvements on the proposed methodology, and new avenues of exploration unlocked by our findings.

By sequentially unfolding our study on SoP in VR from literature review, methodology proposal, experimental design and execution, to final conclusions and future prospects, we aim to build a comprehensive understanding of SoP and its enhancement in VR environments

## Chapter 2 Literature review

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## **2.1 Overview of relevant literature on virtual immersion, sense of presence, and individual differences in perception and cognition**

### **2.1.1 VR Technologies:**

Virtual reality (VR) is a technology that allows users to experience a completely artificial environment that can be simulated by a computer. VR systems typically involve a headset that is worn over the eyes, which displays a high-resolution, three-dimensional image of a virtual environment.

Through the use of a head-mounted display (HMD), virtual reality (VR) offers a three-dimensional experience within a computer-generated environment (Riva et al., 2015). Although the HMD presents two two-dimensional images (via stereoscopy), the user's brain processes these images to create the perception of a three-dimensional space. Through various input devices, such as handheld controllers, users interact with the virtual environment and translate their movements into corresponding actions in the virtual environment, thereby creating a sense of presence and interaction within the digitally crafted environment. Morton introduced VR as a concept in the 1960s with the Telesphere Mask and the Sensorama (Bown, et al., 2017). Originally, these technologies were designed to make users feel like they were a part of the video display around them. Ivan Sutherland developed an idea called the Ultimate Display (Sutherland, 1965), which uses multiple input and output devices to allow the user to feel immersed in an artificial environment (Steinicke & Steinicke, 2016) (Anthes, et al., 2016). A large change in VR technology development took place in the early 2010s following the creation of Sensorama and the concept of the Ultimate display in the 1960s. VR was still considered a trick at this time - it was expensive and it was not expected to become popular with consumers. As a result, things began to change in 2012 when Palmer Luckey debuted the prototype for the first Oculus. Following Facebook's acquisition of Oculus in 2014, the popularity of VR devices for home use significantly increased. In recent years, VR has grown in popularity and become more widely accessible to consumers, with more VR headsets available on the market, such as HTC Vive, Samsung VR, Oculus, and Google Cardboard, among others (Hamad & Jia, 2022).

VR has a wide range of potential applications, including gaming, education, training, therapy, and entertainment. It has been used to simulate real-world experiences, such as flying an airplane or performing surgery, as well as to create entirely fictional environments that can be explored and interacted with. Using VR applications, scientists and engineers can interpret and visualize science data in new ways and experience environments that are otherwise difficult, impossible, or too expensive to visit in person. As one example, NASA's Goddard Space Flight Center (GSFC) has developed immersive tools to explore regions in space from the depths of oceans to distant galaxies (Memarsadeghi & Varshney, 2020).

Virtual reality (VR) has evolved considerably in recent years, bringing about new technologies that redefine accessibility and user immersion. Standalone VR headsets, such as the Oculus Quest series, have emerged as pivotal innovations, eliminating the need for complicated setups and offering advanced processing within the device itself (Hosny, et al., 2020). Integrating high-resolution displays without requiring external computers enables these devices to provide a compelling user experience.

Additionally, devices like Microsoft's HoloLens and Magic Leap 1 are leading the way in augmented reality (AR) and mixed reality (MR) applications (Sanna, et al., 2019). These



technologies combine virtual and real elements to create unique immersive experiences, with applications ranging from healthcare to entertainment (Nesamalar & Ganesan, 2012). Further enhancing the VR user experience has been the introduction of intuitive eye-tracking and gesture recognition technologies, which provide tactile sensations and natural interfaces for interaction within virtual environments (Joo & Jeong, 2020). With 5G networks emerging, cloud-based VR is also becoming more accessible, allowing devices with limited processing power to deliver high-quality VR experiences, democratizing access to this transformative technology (Zhuang, et al., 2020).

One of the most exciting aspects of VR is its potential to revolutionize the way we experience entertainment, communication, and even work. As with smartphones, VR utilizes a new interface format (a head mounted display and hand controllers) to make accessing a computing device more intuitive and natural. In a similar way to the Internet, it allows people across the globe to communicate with one another, however, this time with a natural human experience that is virtually indistinguishable from standing face to face (Rosedale, 2016). As the technology continues to evolve and become more widely available, it is likely that we will see even more innovative applications of VR in close future.

### ***2.1.2 Immersion and Sense Of Presence***

The two main types of VR are immersive and non-immersive (Wohlgenannt, et al., 2020). In a non-immersive VR experience, the user is surrounded by different screens which present the virtual information. Flight simulations are examples where the user sits in a chair and is surrounded by multiple screens (Rahouti, et al., 2021), giving the user the feeling of being in the cockpit without fully immersing themselves. Immersive VR (Slater & Sanchez-Vives, 2014) involves tracking movement with a wearable display, e.g., head mounted display, and presenting VR information based on the position of the user, which enables users to immerse themselves in the virtual environment 360 degrees (Hamad & Jia, 2022)

While non-immersive VR technologies offer unique advantages, such as a more comfortable and less disorienting user experience in certain scenarios, they inherently lack the full range of sensory engagement that immersive VR offers. In the paragraph mentioned above, we distinguish between immersive and non-immersive VR, highlighting how immersive VR allows the user to engage with the virtual environment from a 360-degree perspective. It is crucial to acknowledge that immersive VR facilitates a depth of presence and interaction unparalleled by non-immersive alternatives. Immersive VR provides a heightened sense of presence that is critical to applications requiring full spatial orientation and engagement, resulting in an experience that is closer to real-life perceptions and reactions. As an example, immersive VR is the optimal option for medical training, architectural visualization, and any scenario requiring a rich, interactive spatial understanding. In order to create a seamless, integrated virtual experience, it tracks the user's movements in real time and adjusts the visual display accordingly. Non-immersive VR has its place, but its application is somewhat limited to situations where complete immersion isn't necessary or desirable, and it cannot fully replicate immersive VR's sensory-rich, engaging experience.

The goal of VR is to create an experience that feels as close to real life as possible, allowing users to fully engage with and explore virtual worlds in a way that is both captivating and transformative. Immersion is a key aspect of this experience, as it creates the feeling of "presence" within the virtual environment, giving users the sense that they are actually there.

In virtual reality (VR), the sense of presence is usually considered the most important factor. In spite of the lack of a common definition, presence is defined as a multi-component construct. There are two general categories of variables that determine presence: (Coelho, et al., 2006) media characteristics and user characteristics. A media characteristic can be classified into two types: media form and media content. An example of a media form is the extent to which sensory information can be obtained, how users can modify their sensors within an environment, and how users can manipulate the environment. The content of a media medium may include objects, actors, or events. A user's characteristics may refer to a range of factors ranging from age, gender, or cultural variables to their perceptions, cognitive abilities, motor capabilities, prior experience with mediated experiences, willingness to suspend disbelief, and personal preferences. There is a significant impact of media form characteristics on the perception of presence. It is undeniable that immersion, interaction, and perceptual realism are essential. In some theoretical models, (Schubert, et al., 2001) suggest that the sense of presence is perceived as an outcome or direct consequence of immersion. Therefore, it has been assumed that the more inclusive, extensive, surrounding, and vivid the virtual environment (VE), the higher the sense of presence (Baños, et al., 2004).

Other studies have also found that the degree of immersion and sense of presence can impact a user's cognitive and emotional responses to the VR experience. For example, a highly immersive and believable virtual environment can enhance a user's memory recall of the experience and can even influence their attitudes and behavior in the real world. There has been evidence that VR-specific factors, such as immersion and sense of presence, affect episodic memory in virtual environments (VE). In general, it is believed that the more immersed and present someone feels in a virtual world, the more satisfying and memorable the VR experience will be (Cadet & Chainay, 2020).

Furthermore, researchers have investigated the neural mechanisms underlying immersion and sense of presence in VR. Studies have found that the brain processes information from VR environments in a similar way to real-world environments, which contributes to the feeling of presence. According to (Loomis, et al., 1999), "presence is one of the fundamental properties of consciousness". It has also been noted by (Sanchez-Vives & Slater, 2005) that inside the virtual experience, you are simultaneously aware of the "place" and the "events" and simultaneously aware that there is no such place or event; however, you behave and think as though the place and events were real. By blurring the distinction between real and virtual, the barrier between your mind and the VE diminishes, allowing you to better interact with the computer generated environment.

However, there are also limitations to the current understanding of immersion and sense of presence in VR. For example, individual differences in sensory experiences and expectations can influence the degree of immersion and sense of presence that users experience. Additionally, research is needed to better understand the long-term effects of immersion and sense of presence on user behavior and attitudes.

The literature on immersion and sense of presence in virtual environments suggests that the subjective experience of presence is influenced by multiple factors, including sensory feedback, interactivity, cognitive engagement, emotional involvement, and behavioral engagement. Various frameworks have been proposed to understand these different factors, including (Heater, 1992) framework that identified sensory immersion, emotional involvement, cognitive absorption, and behavioral engagement as dimensions of presence. (Slater & Wilbur, 1997) proposed the FIVE framework that highlighted the importance of sensory fidelity, interactivity,

richness, narrative, and sociality in creating presence. (Lombard & Ditton, 1997) proposed a framework for understanding presence in computer-mediated communication that identified sensory fidelity, interactivity, copresence, and social richness as factors that influence the sense of presence. (Biocca, 1997) explored the concept of embodiment in virtual environments and the challenges and opportunities that arise from using technology to create virtual bodies. (Witmer & Singer, 1998) developed a Presence Questionnaire to measure the subjective feeling of presence in virtual environments. Finally, (Loomis, et al., 1999) explored the use of immersive virtual environment technology as a tool for basic research in psychology, highlighting its potential advantages and challenges.

Previous studies have proposed that presence is determined by the degree to which a medium seems realistic e.g. (Heeter, 1992); (Welch, et al., 1996); (Lombard & Ditton, 1997); (Bystrom, et al., 1999). It is interesting to note that perceived realism is not included in the most widely used definitions of presence. Definitions of SOP emphasize the experience of being present in a mediated environment. The sensation of being surrounded by a mediated world, as well as attentional allocation is strongly associated with being there. SOP is a multifaceted concept with many dimensions and complexities in Virtual Reality (VR). In traditional terminology, it is defined as the sensation of 'being there' within a virtual environment (VE). As a result, this definition is too general and may not adequately capture the various aspects of the experience of presence.

### ***2.1.3 Individual perception and cognition***

Individual perception and cognition are important aspects of how people understand and interact with the world around them. Perception refers to the way that people interpret and make sense of sensory information, while cognition refers to the mental processes involved in thinking, problem-solving, and decision-making.

The important note is to distinguish an intuitive difference existing between perceptual states like seeing red an object or hearing the note of a trumpet, and cognitive states like determining that justice is fair (Beck, 2018).

Perception is influenced by a variety of factors, including physical environmental factors (Luppicini, 2003), past experiences (Robinson, et al., 1964), and cultural background (Bossuroy, et al., 2014). For example, two people may perceive the same object in different ways based on their personal experiences or cultural beliefs.

Cognition involves the mental processes of attention, memory, perception, language and reasoning. These processes are used to interpret and analyze information, make decisions and solve problems. Individual differences in cognition can have a significant impact on how people perceive and interact with the world. In simple word, individual perception and cognition are complex and multifaceted aspects of human experience that are shaped by a variety of factors.

Individual perception and cognition in virtual reality (VR) is an area of growing interest and research. VR provides a unique environment in which to study perception and cognition because it allows researchers to manipulate and control the sensory information that participants receive. For instance, researchers (Brown & Gallimore, 1995) showed that in order to visualize and interpret computer-generated 3D objects, they need to be a) accurate descriptions of the model being created, and b) presented in a realistic and integrated manner. It is important to consider which perceptual/cognitive operation the user performs when designing a 3D image.

Perception in VR is influenced by a variety of factors, including the quality of the visual like color and light (Billger, et al., 2004) and auditory information (Billger, et al., 2004) provided by the VR system, the level of immersion and presence experienced by the user, and the individual's prior experiences with VR. For example, a person who is accustomed to using VR may perceive and interpret visual and auditory information differently than someone who is using VR for the first time.

On the other hand, the emotional cues in virtual reality (VR) are reliant on perceptual simulations, which is inherent to its nature. However, recent studies have emphasized the importance of considering not only the bottom-up processes of perception, but also the top-down effects in understanding how VR can be emotionally captivating. For instance, incorporating a background narrative to a VR scenario may enhance the emotional experience (Bouchard, et al., 2008); (Gorini, et al., 2011); (Mühlberger, et al., 2012); (Peperkorn & Mühlberger, 2013).

Cognition in VR is also influenced by a variety of factors, including the level of engagement and interactivity provided by the VR environment, the cognitive demands of the tasks being performed, and the individual's prior experience with similar tasks. For example, a person who experiences with video games may perform better on a task in VR that requires spatial navigation and problem-solving than someone who is not familiar with video games.

Cognition plays an important role in virtual reality (VR) experiences. Cognition refers to the mental processes involved in perception, attention, memory, reasoning and problem-solving (Sreena & Ilankumaran, 2018). In VR, cognitive factors can influence how users perceive and interact with the virtual environment. The following factors are listed as instrumental for deep immersion by Pimentel et al (Pimentel & Teixeira, 1993): interactivity, rapid update rate, complex images, engaging 3D audio, head-mounted display, stereoscopic, wide field of view, and head tracking.

For example, cognitive load, or the amount of mental effort required to complete a task, can impact user engagement and performance in VR. If the cognitive load is too high, users may become overwhelmed and disengage from the experience. On the other hand, if the cognitive load is too low, users may become bored and disinterested. For example, for learning in VR environment, cognitive load is considered as a promising factor of student's engagement in the context of virtual reality (Bueno-Vesga, et al., 2021).

Another cognitive factor in VR is the user's expectations and beliefs about the experience (Makransky & Petersen, 2021). Users may bring preconceived notions about what VR is or how it works, which can impact their perceptions and interactions with the environment. For instance, if users expect the VR experience to be highly realistic, they may be more critical of any inconsistencies or discrepancies in the environment. Psotka et al. (Psotka & Davison, 1993) explained that VR realism depends on how vibrant dream worlds are compared to the real world. A person who can vividly recall their dreams may have higher and similar expectations for the VR experience. The depth of the immersion experience also seems to be influenced by these expectations, as those who expect too much seem to be disappointed.

Additionally, cognitive factors can impact the emotional experience in VR (Sas & O'Hare, 2003). Users' interpretations and evaluations of the VR environment can influence their emotional reactions. For example, if a user perceives a VR scenario as threatening, they may experience fear or anxiety. A number of studies have demonstrated that objective physiological

measurements, such as electrodermal activity (EDA), can be used to investigate the emotional effects of 2D or 3D displays.

Individual perception and cognition in VR are complicated and ever-changing process, influenced by many different aspects. If we can figure out how all these aspects work together, it will help designers and developers make VR experiences that are more captivating and useful.

#### ***2.1.4 Evaluating immersion and sense of presence in virtual reality***

The causal connection between presence and perceived realism in virtual reality (VR) has been well-established, leading researchers to concentrate on devising dependable techniques for measuring presence. Although various questionnaires and surveys have been created to assess presence by considering causal factors and determining variables, only a select few have become widely accepted. To guarantee reliability, it is crucial that presence measurements are designed to rely solely on the considered characteristics and only assess what they are intended to measure. Researchers have tackled presence from various viewpoints, resulting in the development of both subjective and objective measurement methods (Coelho, et al., 2006).

Subjective measurements derive from individuals' self-reported experiences and emotions, gathered through approaches like questionnaires or interviews. Lots of studies assess the emotional reactions following exposure to the VR stimulus by administering questionnaires (Oliveira, et al., 2018) (Trindade, et al., 2018) (Estupiñán, et al., 2014) (Ma, et al., 2018; Livatino & Koffel, 2007). These measurements depend on the user's personal interpretation and assessment of their experience, which may be affected by individual biases and situational factors. In the context of VR, examples of subjective measures encompass self-reported presence ratings and questionnaires.

In evaluating presence within virtual reality (VR) experiences, objective measurements present a more quantifiable and arguably less intrusive alternative to subjective interpretations. Leveraging physiological responses and behavioral measures can provide a more genuine insight into the user's cognitive and emotional state within the VR environment.

Objective measurements in VR assessments stem from quantifiable behaviors or physiological responses. These responses, such as variations in heart rate, skin conductance, or task performance, are evaluated during the user's exposure to VR stimuli (Oliveira et al., 2018). Notably, the assessment's non-intrusiveness enhances its appeal, with devices such as cardio-frequency meters designed similarly to wristwatches for convenience and minimal disruption.

Various studies have attempted to correlate presence within VR with electrophysiological measures. These measures encompass factors like heart rate, respiration rate, skin resistance, and peripheral skin temperature. By offering an objective and quantifiable perspective on the user experience, these measures present an evaluation less influenced by personal opinions of participants and more directly linked to their cognitive or emotional state.

Objective measures within VR include behavioral measures and physiological responses. Behavioral measures refer to the user's actions within the VR environment, with task performance being a common metric. On the other hand, physiological responses can include changes in heart rate or skin conductance in response to the VR stimuli.

A VR experience's evaluation occurs within two distinct realms: objective and subjective measurements, each with its own unique strengths and weaknesses.

### **The Value of Objective Measures: Action Speaks Louder than Words**

The objective measurements, like an impartial observer, provide solid, numerical data that does not suffer from personal bias. As a result, they provide insight into physiological or behavioral reactions that may not be consciously expressed by the user as they navigate through the VR environment (Kober & Neuper, 2012). These measures function subtly in the background, ensuring that the VR experience remains undisturbed.

By focusing on spontaneous, sensible responses that correlate with the user's presence in a given scenario, behavioral measures provide an alternative to questionnaires' subjectivity. Such measures lean into a simple premise: If a user feels present in a virtual environment, they will more likely respond to stimuli in a similar real-world situation if they feel present. For instance, if a virtual ball is thrown at a user's head and they duck, it's a strong signal of their presence in the virtual environment. Several different measures have been examined over the years.

A study conducted by Freeman et al (Freeman, et al., 2000) examined postural responses as a measure of presence. In their study, participants watched videos from the hood of a rally car and swayed in response. As they experienced motion and felt part of the video, they adjusted their posture more. Postural responses among subjects were not directly correlated with subjective presence ratings despite stereoscopic presentation leading to more postural movement.

During VR sessions, physiological measures provide a way to assess user experience directly, non-invasively, and continuously. They promise a deeper understanding of presence and its evolution over time, and they can help identify strategies to enhance presence (Sadowski & Stanney, 2002).

Virtual reality exposure can be assessed simultaneously with functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), which poses unique challenges but can yield rich data. Because EEG can measure electrical activity generated by neurons (Grassini & Laumann, 2020), it has been widely used for studying the sense of presence. However, integrating fMRI is significantly more challenging. Due to the immobility requirements during fMRI scans, the sensitivity of fMRI equipment to electromagnetic noise, and the need for specialized equipment within the scanner environment, it is indeed a challenging combination.**Objective Measures: The Other Side**

However, objective measurements, like a complex puzzle, can be tricky to decode. Physiological or behavioral responses can be interpreted differently depending on the context. For instance, an elevated heart rate can indicate exhilaration or stress (Mandryk & Klarkowski, 2008), making interpretation challenging. In addition, many of these measurements require specialized tools, increasing the complexity and cost of research.

Evaluating VR solely based on *behavioral measures or physiological measures* have some drawbacks:

*behavioral measures weaknesses:*

a) **Ecological Validity:** They may not fully capture the complexity and richness of real-world experiences (Anderson, et al., 2013).

b) **Limited Scope:** They often focus on narrow aspects of user experience like task performance, potentially missing emotional engagement or sense of presence (Tio, et al., 2019).

c) **Demand Characteristics:** Participants may modify their behavior based on the experimental design, which can bias the results (Orne, 1962).

d) **Task-Specificity:** These measures are often specific to tasks, limiting their applicability to other VR experiences or real-world situations (Wallach, et al., 2009).

e) **Limited Subjective Insight:** They provide limited insight into subjective experiences, such as immersion level or sense of presence (Rock, et al., 2022).

#### *physiological measures weaknesses:*

a) **Invasive or Uncomfortable:** Some measures, like EEG or blood sampling, can be invasive or uncomfortable for the user, potentially affecting their VR experience (Clemente Bellido, 2014); (Sadowski & Stanney, 2002).

b) **Expensive or Time-Consuming:** Some methods, like EEG, fMRI, or eye tracking, can be costly or time-consuming to administer, making large-scale or real-world VR applications challenging.

c) **Limited to Specific Responses:** These measures are typically limited to specific physiological responses, such as heart rate or skin conductance, and may not capture other crucial aspects of the user's emotional or cognitive state or engagement level.

### **The Human Touch of Subjective Measures**

As opposed to objective measures, subjective measures, on the other hand, allow users to share their feelings, thoughts, and emotions, enriching the data with a human touch (Slater, 2003). It is easy to implement and interpret these measures, as they usually require little more than the input of the user.

#### **Subjective Measures: Challenges**

Subjective measures are important, but they may not accurately reflect subconscious reactions due to personal biases. In addition, they can be subject to response bias, where users modify their responses to align with perceived expectations (Kluger & DeNisi, 1996). As a result, subjective measures are only successful if the user is able to reflect on and articulate their experiences. Below, some of the methods used in measuring the sense of presence and their associated drawbacks are explained:

### **The Subjective Self-Report: A Personal Lens**

Subjective self-reports are deeply rooted in the user's personal experiences, with identical journeys in a virtual environment (VE) often leading to unique user reports (Slater & Wilbur, 1997). A critical perspective from Slater argues against the appropriateness of self-report for measuring presence, due to its profound ties to individual user characteristics. This personal viewpoint aligns with the theory put forth by (Nisbett & Wilson, 1977), where introspective reports are understood not as recollections of mental processes, but as constructs of personal behavior explanations.

### **The Power and Pitfalls of Questionnaires**

Questionnaires commonly serve as a tool to gauge a user's immersion level and sense of presence in a VE, with users rating their agreement with statements such as "I felt like I was actually in the virtual environment" or "I forgot I was wearing a headset". Presence measurements often utilize post-experiment questionnaires, standardized and validated, to record user experiences (Slater, et al., 1998) (Slater & Usoh, 1993) (Usoh, et al., 2000) However, even this traditional method is not devoid of its share of weaknesses.

a) **Response Bias:** Questionnaires may be influenced by response bias, where participants tend to echo expected answers rather than their true sentiments, which may distort results (Graf & Schwind, 2020).

b) **Social Desirability Bias:** Social desirability bias can potentially lead to inflated immersion and presence estimates, as users aim to project a favorable image of themselves or the VR experience (Kaminska & Foulsham, 2016).

c) **Lack of Context:** The ability of questionnaires to provide context for user experiences is limited. The nuances of user experiences may be lost in translation or omitted due to vocabulary restrictions (Galasiński & Kozłowska, 2010).

d) **Narrow Focus:** Questionnaires often emphasize aspects like immersion or presence, overlooking other pivotal elements of the experience like emotional engagement or spatial presence (Tcha-Tokey, et al., 2016).

e) **Individual Differences:** Questionnaires might overlook the role of individual characteristics such as age, gender, personality, or prior VR experience. These variables could significantly impact the user's subjective experiences (Ling, et al., 2013).

f) **From Bodily Experience to Verbal Judgment:** After exiting the VE, users must transform their bodily experiences into verbal judgments, a task that may challenge the authenticity of the report (Stelter, 2000).

### **Bringing it All Together**

While both objective and subjective measurements come with their unique strengths and complexities, a blend of these methods can provide a more comprehensive and empathetic understanding of presence in VR. Future studies should aim to integrate these methods effectively, thus capturing the intricate tapestry of the human VR experience.



## 2.2 Review of existing models of interaction in VR and their limitations:

### 2.2.1 *Direct manipulation:*

As one of the most popular interaction models in Virtual Reality (VR), direct manipulation allows users to interact with virtual objects in a way that feels natural and intuitive, much like they would in real life. Known as "what you see is what you get", this method lets users visualize and manipulate virtual objects just as they would in the real world, thanks to (Bryson, 2005).

As defined by (Shneiderman, 1982), "direct manipulation" includes three elements:

1. An accurate representation of the object in focus,
2. Overriding complex syntax with tangible actions or labeled buttons,
3. A quick, incremental, and reversible operation that instantly reflects the impact it has on the object.

It turns out that these properties are also present in video games, spreadsheets, computer-aided design systems, and even some office software!

Due to its high level of immersion and presence, direct manipulation has gained a lot of popularity in VR. Imagine users reaching out to grasp virtual objects, moving them around, and interacting with them in a way that feels completely natural. In addition to gaming and education, this hands-on approach is also useful for simulation training.

Its ability to mimic real-world interactions makes direct manipulation so relatable. Users not only get to hold objects and feel their weight, but they also get to experience virtual constraints as well. As a result, users feel as if they are genuinely engaging with the virtual objects, which enhances their sense of presence and involvement in the virtual environment. This interaction is not one-sided; virtual objects are designed to interact with one another as well. Furthermore, users can manipulate these objects not only through direct physical actions but also by altering their positions or orientations within the virtual space, serving as additional input methods. This dynamic interaction facilitates a more immersive and intuitive experience, allowing for a deeper connection and engagement with the virtual environment. For instance, in a study by (Zhao, et al., 2017), users adjusted light intensity by moving a handle prop in the real environment. It is also possible for objects to communicate their dynamic use to the user, as shown in a study by (Lopes, et al., 2015) where a virtual object conveyed its movement to the user in real-time (adapted from sources including (Lopes, et al., 2017); (Zenner & Krüger, 2019) (Heo, et al., 2018); (Sagheb, et al., 2019); (Zhao, et al., 2017); (Zhao, et al., 2017)).

Although widely favored in Virtual Reality (VR), direct manipulation has its own set of challenges.

As a first point, virtual objects lack physical attributes such as weight, texture, and resistance, which are crucial for precise manipulation. In the absence of this tangible interaction, (Sutcliffe & Kaur, 2000) note that users can become frustrated and confused.

Spatial constraints are another limitation. When interacting with virtual objects, users may have to move around physically, a task that becomes increasingly difficult in cramped or cluttered environments with a lack of free movement space. According to (Slater & Usoh, 1993), this point is particularly important.

Last but not least, direct manipulations can turn into quite a workout. Research by (Bowman & Wingrave, 2001) highlights the concerns that prolonged arm holding can lead to physical fatigue and discomfort. VR users may find this physical exertion distracting from the overall experience.

### 2.2.2 *Gesture-based interaction*

A gesture-based interaction involves the use of physical movements, primarily the hands and fingers, to interact with digital devices. A detailed discussion of this technology was provided by (Saffer, 2008), which outlined its historical context, prominent methods, and potential applications. A number of devices, including gaming consoles such as Nintendo Wii and Xbox Kinect, as well as smartphones such as Apple's iPhone and Samsung's Galaxy series, have used gestures to interact with them.

A further discussion of applications can be found in (Norman, 2010), who presented case studies demonstrating the use of gestures in virtual reality environments, robotic controls, and augmented reality applications. In these cases, gestures were demonstrated to be a flexible and intuitive method of interacting with the user.

Different researches utilized gesture based interaction to improve sense of presence. For example, (Céspedes-Hernández, et al., 2018) paper proposes a method for enabling gesture-based interaction in virtual reality environments through the use of user-defined commands, improving user experience and allowing for more personalized interaction (Pop & Sabou, 2017) presents a framework for gesture-based visual analytics in virtual reality, allowing for intuitive and immersive exploration of complex data. (Yang, et al., 2019) discusses the current state-of-the-art in gesture interaction technology for virtual reality and identifies potential research directions for future development. It explores the advantages and limitations of different types of gesture recognition technologies and their potential applications in virtual reality environments. Raess et al. (Raees & Ullah, 2019) proposes GIFT, a gesture-based interaction technique for virtual environments that uses finger tracking to enable natural and intuitive interaction, and demonstrates its effectiveness through user testing.

### 2.2.3 *Haptic feedback*

As virtual reality (VR) has evolved to include haptic feedback, a technology that simulates tactile and force feedback, our interactions with virtual environments have become more humanized and tangible (Burdea & Coiffet, 2003). It provides a user with a greater sense of immersion and authenticity in the virtual world, leading to more instinctive and realistic interactions with virtual objects (Kuchenbecker, et al., 2006).

Through the use of wearable devices such as handheld controllers or gloves, haptic feedback in VR simulates the sensations of touch or resistance of physical objects by generating vibrations or pressure signals (Sato, et al., 2007). By combining haptic feedback with visual and auditory cues, VR environments are enhanced in depth and realism when combined (Srinivasan & LaMotte, 1995).

Several technological advancements have contributed to the development of haptic feedback in virtual reality, including vibration motors, force sensors, and electro-tactile actuators. By integrating these into wearable devices or controllers, users are provided with tactile sensations

that are similar to those experienced in the real world when interacting with the virtual world (Wang, et al., 2006).

Mousavi et al (Mousavi & Aziz, 2008) provided an overview of the current state-of-the-art in haptic feedback technology for virtual reality (VR) applications in the manufacturing industry. The paper discusses the potential benefits of haptic feedback for enhancing the realism and usability of VR systems in manufacturing, and reviews the technical and design considerations involved in implementing haptic feedback systems. G. Burdea (Burdea, 1999) provided an overview of the different types of haptic feedback devices available, such as gloves, exoskeletons, and force-feedback devices, and how they can be used in VR environments. The author also discussed the challenges associated with haptic feedback, such as the need for high-resolution feedback and the difficulty in providing realistic tactile sensations. Julian Kreimeier et al. (Kreimeier, et al., 2019) investigate the effect of different types of haptic feedback on user performance and presence in virtual reality (VR) environments. The authors conducted a study in which participants performed a virtual assembly task using three different types of haptic feedback devices: a vibration-based device, a force-feedback device, and a hybrid device that combined both vibration and force-feedback. The authors measured the participants' performance on the task and their sense of presence in the VR environment using a questionnaire. The results showed that the hybrid device provided the best performance and presence scores, followed by the force-feedback device and then the vibration-based device. The authors attribute this to the hybrid device's ability to provide both tactile and kinesthetic feedback, which is more effective for simulating real-world interactions. The study also found that haptic feedback significantly improved user performance and presence in the VR environment compared to a no-haptic feedback condition. Lécuyer et al. (Lécuyer, et al., 2004) explored the potential of haptic feedback to enhance the perception of self-motion in virtual reality (VR) environments. The authors conducted a study in which participants were presented with a visual simulation of self-motion in a car, and were randomly assigned to one of three conditions: no haptic feedback, vibration-based haptic feedback, or vibration and wind-based haptic feedback. The authors measured the participants' perception of self-motion using a questionnaire. The results showed that participants who received haptic feedback had a significantly better perception of self-motion compared to those who did not receive haptic feedback. Furthermore, the participants who received both vibration and wind-based haptic feedback had a significantly better perception of self-motion compared to those who received only vibration-based haptic feedback. The authors concluded that haptic feedback can enhance the perception of self-motion in VR environments, and that the combination of different types of haptic feedback can be particularly effective. They suggested that future research should focus on developing more advanced haptic feedback devices that can provide even more realistic sensations of self-motion, and on exploring the potential of haptic feedback to improve other aspects of the VR experience.

However, G. Burdea (Burdea, 2000) discussed some of the key issues and challenges related to haptic feedback in virtual environments. The author argued that haptic feedback is an essential component of virtual reality (VR) technology, as it provides users with a sense of touch and texture that is crucial for realistic simulations. However, there are several challenges associated with haptic feedback, including:

1. **Latency Issues:** (Azmandian, et al., 2016) in their work 'Haptic Retargeting: Dynamic Repurposing of Passive Haptics for Enhanced Virtual Reality Experiences', point out the presence of latency issues in haptic devices. This delay in feedback disrupts the seamless immersion of VR experiences.

2. **Resolution Constraints:** (Culbertson, et al., 2018) in their research 'Haptics: The Present and Future of Artificial Touch Sensation' discuss how limitations in the range of sensations that haptic devices can replicate may dampen the overall effectiveness of VR interactions, leading to a less believable VR environment.
3. **Complexity of Use:** (Jones & Berris, 2002) in their study 'The Psychophysics of Temperature Perception and Thermal-Interface Design' highlighted the difficulties users may face when trying to set up and navigate haptic devices. This could discourage widespread adoption of VR technology.
4. **Integration Difficulties:** (Prattichizzo, et al., 2012) in 'Cutaneous Feedback of Fingertip Deformation and Vibration for Palpation in Robotic Surgery' pointed out how haptic devices might not always integrate smoothly with the VR environment, reducing the overall effectiveness of the system.
5. **High Cost:** (Minsky, 1995) in his paper 'Computational Haptics: The Sandpaper System for Synthesizing Texture for a Force-Feedback Display' brought attention to the potentially high cost of haptic feedback devices, which can prevent certain users from adopting the technology.
6. **Technical Complexity:** (Follmer, et al., 2012) in 'Haptic Shape Perception in 2D and 3D' discussed the difficulties associated with setting up and fine-tuning haptic feedback devices, which could act as a deterrent for some users.
7. **Discomfort:** (Jang, et al., 2016) in their study 'Haptic Feedback in Needle Insertion Modeling and Simulation' noted that haptic feedback can sometimes cause discomfort or even pain when its intensity or frequency is too high.
8. **Uncanny Valley Effect:** (Berger, et al., 2018) in 'The Uncanny Valley of Haptics' discussed how the evolution of haptic feedback devices might lead users to be conscious of the gap between simulated sensations and real-world experiences, detracting from the VR experience.
9. **Inherent Limitations:** (Brooks Jr, 1999) in his work 'What's Real About Virtual Reality?' stressed on the limitations of haptic feedback devices, especially when they fail to mimic certain types of interactions such as the weight or resistance of VR objects.
10. **Weight perception:** one of the biggest challenges concerns the feeling of weight in virtual reality, which is caused by the lack of kinaesthetic cues in this kind of environment. In the real environment, to perceive the weight of an object, the integration of the visual and real information provided by visual and real sensory systems helps human to understand the heaviness of objects (Ernst & Banks, 2002). The real sensory system provides various sources of information, including force feedback, proprioception, and tactile feedback. As a result, real perception is multimodal, encompassing multiple sensory inputs. On the other hand, visual information is unimodal as it is solely obtained through the retinas of our eyes (Aman, et al., 2010). In virtual environments, visual information is totally provided through the virtual scene via a head-mounted device (HMD). Despite technical progress in visual simulation in terms of quality, part of information related to virtual objects like texture shape, size, and weight are still partially missing. These kinds of information are mostly provided by real feedback (force feedback tactile and proprioception), but it remains a challenge because of the lack of presence of virtual objects in the real environment.

#### 2.2.4 *Multi-sensory interaction:*

- *Human Sensory system*

Our sensory system comprises five main senses, namely sight, hearing, smell, taste, and touch. These senses work together to help us interact with our environment. As stated by

Schiffman (2013), these senses are vital for survival, communication, and understanding the world around us.

**Sight:** Vision is often considered our most crucial sense, helping us perceive our surroundings with great detail. (Ackerman, 2018) explains that the eyes capture light and convert it into electrical signals, which the brain interprets as images. This intricate process enables us to appreciate colors, recognize faces, and navigate the world.

**Hearing:** Our sense of hearing allows us to perceive sounds by detecting vibrations and changes in the pressure surrounding our ears. According to (Moore, 2012), hearing helps us communicate effectively and alerts us to potential dangers.

**Smell and Taste:** Smell and taste are closely linked and are primarily responsible for our food enjoyment. (Shepherd, 2006) states that our nose and mouth contain specialized sensory cells that interact with molecules of food and air, sending signals to our brain, which we perceive as flavors and scents.

**Touch:** As a primary sense, touch provides essential information about our surroundings, helping us interact effectively. Among the many sensations that it encompasses are tactile feedback, temperature, and pain, all of which are mediated by different pathways and receptors. (Gallace & Spence, 2014) explain that the skin has multiple receptors that respond differently to different stimuli. There are mechanoreceptors, which sense pressure and touch, thermoreceptors, which sense temperature changes, and nociceptors, which sense pain. Due to their distinctive physiological bases and perceptual qualities, temperature and pain sensations are often considered separate from tactile sensations, despite the fact that they are transmitted through the sensory system. To navigate and respond to our environment, it might be more accurate to consider the sensory system as comprised not only of the traditional five senses, but of a wider array of sensing mechanisms.

**Multisensory Integration:** All our senses work together to provide a complete perception of our environment. (Stein, et al., 2014) explain that our brain integrates sensory information from various sources, creating a consistent and comprehensive representation of the world around us.

#### *Enhancing the existing model of interaction in VR by multi-sensory interaction*

In VR, we're essentially tricking our senses to believe we're in a different reality. For sight, VR headsets use high-definition screens to cover our field of view, giving us a fully immersive visual experience. For hearing, VR creates a 3D audio environment that replicates realistic sounds and their sources. For touch, haptic feedback devices create tactile sensations, letting users feel the virtual world.

Taste and smell are tougher to replicate in VR (Ischer, et al., 2014), but there's promising research being done to digitally recreate these senses. This would be especially useful in industries like food and beverage, medicine, and entertainment.

Now, let's look at some studies that dive deeper into this subject. (Lee & Xu, 2000), discuss the importance of accurately modeling human senses in VR to create a more immersive experience. They mention various factors like visual, auditory, haptic, and olfactory stimuli that influence our senses, and different modeling techniques used to create them.

(Wu & others, 1996), talked about integrating sight and touch in VR to make the experience more immersive. They highlighted potential uses in entertainment, education, and medical training, and suggested future work like developing advanced haptic devices and machine learning techniques.

A study by (Choi & others, 2016), examined how the integration of multiple senses plays a role in the virtual hand illusion. They discovered that consistent visual and tactile feedback led to a stronger illusion, suggesting this finding could help improve VR design.

(Noccaro & others, 2020), described a VR platform designed to integrate sight, sound, and touch. They conducted experiments using this platform and suggested its potential use in entertainment, education, and medical training.

(Kim & others, 2020), studied the relationship between multisensory integration and experiences like scene instability, presence, and cybersickness in VR. They found a connection between these factors, which could impact how we design virtual environments.

(Gallace & others, 2012), provided a review of the possibilities and limitations of multisensory presence in VR. They discussed various ways to create a more immersive experience, including the use of haptic devices, spatialized audio, and immersive displays, and the challenges of simulating certain senses.

Finally, (Fröhlich & Wachsmuth, 2014), discussed the progress in using multisensory stimuli in VR. They highlighted the importance of synchronizing visual, auditory, and haptic feedback in real-time, and mentioned the need for more advanced sensory feedback systems.

## **2.3 Multi-sensory conflict**

Multi-Sensory Conflict (MSC) represents a discrepancy between sensory modalities, leading to a distortion in the perception of the user's environment (Howard & Templeton, 1966). This conflict typically occurs when visual, auditory, haptic, or other sensory information provided to an individual is inconsistent or incompatible, resulting in confusion and potentially causing cognitive overload, motion sickness, and disorientation (Reason & Brand, 1975).

From a neuroscience perspective, MSC emerges from the conflict in the brain's multisensory integration processes, wherein the brain attempts to reconcile the differing sensory inputs and form a coherent perception of the world (Ernst & Bühlhoff, 2004).

### **2.3.1 Multi-sensory conflict in virtual Reality**

The complexity of human perception comes from synergistic integration of multisensory information. Virtual reality environments aim to align visual, auditory, and sometimes haptic and olfactory stimuli to create a cohesive experience. However, discrepancies between these stimuli, referred to as MSC, can disrupt coherence, causing discomfort or destroying the illusion of presence (Sanchez-Vives & Slater, 2005).

A discrepancy between senses can be either inter-sensory (between senses) or intra-sensory (within the same sense), according to Meehan et al. (Meehan, et al., 2002). The former could

include visual stimuli that indicate movement, while the vestibular system indicates stillness, whereas the latter might include visual inconsistencies, such as perspective errors or late rendering.

Loss of immersion is not the only effect of MSC in VR environments. A number of studies have shown that these conflicts can cause symptoms similar to motion sickness, often called "cybersickness" (Keshavarz & Hecht, 2011), (LaViola Jr, 2000). A VR system's appeal and usability can be greatly diminished by symptoms such as disorientation, nausea, and eye strain.

According to Stanney et al. (Stanney, et al., 1997), MSC can also cause negative cognitive effects, such as decreased spatial awareness and memory. Further, users may experience after-effects even after leaving the VR environment (Duh, et al., 2004).

### **VR Metaphoric Experiences**

Virtual reality uses metaphors to create abstract, non-realistic environments that engage the user's cognitive and affective functions. As a result of metaphoric interactions, users can interact with the virtual environment more intuitively and meaningfully (Slater & Sanchez-Vives, 2016), potentially enhancing the immersion.

It is suggested by (Heeter, 1992) that metaphoric interfaces offer a level of interaction fidelity that matches or even surpasses that of the real world, which can effectively engage users. As an example, it is possible to simulate flying through physical movements or to represent data as physical objects.

### **Metaphoric experiences enhance immersion**

By providing an alternative framework of interaction, metaphoric experiences can reduce MSC. When the virtual environment aligns with the metaphoric interpretation of the real world, any sensory discrepancies become less jarring and more compatible with the user's overall experience (Brade, et al., 2017).

In VR environments, metaphoric interfaces can be used to describe motion and interaction. When users "fly" through a virtual environment using body movements, the metaphor can compensate for the lack of physical motion sensed by the vestibular system (Jones & Tan, 2013).

By leveraging their intuition and pre-existing knowledge, metaphoric experiences can also facilitate cognitive offloading, which allows users to engage with VR more directly. As a result (Risko & Gilbert, 2016), cognitive load can be significantly reduced and immersion enhanced.

## Chapter 3 Methodology

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### 3.1 Scientific Issue:

We argue that presence in VR is much more than just “being there”. Since VR technology has become so prevalent, it has become easier to immerse users in VE. In this regard, judgments about the realism of VEs become more important.

While traditional tools for measuring Sense of Presence (SoP), such as questionnaires, offer valuable insights, they cannot fully quantify and capture the nuanced, context-dependent nature of SoP. Sense of Presence is intrinsically linked to an environment and the unique experiences of an individual. Despite their ability to generalize across diverse contexts and user backgrounds, questionnaires may not fully capture the individual and context-specific aspects of presence in VR.

Users might not be able to accurately recall or articulate their in-the-moment experiences when filling out questionnaires due to the reliance on post-experience reflection. It is possible that this reflective process will diverge from the immediate experiences and perceptions users have during their VR interactions, leading to discrepancies in the data collected.

It's important to acknowledge, however, that this limitation is not exclusive to questionnaires, but also applies to objective measures. Both types of measures might fail to fully consider individual characteristics when they are designed or analyzed. In order to gain a deeper understanding of users' experiences in VR, it's essential to assess SoP using a combination of methods that take individual differences and contextual factors into account.

Numerous methods have been introduced in the literature to enhance and measure the sense of presence in virtual reality. The objective of this research is to propose a methodology to define SOP and measure it according to the context of the VE and the user's characteristics, as well as to explore some metaphors to increase SOP. Additionally, we suggest that metaphors can be useful tools in enhancing the SOP. In addition to their capacity to evoke vivid and familiar mental images, metaphors can also facilitate users' cognitive assimilation into VEs, potentially increasing the sense of presence.

In this context, the main research questions we want to address in our research are the following ones:

Q1: Is it possible to define a dedicated SOP in the context of the user's experience?

Q2: How to measure SOP in a specific context?

Q3: How to enhance SOP?

There are therefore two aspects to the research question at hand. Firstly, it requires the exploration and development of context-aware methods for measuring SOP in VR that go beyond generic questionnaires in order to capture users' individual and nuanced experiences. Secondly, it involves an investigation of the use of metaphors to enhance SOP, as well as an understanding of how these tools can be calibrated to work within specific VE contexts.

### 3.2 Proposed approach:

Literature showed that SOP is very application dependent and task-oriented and General and uncustomized methods like questionnaire are unable to quantify the sense of presence.

Based on these constraints that mentioned above and also in the literature review, we propose that presence, as a context-dependent concept, should not be solely assessed through traditional questionnaire methods. We should explore and develop other measurement approaches that can capture the immediate, subjective, and contextual nature of presence. Such methodologies may be able to provide a richer and more delicate understanding of presence that is in line with the actual experiences that users have within virtual environments. It is crucial to develop context-sensitive measures in order to assess presence in VR in a way that is more valid and reliable.

Addressing the complexities of the sense of presence (SOP) in VR environments necessitates a nuanced approach. For this study, the focus will be on individual behavior and the sensation of performing specific tasks within certain contexts. In this study, we tried to introduce a methodology for quantifying sense of presence, which can be applicable for different use cases and different virtual contexts. Therefore, we utilized mixed-methods approach to provide a comprehensive analysis of SOP.

The first step in this method is to determine the use case of the virtual environment, followed by the characteristics and specifications of the use case. Our next step is to observe the users' behavior and then define the SOP in the context of the use case. By defining the SOP within the context of the use case, we can introduce objective or subjective indicators to dedicated users' sense of presence. In addition, we will be able to introduce different metaphors to enhance the SOP of VR users. Following is a detailed description of each step.

1. Definition of Use Cases and Characteristics and Context
2. Observation and Data Collection
3. Defining dedicated SOP and proposal of metrics
4. Introduction and Testing of Metaphors
5. Validation of Indicators and Metaphors

#### Phase 1: Definition of Use Cases and Characteristics and Context

- Definition of Use Cases and Contexts

Multiple VR use cases such as, training, interacting, and therapy session (increasing and decreasing stress) are identified to ensure the methodology is applicable for different virtual contexts.

- Defining Characteristics and Context

For each use case, the characteristics and specifications are defined. This includes the type of tasks users are required to perform, the virtual environment's features, and the expected interactions.

### Phase 2: Observation and Data Collection

- Selection of Participants:

Participants are selected based on criteria relevant to the use cases being studied. Demographic diversity is also considered.

- Behavioral Observation

Participants' behaviors, interactions, and responses are closely observed as they perform specific tasks within the VR environments. Special attention is given to signs that may indicate the level of presence such as immersion, engagement, and naturalness of interactions.

- Data Collection

Both qualitative data (through interviews and open-ended questions) and quantitative data (through tracking movements, response times, and interaction rates) are collected.

### Phase 3: Defining SOP in Context and proposal of metrics

- Definition of Dedicated SOP

Data collected in phase 2 are analyzed to understand how SOP is experienced within different contexts and tasks. This includes identifying commonalities and differences across use cases.

- Development of Context-Sensitive Indicators

Based on the analysis, new context-sensitive indicators are developed to define and measure SOP. These indicators are both objective and, where necessary, subjective.

### Phase 4: Introduction and Testing of Metaphors

- Identification of Metaphors

Potential metaphors that could enhance SOP based on context are identified. These metaphors could be visual, auditory, or haptic enhancements.

- Testing of Metaphors

Participants are exposed to the identified metaphors within VR environments, and feedback is collected regarding their effect on SOP.

### Phase 5: Validation of Indicators and Metaphors

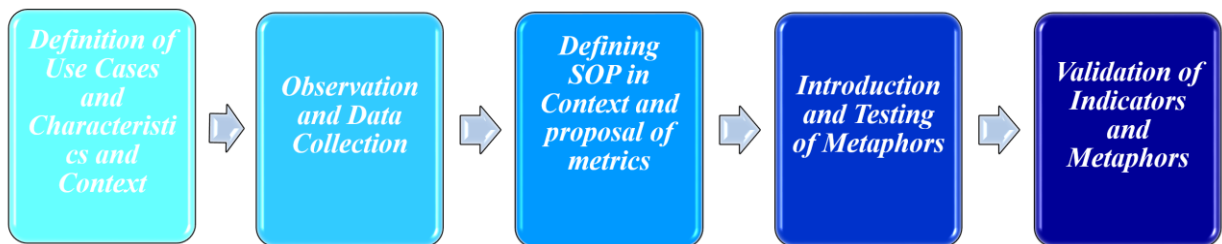
- Statistical Analysis

Statistical analysis is conducted to validate the developed indicators, ensuring that they accurately represent SOP in different contexts.

- Effectiveness of Metaphors

The effectiveness of metaphors in enhancing SOP is assessed based on participants' feedback and observable changes in behavior and interactions.

Here is the scheme of the presented method:



To test our method, we applied it on different contexts that we will explain them in following use cases.

## Chapter 4 Experimental Studies

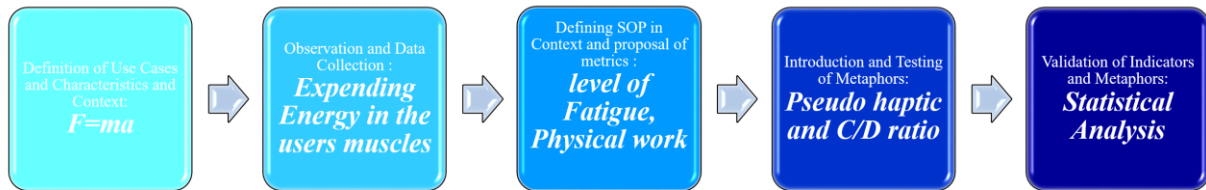
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## 4.1 Use Case1: Lifting Virtual Bottles



### 4.1.1 Phase 1: Definition of Use Cases and Characteristics and Context

- **Definition of Use Cases and Contexts**

When a person wants to lift an object, the force they have to exert on the object must be equal to or greater than the weight of the object in order to lift it against the gravitational force acting on it. The weight of the object is the force due to gravity acting on the object and can be calculated as:

$$\text{Weight} = \text{mass} \times \text{acceleration due to gravity } W = m * g$$

Where:

W is the weight of the object (usually measured in Newtons),

m is the mass of the object (usually measured in kilograms),

g is the acceleration due to gravity (approximately 9.8 m/s<sup>2</sup> on the surface of Earth).

To start lifting an object, you must exert an upward force that is just slightly more than the weight of the object. This is because if you exert exactly the same force as the weight, the object will be in equilibrium and will not move.

However, it's important to consider that this analysis is simplified. In real-life scenarios, additional factors such as friction, the object's center of mass, and your own physical capabilities can also play a significant role in the amount of force needed to lift an object.

- **Defining Characteristics and Context**
- As highlighted in Chapter 2 (Literature Review), inducing the sensation of virtual objects' heaviness remains a significant challenge in crafting rich and believable virtual environments. Generating a perception of virtual weights necessitates the integration of multiple principles to offer users a compelling and convincing experience. Initially, haptic feedback devices play a pivotal role. These devices, including gloves or VR hand controllers providing vibrational feedback, can simulate a sense of heaviness. Haptic feedback is inherently multimodal, encapsulating tactile sensations, force feedback, and proprioception. This complex sensory system, therefore, not only perceives tactile sensations but also interprets forces and the spatial positioning of body parts, providing a holistic sensory experience that goes beyond mere tactile feedback.
- However, the perception of an object's weight isn't solely reliant on our multifaceted haptic sensory system; it significantly interacts with our visual sensory system. Unlike

the haptic system, the visual system is unimodal, primarily receiving information through the retina. In scenarios where there is conflicting information, studies have shown that the visual system often dominates over haptic perception (refer to specific studies). Visual cues, such as object deformation or positional changes, contribute to our understanding of weight. For instance, a virtual object appearing heavy might visually compress or bend, providing cues to its assumed weight. Furthermore, physics simulations act as another fundamental layer, replicating the diverse behaviors of objects with varying masses and making distinctions in the ease or difficulty of moving objects based on their simulated weight (Samad, et al., 2019). Beyond these, audio cues and interaction techniques also play crucial roles in this intricate symphony of sensory feedback, contributing to the nuanced perception of weight in virtual environments.

In this experiment, we want to propose a model to induce the virtual objects' weight to the VR participants in a virtual environment and also compare subjects' lifting behavior in VR conditions with real object lifting. To do this, subjects lift real bottles in real conditions, while in virtual conditions they lift virtual bottles with VR hand controllers.

Our proposed model integrates haptic feedback, visual cues, physics simulation, and specialized interaction techniques to create a more immersive and realistic experience in the virtual environment. After designing the environment, we asked different participants to join to the experiment.

#### 4.1.2 *Phase 2: Observation and Data Collection*

- **Selection of Participants:**

Twenty right-handed users (6 women and 14 men, ranging from 18 to 44 years with a mean age of  $26.24 \pm 7.98$  SD) participated in our experiment. All were healthy and had no neurological, muscular, or cognitive disorders, with normal or corrected-to-normal vision. Users' heights ranged from 156 to 185 cm, with a mean height of  $173.74 \pm 6.57$  cm. Users from different backgrounds, either from inside or outside the university, agreed to participate voluntarily without compensation. These participants were the same participants of the experiment one.

#### **Behavioral Observation**

When participants are asked to lift bottles, their muscles are indeed expending energy. Lifting any object, including a bottle, requires the muscles to contract and work against the gravitational force pulling the object down. Here's a basic overview of what happens:

*Neural Activation:* The brain sends signals through the nervous system to the muscles involved in lifting the object.

*Muscle Contraction:* The muscles receive the signals and contract. Muscles can only pull, not push, so different groups of muscles work together to achieve the lifting motion. For instance,

when lifting a bottle, mainly the biceps, forearm muscles, and some shoulder and back muscles are involved.

*Energy Consumption:* To contract, muscles need energy. This energy is supplied by adenosine triphosphate (ATP) in the muscles. ATP is generated through the metabolism of carbohydrates, fats, and proteins.

*Work Against Gravity:* As the muscles contract, they exert a force on the bottle. This force has to be greater than the weight of the bottle to lift it against gravity.

*Muscle Fatigue:* If the action is repeated or if the weight is substantial, the muscles can experience fatigue due to the depletion of energy stores and the accumulation of metabolic by-products.

The efficiency of energy expenditure and muscle contraction can vary among individuals due to factors like fitness levels, muscle strength, and technique.

- **Data Collection**

Following the behavioral observation, we found that we can measure data relevant to physiological changes in body like “muscle fatigue” and the “work against gravity”. Therefore, we employed Borg CR10 (Borg, 1990) to measure “muscle fatigue” and physical work formula to measure “work against gravity”. In following we explain our measurements in details.

Using the Borg CR10 Scale, physical work measurements, and a presence questionnaire can offer a comprehensive insight into the physical exertion and the subjective experience of the participants during a lifting task. Let’s break down each component:

*1-Borg CR10 Scale:* The Borg CR10 Scale is a subjective rating scale developed by Swedish psychologist Gunnar Borg. It is used for measuring a person's perceived exertion during physical activity. The scale typically ranges from 0 to 10, where 0 indicates no exertion at all and 10 indicates maximal exertion. Participants are asked to rate their level of effort, strain, discomfort, and/or fatigue during the task. This scale is often used in exercise and rehabilitation settings to gauge an individual’s level of intensity during physical activities.

Here is a more detailed breakdown:

- 0: Nothing at all
- 0.5: Extremely weak
- 1: Very weak
- 2: Weak (light)
- 3: Moderate
- 4: Somewhat strong
- 5: Strong (heavy)
- 7: Very strong
- 10: Maximal exertion

*2-Physical Work Measurement:* This can involve various methods of objectively quantifying the physical demands of a task. For lifting tasks, this might include



measuring the weight of the objects being lifted, the frequency of lifts, the duration of the lifting session, and the range of motion involve.

Moreover, to compare whether our virtual environment was close to the real environment we asked participants to fill Presence questionnaire.

*3- Presence Questionnaire:* Presence questionnaires are typically used to measure a person's sense of presence in a virtual environment, but they can also be used more broadly to assess how engaged or immersed a person feels in a given activity or setting. In virtual reality research, for example, a presence questionnaire might ask participants to rate how "real" the virtual environment felt, or how much it felt like they were actually "there". In other contexts, it can be adapted to measure how involved or absorbed participants feel in the task they are performing.

This questionnaire generally covers different aspects including:

- 1) Involvement: represents the level of interest of the participants
- 2) Immersion: the quality of the participant's sense of being inside the VE.
- 3) Realism: the degree of the realistic of the environment
- 4) Adoption: the level of the participant's interaction with the VE become natural over time.

In this work we use, the version of the presence questionnaire (Witmer & Singer, 1998) to measure participants sense of presence.

Combining these three components in data collection can provide valuable insights:

- The Borg CR10 Scale can help to understand the participants' perception of physical effort.
- Physical work measurements can give objective data about the physical demands of the lifting task.
- The presence questionnaire can offer insights into the psychological experience of the participants, including engagement and immersion.

#### ***4.1.3 Phase 3: Defining SOP in Context and proposal of metrics***

Data collected in phase 2 are analyzed to understand how SOP is experienced within different contexts and tasks. This includes identifying commonalities and differences across use cases.

- Development of Context-Sensitive Indicators

Based on the analysis, new context-sensitive indicators are developed to define and measure SOP for lifting a virtual weight in VE. When we asked participants to lift a virtual bottle in VE

using a VR hand controller, we computed the physical work done by the users to perform the lifting task using the following formula:

$$\text{Equation 4-1: } W = m_{\text{controller}} G h + m_{\text{controller}} * \int_s^e a \, dx$$

This formula comes from the general principle of physics about forces, as expressed by the following:

$$\text{Equation 4-2: } \sum_{i=1}^n F = m_{\text{controller}} * a$$

Where  $m$  is the controller's mass, and  $a$  is the acceleration caused by users' movement. Then, still in physics, work can be defined by the following equation at each instant:

$$\text{Equation 4-3 : } dw = F \cdot dx,$$

where  $dw$  is the element of work at each time,  $F$  is the force obtained from (EQ 4-2), and  $dx$  is the displacement. In this study, two main forces were applied to the object, as shown in Figure 4.1 . The first one is the users' hand force ( $F$ ) applied to lift the object upward, and the second is gravity ( $P$ ).

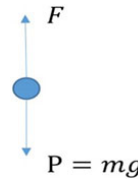


Figure 4.1 Forces applied to an object during the lifting task.

$F$  is the force applied by the participants' hand on the object. Therefore, according to the physics rules, we obtain:

$$\text{Equation 4-4: } \vec{F} + \vec{P} = m\vec{a} \quad \Leftrightarrow \quad F - P = ma \quad \text{Since } F \text{ and } P \text{ are not in the same direction}$$

Then, using the formula  $P = mg$ , we can obtain the following equation along the vertical axis:

$$\text{Equation 4-5: } F = mg + ma$$

Using (EQ 4-3), we can express the work of the force applied by the hand of the user between the starting point, called (s) here, and the end point, called (e) here, as follows:

$$\text{Equation 4-6: } W = \int_s^e dw = \int_s^e F \cdot dx \quad \Leftrightarrow \quad W = \int_s^e mg + ma \quad \Leftrightarrow \quad W = \int_s^e mg \, dx + \int_s^e ma \, dx$$

Finally, from (EQ 4-6), (EQ 4-1) is obtained and used to compute the user's physical hand work when lifting.

#### 4.1.4 Phase 4: Introduction and Testing of Metaphors

- **Identification of Metaphors: Pseudo Haptic**

Pseudo-haptic is a technique to evoke haptic perception through visual cues (Ujitoko & Ban, 2021). As a result, they can provide haptic perception without using expensive or restrictive haptic devices. It is also consistent with findings by (Ernst & Banks, 2002) who found that visual-haptic perception dominates in judging objects' shape, size, and position.

Pseudo-haptic feedback can be provided by manipulating the control display (C/D) ratio (Poupyrev, et al., 1996) (Argelaguet & Andujar, 2013). The term "C/D ratio" in the context of pseudo-haptics typically refers to the "Control/Display ratio." The C/D ratio is used to manipulate the relationship between the user's input (control) and the system's output (display).

This work introduced an approach based on physics to produce pseudo-haptic feedback, in which the sole opposition force to a vertically lifted object is its weight, when friction is ignored. Thus, the user must produce at least a force equivalent to the weight of the lifted object, but in the opposite direction. Traditional VR setups, however, do not provide real props that users can use to interact with virtual objects. As a result, users only need to compensate for the weight of a VR controller during such a lifting operation, in contrast to the actual weight of the virtual object being viewed. Therefore, the relationship between the force exerted by the user to lift the VR controller and the force expected based on the weight of the virtual object viewed can be expressed as a ratio function called  $k(m)$ , which  $m$  is the weight of the object:

$$\text{Equation 4-7: } k(m) = \frac{\overline{||\text{Weight}_{\text{controller}}||}}{\overline{||\text{Weight}_{\text{object}}||}} = \frac{\text{mass}_{\text{controller}}}{m}$$

As a result, we propose to use this ratio function to provide pseudo-haptic feedback. To do so, we transform it into a ratio of work using (EQ 4-8) or into a ratio of power as in (EQ 4-9):

$$\text{Equation 4-8: } W = \overline{||F||} * d * \cos(\theta) = \overline{||F||} * d, \text{ when } \theta = 0$$

$$\text{Equation 4-9: } P_{\text{instantaneous}} = \overline{||F||} * v * \cos(\theta) = \overline{||F||} * v, \text{ when } \theta = 0$$

In this equation,  $d$  is the displacement distance,  $v$  is the motion velocity, and  $F$  is the force applied. In addition, we propose to use (Eq. 4-8) to provide pseudo-haptic feedback in a distance-based approach and (Eq.4-9) in a velocity-based approach. In our case,  $\theta=0$  as the movement is on the vertical axis.

*Distance-based approach: our "direct-weight" technique*

From (EQ 4-7), (EQ 4-8) transforms to the following:

$$\frac{W_{\text{controller}}}{W_{\text{object}}} = \frac{\overline{||\text{Weight}_{\text{controller}}||} * d_{\text{controller}}}{\overline{||\text{Weight}_{\text{object}}||} * d_{\text{object}}} = k(m) * \frac{d_{\text{controller}}}{d_{\text{object}}}$$

Further, conditions of feedback that fully compensate for the difference of masses between object and controller mean a ratio of *work* equal to 1:

$$\frac{W_{controller}}{W_{Object}} = 1 \quad \Leftrightarrow \quad k(m) * \frac{d_{controller}}{d_{object}} = 1$$

$$\Leftrightarrow d_{object} = k(m) * d_{controller} \quad \Leftrightarrow \quad d_{object} = \frac{\text{massController}}{m} * d_{controller}$$

To allow ranges of masses for virtual objects that can be easily more than 10 times the VR controller one, a constant  $c$  can be added in the previous relation as follows:

$$\text{Equation 4-10: } d_{object} = \left( \frac{\text{massController}}{m} + c \right) * d_{controller}$$

In addition, such a constant gives a limit to the ratio applied between the two distances, as the ratio of masses would tend to 0 when  $m$  increases. Such a limit prevents from applying pseudo-haptic feedback that would introduce so much difference between real and viewed displacements that it would break the sensation of presence for the VR users. Moreover, it determines the minimal mass to get some pseudo-haptic feedback, i.e., the mass for which the applied ratio is 1, as expressed by the following:

$$\text{Equation 4-11: } \frac{d_{object}}{d_{controller}} = 1 \quad \Leftrightarrow \quad \frac{\text{massController}}{m_{min}} + c = 1 \quad \Leftrightarrow \quad m_{min} = \frac{\text{massController}}{1-c}$$

Finally, we used the relation defined in (EQ 4-10) between distances to define some pseudo-haptic feedback in VR depending on the virtual object mass and that of the controller; it consists in applying a C/D ratio higher than 1, defined here by the opposite of  $\left( \frac{\text{massController}}{m} + c \right)$ , to scale down the distance traveled by the object in VR compared to that of the controller in the real world. We call this pseudo-haptic technique, based on distances, the direct-weight technique (direct modification of C/D ratio, related to weights ratio).

*Velocity-based approach: our "speed-control" technique*

From (EQ 4-7), (EQ 4-9) transforms to the following:

$$\frac{P_{\text{instantaneous}_{controller}}}{P_{\text{instantaneous}_{object}}} = \frac{||\text{Weight}_{controller}|| * v_{controller}}{||\text{Weight}_{Object}|| * v_{object}} = k(m) * \frac{v_{controller}}{v_{object}}$$

Further, conditions of a feedback that fully compensates the difference of masses between object and controller mean a ratio of *power* equal to 1:

$$\frac{P_{\text{instantaneous}_{controller}}}{P_{\text{instantaneous}_{object}}} = 1 \quad \Leftrightarrow \quad k(m) * \frac{v_{controller}}{v_{object}} = 1$$

$$v_{object} = k(m) * v_{controller} \quad \Leftrightarrow \quad v_{object} = \frac{\text{massController}}{m} * v_{controller}$$

As in Section 3.2.1, to allow wider ranges of masses for  $m$ , a constant  $c$  is employed here as follows:

$$\text{Equation 4-12: } v_{object} = \left( \frac{\text{massController}}{m} + c \right) * v_{controller}$$

Subsequently, for each determined mass  $m$ , the following algorithm is applied:

*Equation 4-13: if  $V_{controller} < V_{max_{object}}$ , then  $v_{object} = v_{controller}$*

*Equation 4-14: else  $v_{object} = V_{max_{object}}/v_{controller}$*

The relationship between velocities defined in (EQ 4-12), (EQ 4-13), and (EQ 4-14) was used to provide some pseudo-haptic feedback in VR in accordance with the mass of the virtual object and the controller. When a real motion velocity exceeds a maximum speed authorized by the software, a C/D ratio greater than 1 is applied. Based on velocity restriction, we call this pseudo-haptic technique the speed-control technique.

#### *C/D ratio, visual discrepancy, and objects masses*

As explained in (EQ 4-11) and applied to the two techniques described in (EQ 4-10) and (EQ 4-12), a constant  $c$  must be defined with respect to the experimental conditions and not with respect to the physics model itself. For the following reasons and implications, we set  $c$  to 0.5 in our experiment:

i) By setting a constant of 0.5, the functions  $d(m)$  and  $v(m)$  defined in (EQ 4-10) and (EQ 4-12) tend to 0.5. This reduces the visual discrepancy between user movements (reflected by the controller position in VR) and the movements of virtual objects to a factor of 0.5. This discrepancy reduction guarantees that the user's sense of presence is maintained.

ii) According to (EQ 4-11), for a 0.308 g VR controller, a value of 0.5 produces a minimum mass ( $m_{min}$ ) of 0.616 g. Hence, pseudo-haptic feedback would begin at masses greater than 0.616 g, with ratios decreasing from 1 to 0.5. There would thus be interesting intermediate points at 1 and 2 kg, and a 5 kg point that would already be near 0.5. As a result, the masses used in our experiment were fixed to 0.616, 1, 2, and 5 kg. In addition, these values would allow a significant evaluation of our pseudo-haptic techniques with masses that are already well beyond the 0.308 grams of the VR controller and are close to the masses of a large number of everyday objects.

#### **• Testing of Metaphors**

Participants are exposed to the identified metaphors within VR environments, and feedback is collected regarding their effect on SOP. In this experiment, we considered 4 lifting object conditions. These conditions are explained in the following:

##### ***Direct-weight condition***

We do not need to set any additional parameters for this first incongruous condition, other than the constant  $c$  and considering the masses of the objects.

##### ***Speed-control Condition***

This second condition requires the parameter (parameter C) for our experiment to be set according to (EQ 12A-12B), determined for a lifting task in VR without any additional mass. It is possible to estimate this value empirically using some users in a pre-experiment. The value can also be estimated theoretically by referring to Fitts' Law studies, particularly those of K. T. Hagadorn's (Hagadorn, 2004). The originality of these values explains Fitts' law's applicability to human movement in three dimensions, involving the manipulation of moving objects (Gillan, et al., 1990) (MacKenzie, 1993). A further finding of this study was that different Fitts' laws could exist depending on the mass of the object being manipulated. Accordingly, we used the coefficients given in this study for objects weighing less than 450 grams,  $a = 0.2138$  and  $b = 0.473$ , in their formula:

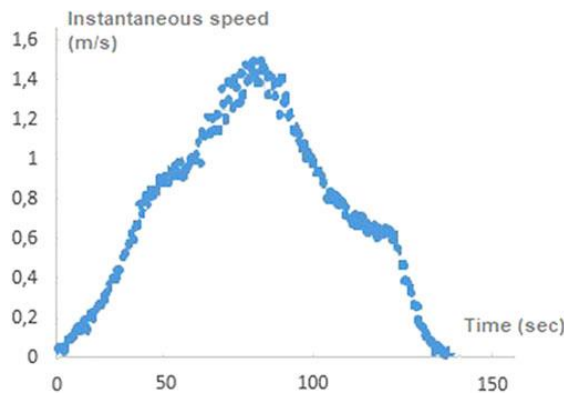
$$\text{Equation 4-15: } MT = a + \text{Log}_2(2 * d/w) * b$$

where MT is the task completion time, d is the manipulation distance, and w is the size of the target to reach.

The distance in our experiment was 1 m, and the target size was 0.4 m, yielding an MT of 1.32 s, which implies an average speed of 0.75 m/s. In order to calculate the maximum speed during a vertical lifting task, we needed to compute the average speed. We captured the motion of a lifting task and calculated the instantaneous speed, as shown in Figure 4.2. Due to strength and other individual variability, the maximum speed value cannot be directly considered as our experiment's value. However, the shape of the velocity profile for this type of task can be maintained and analyzed (the same across multiple users). As can be observed, such motion can be decomposed in terms of velocity phases into acceleration and deceleration, each representing half of the motion. By representing this motion profile with two affine functions f1 (ascending) and f2 (decreasing), we can calculate the maximum speed:

$$\begin{aligned} \text{Equation 4-16: } V_{average} &= \frac{1}{2} * \int_0^{0.66} f1(t) + \frac{1}{2} * \int_{0.66}^{1.33} f2(t) \\ \Leftrightarrow V_{average} &= \frac{1}{2} * \left( \frac{0 + v_{max}}{2} \right) + \frac{1}{2} * \left( \frac{v_{max} + 0}{2} \right) \Leftrightarrow V_{average} = \frac{1}{2} * v_{max} \Leftrightarrow V_{max} \\ &= 2 * v_{average} \end{aligned}$$

Thus, for our experiment, we found and set the maximum speed to 1.5 m/s ( $0.75 \times 2$ ) for masses below or equal to 0.616 g, and for higher masses.



*Figure 4.2. Hand motion instantaneous speed across time for a lifting task (1 m distance, no extra mass)*

Besides the two conditions described in the previous, our experiment also included the following two congruent conditions without visual discrepancy. Under this condition, visual feedback corresponds to real hand motion, as under controlled conditions. The "**isomorphic condition**", which refers to the "traditional" virtual manipulation techniques with no pseudo-haptic feedback, and the "**haptic condition**", which refers to the "traditional" real manipulation techniques with full haptic feedback upon lifting a real object.

To test the proposed metaphor we used the following devices:

A HTC Vive Pro VR head mounted device (HMD) was used for our experiment, equipped with two cameras, hand controllers to manipulate virtual objects, and hand trackers to record arm movements. The HTC vive pro has a  $1440 \times 1,600$  pixel resolution with a  $110^\circ$  field of view. This HMD featured an electronic gyroscope, and an eye comfort setting system (IPD) (Figure 13 A). The HMD was connected to Unity3D via SteamVR and VRTK SDK which provides many built-in APIs for developing VR user interfaces. With this SDK, users and the VE interaction could be achieved in real-time with negligible delay.

The hand controller (Figure 4.4 C) provides an indication of the position of the subject's dominant hand (left or right) in the real environment, allowing the rendering engine to generate a visual representation of the hand in VR in all conditions that involved virtual objects to lift. Using the trigger button subjects were able to grab the virtual bottle in VE and lift it.

Two hand trackers (Figure 4.3 B) for lifting real objects, attached to the wrist of the subjects, provide locational information to the rendering engine. This information is used in order to generate a model of the subject's hand and the visual feedback about the position of the user's dominant hand in haptic condition. Additionally, one tracker was placed on the real object (Figure 4.4 A) to track its displacement and to display it in the virtual environment (Figure 4.4 B).



Figure 4.3 A: Vive eye pro equipped with two cameras and 2 hand controller B: HTC vive hand tracker.

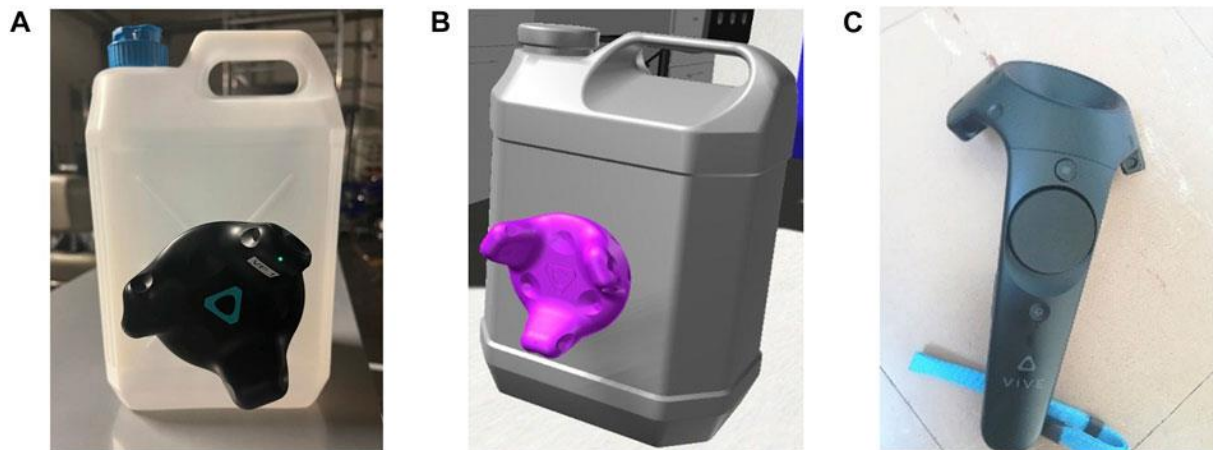


Figure 4.4 Real bottle attached to a hand tracker (A) and virtual bottle (B) representations in our experiment, and (C) their tracker, the HTC Vive VR controller.

#### Experimental procedure:

The procedure was designed as follows

- A) This study required users to stand throughout the whole experiment when lifting the objects from bottom to top. However, they were permitted to rest at any time, especially between blocks of four conditions. Physically, they were placed in a calm room. In front of them there was a 46 cm high box at a distance, allowing them to comfortably grasp and lift the objects placed on the box without bending. Before starting the experiments we gave them a brief training on the tasks including what they were going to do and how to and how to perform the task.
- B) We asked them to put on the HMD and see the VE which was a small office with some chairs and tables. In the VE they found a small white platform in front



of them and a green window on top of that with a distance equal to one meter. (Figure 4.5 A, B).

- C)** User task was to lift an object upward with a single joint arm movement, with natural self-selected speed (with rotation around the shoulder and maintaining the arm entirely extended). This object was visible in the environment as a water bottle and had to be placed at a defined height, represented by a green window. We conducted two phases of our experiment: the training and the main phases.
- D)** Training phase: In this phase, eight lifting movements are performed before each manipulation interaction condition, in order to teach users how to perform upward lifting in our VR setup. The training phase was meant to introduce users to our unusual manipulation techniques, compared to real-world lifting, notably for the incongruous conditions that cause conflicts between the actual hand movement and the given visual feedback. It would then help users to avoid “failing” to accomplish their lifting motion in terms of performance and “naturalness”.
- E)** Main phase: The main phase was divided into four blocks of lifting trials, one for each manipulation condition. With all our techniques, grabbing was always done through direct contact with objects, using a virtual hand metaphor. Each block included 20 trials, each consisting of five repetitions of lifting objects of four different masses (0.616, 1, 2, and 5 kg). In all trials, users performed vertical arm motions almost exclusively at a distance of 1 m, starting from a similar point (46 cm from the ground)(Figure 4.5 C). The mass of the objects was never disclosed to the users. Furthermore, the virtual objects displayed all had the same design, without any variation in size or shape (Figure 4.4A, B). The users were asked to perform natural and self-selected-speed movements under all conditions, with congruent conditions more favorable because of the absence of visual discrepancy, and incongruous conditions more challenging due to pseudo-haptic feedback.
- F)** We used a repeated-measure design to increase the number of measures and control differences between users, as they are usually not equal in terms of strength. A Latin-square order was used between participants, with the order of blocks within each block, i.e., between masses of objects, randomized for each participant. Thus, we used 20 of the 24 possible orders across our four manipulation conditions.
- G)** After performing each block of the experiments, we asked users to fill Borg CR10 questionnaire to measure the sense of hand tiredness in subjects’ hand related to each condition. In order to subjects’ convenience, the questionnaire was translated into French .
- H)** After Filling Borg questionnaire we asked subjects to fill presence questionnaire to understand their level of presence in each condition.

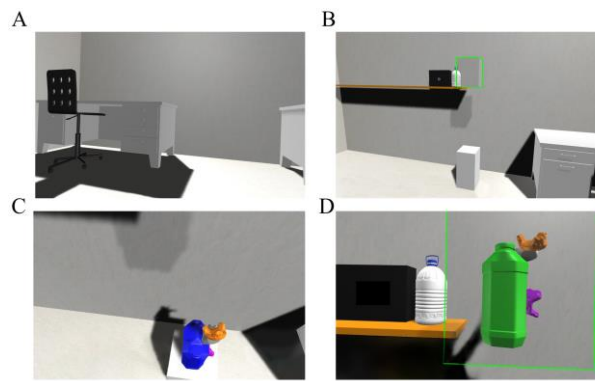


Figure 4.5 Virtual environment. A: office environment with desks and chairs. B: white box is the starting point of the bottle lifting and the green square is the ending point of the bottle lifting. C: the initial point of the bottle. blue. D: The ending position of the bottle.

The whole procedure of the experiment is given in Figure 4.1-6. The participants were exposed to the VE each time between 4 and 6 minutes. Participants were given a small gift of chocolate bar of their choice to compensate the participation time.

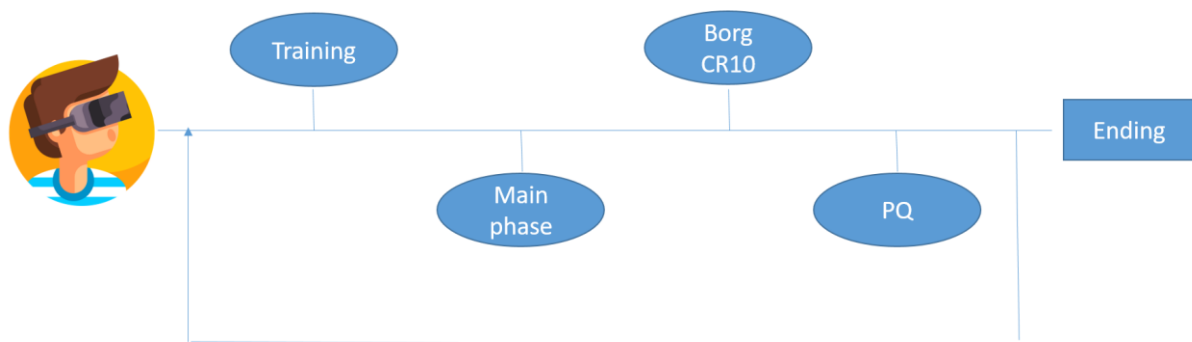


Figure 4.6 Experimental procedure conducted to obtain the datasets

In the summary of this section, we introduced physical work as an objective measurement and Borg CR10 as a subjective measurement. We utilized the concept of pseudo-haptic feedback to enhance the sense of presence (SOP).

#### 4.1.5 Phase 5: Validation of Indicators and Metaphors

- **Statistical Analysis**

Statistical analysis is conducted to validate the developed indicators, ensuring that they accurately represent SOP in different contexts. To do the statistical analysis we used following tests:

##### *Two-Way ANOVA Analysis*

The two-way analysis of variance (ANOVA) was conducted to examine the interaction effects between the independent variables "condition" and "weight". The "condition" variable comprised four levels; haptic, isomorphic, speed-control, and direct-weight. Similarly, the "weight" variable also had four levels; 0.616, 1, 2, and 5 in kg. The level of significance was set at  $\alpha = 0.05$ .

### *One-Way ANOVA Analysis for Each Condition*

In order to investigate the effect of real and virtual weight (independent variable) on physical work (dependent variable), a one-way ANOVA test was separately applied for each condition.

We applied this test, to get a better understating about the each feature during specific condition.

### *Benjamini–Hochberg Correction*

In our research, we implement the Benjamini-Hochberg Correction (Benjamini & Hochberg, 1995) as a means to mitigate the risks associated with false discovery rates. This technique is essential when dealing with multiple comparisons, as it helps us avoid mistaking random variations for actual discoveries, which is a common risk when small p-values are considered significant.

To elaborate on the mechanism of the Benjamini-Hochberg Correction, let's understand the scenario it addresses. When conducting multiple tests, occasionally a p-value less than the accepted significance level (often 0.05) might appear purely by chance. In traditional hypothesis testing, a p-value under 0.05 would typically lead researchers to reject the null hypothesis. However, when multiple tests are involved, the probability of obtaining at least one p-value under 0.05 purely by chance increases.

The Benjamini-Hochberg procedure helps by controlling the false discovery rate (FDR), which is the expected proportion of false positives among all significant results. The process is relatively straightforward:

1. First, all p-values from the tests conducted are arranged in ascending order.
2. A significance level ( $\alpha$ ) is selected, often set at 0.05.
3. For each p-value, it is compared with  $i \cdot \frac{\alpha}{m}$  where  $i$  is its rank, and  $m$  is the total number of tests. If a p-value is less than or equal to this calculated threshold, it and all smaller p-values are considered significant.

Through this procedure, the Benjamini-Hochberg Correction efficiently controls the FDR, providing a balanced approach to maintaining the integrity of the multiple testing process. In our study, the B-H procedure was applied at the 0.05 level to ensure a rigorous control over potential false discoveries, maintaining the reliability of our results.

### *Interpretation of Significance Levels*

In all presented tables, the p-values have been shown by using an asterisk. A single asterisk represents a p-value less than 0.05, indicating a statistically significant finding at the 5% level. Two asterisks represent a p-value less than 0.01, signifying a statistically significant finding at the 1% level. Finally, three asterisks (\*) indicate a p-value less than 0.001.

Detailed findings and interpretations of the statistical analysis will be further discussed in the subsequent sections.

### *Descriptive Statistics:*

As indicated in Table 4.1-1, the mean and standard deviation of kinematic (movement duration MD, arm displacement Disp) and kinetic (physical work) features were calculated. Notably, the displacement (Disp) for congruous conditions was approximately 1 m. However, for incongruous conditions, displacement increased in relation to the object mass, reaching more than 2 m for 5 kg in the direct-weight condition.

#### Effects on Movement Duration

A significant variation in movement duration (MD) was observed when subjects were asked to lift bottles of different weights,  $F(3, 1598) = 10.578$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.019$ . The different conditions also significantly influenced MD,  $F(3, 1598) = 71.208$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.118$ . Moreover, a significant interaction was observed between the conditions and weight, affecting MD,  $F(91, 589) = 7.317$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.04$ .

#### *Post Hoc and B-H Test Results for MD*

According to the Tukey post hoc analysis, MD significantly differed across all multiple comparison conditions ( $p < 0.0001$ ). A pair-wise comparison using the Benjamini–Hochberg (B-H) procedure revealed no false p-values. The post hoc analysis found that MD values for 0.616 kg and 1 kg, as well as for 2 kg and 5 kg, were not statistically different ( $p > 0.05$ ). However, MD values for all other comparisons were significantly different ( $p < 0.05$ ). Additionally, the B-H test confirmed the robustness of the findings obtained from the post hoc analysis.

#### Effects on Displacement

Both conditions and weight significantly impacted displacement (Disp), with  $F(31, 598) = 94.224$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.15$  and  $F(31, 598) = 44.998$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.078$ , respectively. Additionally, the interaction effect of condition and weight on Disp was significant,  $F(91, 598) = 36.369$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.170$ .

#### *Post Hoc Analysis for Displacement*

According to the Tukey post hoc analysis, different weights significantly affected Disp ( $p < 0.0001$ ), except for 0.616 kg and 1 kg ( $p > 0.05$ ). However, the post hoc analysis for all multiple comparisons of different conditions showed a significant discrepancy between different conditions ( $p < 0.0001$ ), except for speed-control and haptic ( $p > 0.05$ ).

#### **B-H Test Results for Displacement**

The Benjamini–Hochberg (B-H) procedure confirmed all post hoc results, with no false discoveries.

#### **Effects on Physical Work**

Physical work was significantly influenced by different weights,  $F(3, 1598) = 22.593$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.041$ , as well as by conditions,  $F(3, 1598) = 118.036$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.181$ . Furthermore, the interaction between condition and weight was also significant for work,  $F(9, 1598) = 10.578$ ,  $p < 0.0001$ ,  $\eta_p^2 = 0.09$ .

**Post Hoc Analysis for Physical Work**

Tukey’s HSD test for multiple comparisons found that the mean value of work was significantly different between haptic and isomorphic ( $p < 0.0001$ , 95% C.I. = 41.65,58.00), between haptic and direct-weight ( $p < 0.0001$ , 95% C.I. = 39.20,55.26), and between haptic and speed-control ( $p < 0.0001$ , 95% C.I. = 40.08,56.28). The mean value of work also significantly differed between different weights. Post hoc HSD analysis revealed significant differences between 0.616 kg and 2 kg ( $p < 0.0001$ , 95% C.I. = -18.84, -2.66), between 0.616 kg and 5 kg ( $p < 0.0001$ , 95% C.I. = -30.65,-14.49), between 1 kg and 2 kg ( $p = 0.026$ , 95% C.I. = -16.93,-0.75), between 1 kg and 5 kg ( $p < 0.0001$ , 95% C.I. = -28.74,-12.57), and between 2 kg and 5 kg ( $p = 0.01$ , 95% C.I. = -19.91,-3.72).

**B-H Test Results for Physical Work**

The B-H procedure confirmed the Tukey post hoc results, detecting no false p-values for multiple comparisons of conditions or weights. It is clear from these findings that the effects observed at work are statistically valid.

	Masses (kg)	Haptic	Isomorphic	Speed-control	Direct-weight
Disp (m)	0.616	1.27 ± 0.05	1.01 ± 0.30	1.17 ± 0.29	1.00 ± 0.76
	1	1.39 ± 0.94	0.94 ± 0.06	1.27 ± 0.40	1.23 ± 0.12
	2	1.22 ± 0.91	0.96 ± 0.19	1.54 ± 0.77	1.79 ± 0.32
	5	1.16 ± 0.54	0.96 ± 0.12	1.56 ± 0.61	2.47 ± 0.68
MD (s)	0.616	4.6 ± 0.6	1.3 ± 0.56	1.7 ± 0.5	1.5 ± 0.68
	1	3.6 ± 0.46	1.3 ± 0.51	1.8 ± 0.39	2.3 ± 0.12
	2	4.5 ± 0.59	1.2 ± 0.51	2.3 ± 0.99	3.7 ± 0.18
	5	4.2 ± 0.55	1.2 ± 0.51	2.4 ± 0.79	5.2 ± 0.37
Work (J)	0.616	21.88 ± 39.93	4.94 ± 2.10	5.30 ± 1.65	4.62 ± 0.62
	1	28.91 ± 51.86	4.51 ± 0.63	5.75 ± 2.26	5.43 ± 0.80
	2	61.72 ± 101.57	4.64 ± 1.07	7.01 ± 3.96	7.99 ± 1.78
	5	106.51 ± 135.02	4.63 ± 0.93	7.02 ± 3.16	11.16 ± 3.00

Table 4.1-1. Kinematic features and physical work of weight lifting movement with different masses in virtual reality.

**Haptic Condition Analysis:**

Figure 4.7 illustrates the mean and standard deviation of the physical work performed by 20 subjects when lifting real bottles with a real mass in an upward movement. The mean ± SD of physical work for this haptic condition, in relation to different weights, reveals a robust correlation between mass and physical work values (refer to Table 4.1-1, Work section, Haptic column).

Since participants in this condition were handling actual bottles, the computed physical work was significantly higher than that in other conditions.

**One-Way ANOVA and Post Hoc Analysis for Haptic Condition**

A one-way ANOVA was conducted to examine the effect of different weights (independent variable with four levels) on work values (dependent variable) in this haptic condition. The results were significant,  $F(3, 390) = 18.041$ ,  $p < 0.0001$ .

Subsequent Tukey post hoc analysis revealed significant differences for all paired comparisons ( $p < 0.05$ ), except between the weights of 0.616 kg and 1 kg ( $p > 0.05$ ), and between 1 kg and 2 kg ( $p > 0.05$ ).

### Benjamini–Hochberg Results for Haptic Condition

The Benjamini–Hochberg (B-H) procedure was used to control for false discovery rate. The B-H results confirmed the findings from the post hoc analysis, further substantiating the observed effects in the haptic condition.

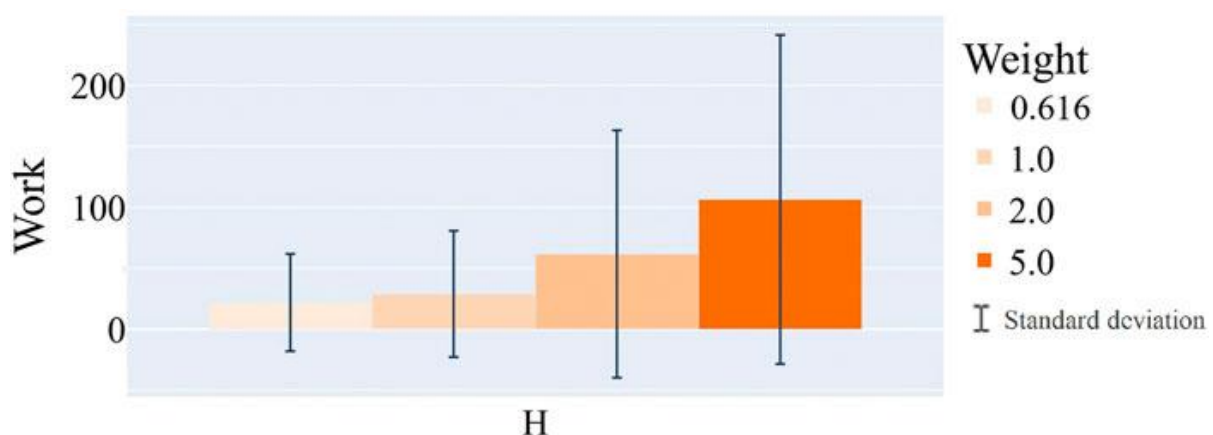


Figure 4.7 Mean  $\pm$  SE of work for 20 users for the reference (Haptic) condition.

### Speed-Control Condition Analysis:

In this condition, the subjects saw a visual conflict when their maximum velocity reached the threshold. For instance, when subjects were tasked to lift lighter virtual objects (0.616 or 1 kg) using the controller, they could effortlessly match their velocity to reach the predefined threshold. However, the lifting of heavier objects (2 or 5 kg) created a disparity where the velocity of the virtual bottles did not align with the actual hand movement. This is depicted in 4.1-9 S, which demonstrates the mean and standard deviation of the physical work performed by the twenty subjects under the speed-control condition.

### A one-way ANOVA and Post Hoc Analysis for Speed-Control Condition

A one-way ANOVA was conducted to compare the effects of different virtual weights on work. This analysis affirmed that virtual weights significantly affect physical activity, as demonstrated by the results [ $F(3, 396) = 9.204$ ,  $p < 0.0001$ ].

The Tukey post hoc analysis revealed several significant differences in work values between various weight pairs: 0.616 and 2 kg ( $p < 0.0001$ , 95% CI =  $-2.76, -0.65$ ), 0.616 and 5 kg [ $p < 0.0001$ , 95% CI =  $-2.75, -0.66$ ], 1 and 2 kg ( $p = 0.012$ , 95% CI =  $-2.31, -0.19$ ), and 1 and 5 kg ( $p = 0.011$ , 95% CI =  $-2.32, 0.21$ ).

### Benjamini–Hochberg Results for Speed control Condition

The Benjamini-Hochberg (B-H) procedure showed no significant differences in work values between the weights of 0.616 and 1 kg, and 2 and 5 kg ( $p$ -value  $> 0.05$ ). This condition thus offers insightful observations about the impact of virtual weight on the effort exerted by the subjects.

### Direct-Weight Condition Analysis

In the direct-weight condition, an interesting correlation was observed, as demonstrated in Table 4.1-1 (column: physical work). As the weight of the virtual object increased, there was a corresponding increase in the subjects' physical work, as visualized in Figure 4.9 D.

### A one-way ANOVA and Post Hoc Analysis for Direct-Weight Condition

A one-way ANOVA was conducted to examine the effects of varying virtual weights on physical work. The results indicated a significant impact of virtual weight on physical work [ $F(3, 421) = 282.456, p < 0.0001$ ].

The Tukey post hoc analysis further confirmed these findings, showing that different virtual weights had a significant impact on physical work ( $p < 0.05$ ).

### Benjamini–Hochberg Results for Speed control Condition

These results were corroborated by the Benjamini-Hochberg (B-H) test, which aligned with the findings of the Tukey post hoc analysis.

These findings indicate a strong relationship between the weight of the virtual object and the physical work exerted by the subjects, demonstrating the potency of the direct-weight condition in affecting perceived effort.

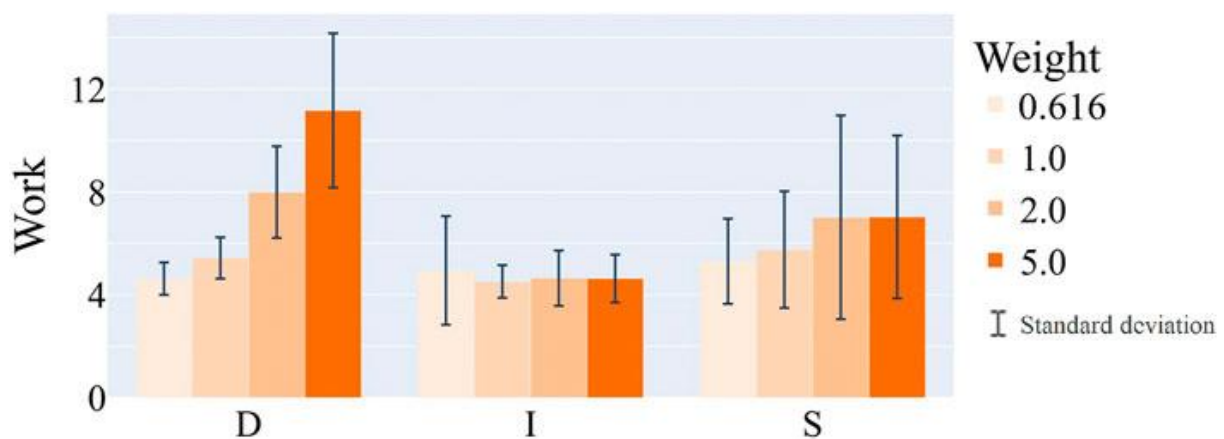


Figure 4.8. Mean  $\pm$  SE of work for 20 users for the VR (non-haptic) conditions. From left to right: D = direct weight condition, I=Isomorphic condition, S = speed control condition.

	Conditions	Masses (Kg)	Physical Work one way -ANOVA(p-value)	Significance
Congruous Conditions	Haptic	0.616	5.537e-11cf0.05***	<0.001
		1		
		2		
		5		
	Isomorphic	0.616	0.1252 > 0.05	0.125
		1		
		2		
		5		
Incongruous Condition	Speed-control	0.616	6.724e-06 < 0.05***	<0.001
		1		
		2		
		5		
	Direct-Weight	0.616	2.023e-100 < 0.05***	<0.001
		1		
		2		
		5		

Table 4.1-2. One-way ANOVA results for the physical work related to different weight in each specific condition. Asterisks show the significances.

**Comparative Analysis of Conditions**

Table 4.1-2 demonstrates the results of a one-tailed paired sample t-test between pair conditions with the similar masses. Despite the small masses, these results suggest that the amount of physical effort users expend when lifting a virtual object is significantly different from real weightlifting. This analysis confirms that there is no significant difference between direct weights and isomorphic for the small mass (0.616 kg) ( $p$ -value > 0.05). In a similar manner, there are no differences between speed control and isomorphic conditions ( $p$ -value > 0.05). Statistical differences were evident for all masses ( $p$ -value < 0.05) except for 1 kg ( $p$ -value > 0.05).

**Analysis of Individual Behavior**

Figure 21 provides a depiction of the individual behaviors of the 20 participants under haptic and non-haptic conditions. A notable observation is the differing trends based on the mass of the object being manipulated.

In the control condition (isomorphic), users exhibited a constant trend with regard to their physical work as the mass of the object increased (refer to Table 4.1-2, Isomorphic column). This suggests that under isomorphic conditions, the participants' physical work remained relatively stable irrespective of the weight of the object.

However, in the other conditions, the amount of physical work exerted by the users showed an increasing trend with the increase in object mass. This implies that the user's perceived exertion and actual physical work done were closely related to the virtual weight of the object



in these conditions. This observation underscores the influence of virtual weight perception on physical work in non-isomorphic environments.

### **Individual Behavior Across Different Conditions**

Figure 4.10 A provides a detailed representation of individual behaviors under non-haptic conditions. A noteworthy observation is the similar trend followed by users in the direct-weight condition (D) as in the haptic condition when the mass of the virtual bottle was increased (refer to Figure 4.10 B). The physical work exerted by the users, which was increased in approximately 95% of users in the direct-weight condition, was similar to the increase observed in 75% of users in the haptic condition. This indicates a strong association between the perceived weight of the virtual object and the physical work exerted by the users in these conditions.

In contrast, the influence of increasing object mass on the physical work exerted by users was less pronounced in the speed-control condition (refer to Figure 4.10 A, S). Although there was a slight increase in the work value for each user with the increase in mass from 2 to 5 kg, this difference was not substantial (T-test,  $p$ -value = 0.05) with only 30% of users exhibiting increased physical work.

The isomorphic condition (refer to Figure 4.10 A, I), on the other hand, did not show any significant change in work values across different masses (refer to Table 4.1-2). This suggests that under isomorphic conditions, the physical work exerted by the users remained relatively constant without paying attention to the virtual weight of the object. In fact, only about 5% of users were able to discern the weight of the object in this condition. This underscores the importance of haptic feedback in the accurate perception of object weight in virtual environments.

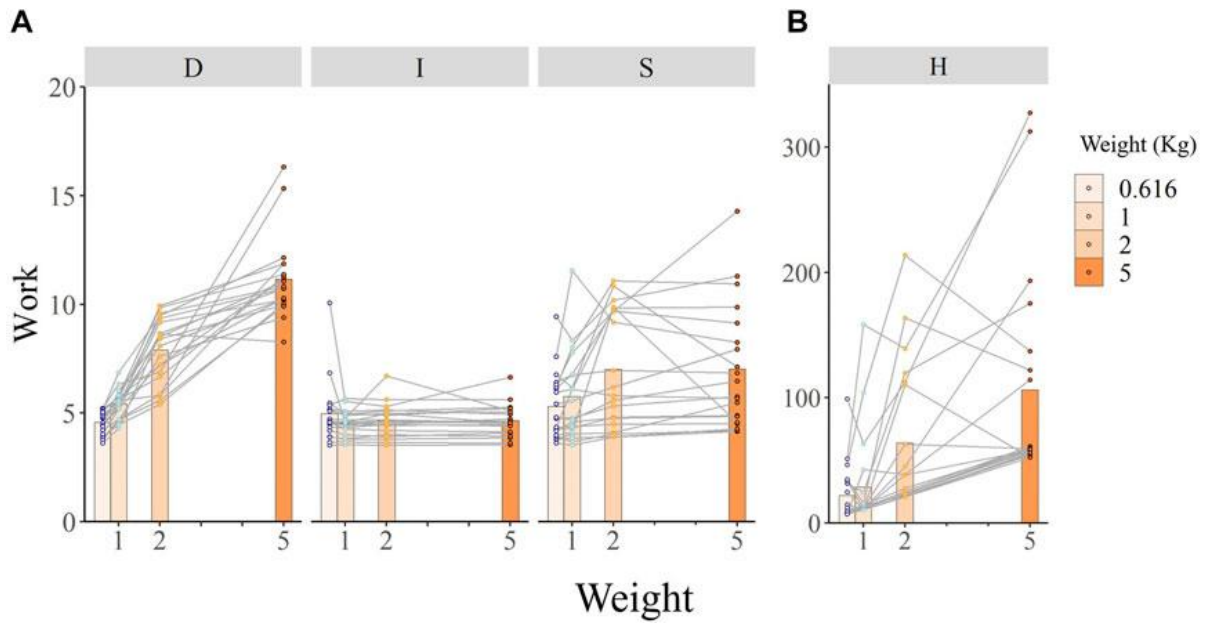


Figure 4.9. Differences between different users' behaviors in haptic and non-haptic conditions. (A) Individual values (dots) and mean values (bar plot) of work in different conditions in VR for different masses. (B) Individual and mean values of "physical work" (bar plot) of work in different conditions in VR for different masses. Gary lines present users' behavior trends for different masses.

Conditions/mass (kg)	H-I (p-value)	H-D (p-value)	H-S (p-value)	D-S (p-value)	D-I (p-value)	S-I (p-value)
0.616	5.06 e-05 ***	3.67e-05***	7.02e-05***	0.0001***	0.1583	0.191
1	9.21 e-06***	1.84e-05***	2.37e-05***	0.177	1.45e-16***	6.64e-07***
2	2.70 e-07***	1.08e-06***	7.31e-07***	0.025**	5.61e-37***	6.94e-08***
5	3.52 e-11***	3.50e-10***	8.24e-11***	3.43e-18***	2.61e-43***	5.00e-11***

Table 4.1-3. Result of t-test analysis for physical work between different conditions and same masses (D: direct-weight, H: haptic, S: speed-control, I: isomorphic).

## Qualitative Analysis:

### Borg CR10:

The Borg CR10 questionnaire, a widely used tool for assessing perceived exertion, was utilized post-experiment to determine the level of fatigue experienced by the subjects. The mean and standard deviation of the fatigue levels reported by the 20 participants across different conditions were computed and visualized in Figure 4.11.

In the isomorphic condition, users reported no noticeable hand fatigue, an observation which stood in stark contrast to the other conditions. The mean fatigue levels for the direct-weight and haptic conditions were identical, reported at  $3.65 \pm 2.4$  and  $3.65 \pm 2.66$  respectively. This highlights that despite the apparent sameness of perceived fatigue levels in the direct-weight and haptic conditions, fatigue did increase when compared with the isomorphic condition.

The one-way ANOVA test was conducted to determine whether the sense of tiredness among subjects was significantly affected by the conditions under which they were tested. The results

confirmed this hypothesis, with the conditions having a significant effect on perceived tiredness [ $F(3, 77) = 6.600, p < 0.0005$ ].

Subsequent post hoc analysis revealed no significant differences between the fatigue levels in the haptic and direct-weight conditions, or between the haptic and speed-control conditions ( $p > 0.05$ ). The B-H results corroborated these findings, further strengthening the conclusions drawn from the post hoc analysis.

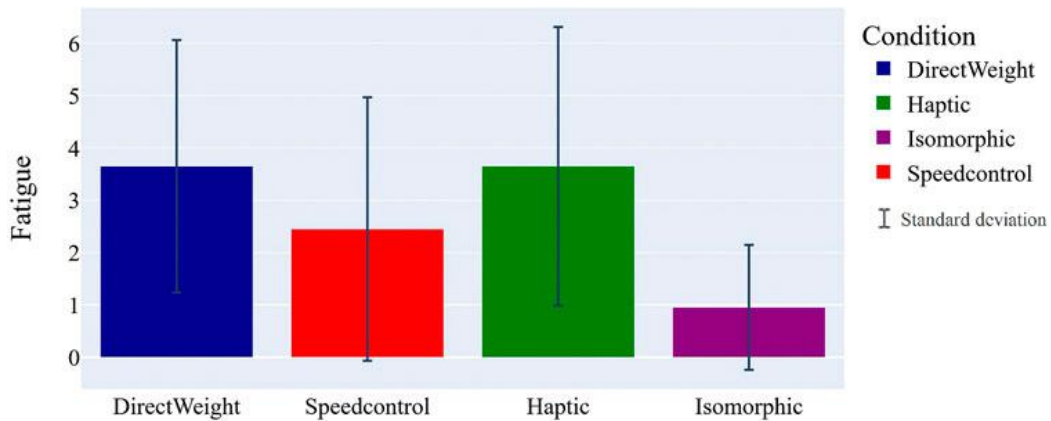


Figure 4.10. Results of the modified Borg CR10 questionnaire: mean and standard error of fatigue for 20 users after performing each condition.

### Presence Questionnaire Analysis:

The sense of presence within our Virtual Environment (VE) was subjectively measured using the Presence Questionnaire. Following each condition, participants were asked to complete this questionnaire, articulating their feelings and perceptions.

Figure 4.12 displays the mean values across six categories: quality of the interface, possibility to examine, self-evaluation of performance, haptics, realism, and possibility to act. From this figure, it is observable that participants' experiences were relatively similar across all conditions. An ANOVA group analysis for each feature of this questionnaire was conducted across all participants and conditions, the results of which are presented in Table 4.1-1. The findings indicate no significant differences in features of presence across different experimental conditions (see Table 4.1-4,  $p$ -value  $> 0.05$ ). The findings indicate a stable perception of presence within the Virtual Environment (VE), irrespective of the distinct conditions participants were subjected to during testing. This questionnaire is designed to juxtapose the real environment with the virtual one, evaluating facets of presence including Spatial Presence, Engagement, Ecological Validity, and Negative Effects. The uniform sense of presence in the VE, regardless of the specific conditions, implies that while the questionnaire is effective in gauging general presence, it may fall short in measuring the sense of presence in specific scenarios, like bottle lifting in VR.

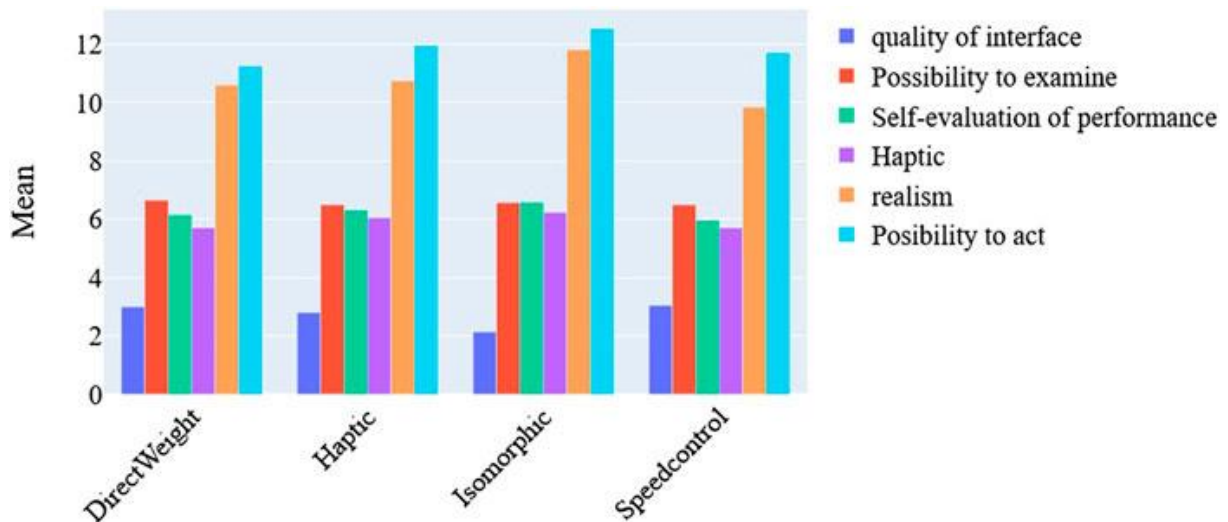


Figure 4.11 Presence questionnaire: Mean of responses of 20 users to measure the different features of presence questionnaire, completed by users after each condition.

Presence questionnaire feature	Conditions	ANOVA ( $p$ -value)
Quality of interface	H, I, S, D	0.444 > 0.05
Possibility to examine	H, I, S, D	0.889 > 0.05
Self-evaluation	H, I, S, D	0.224 > 0.05
Haptic	H, I, S, D	0.320 > 0.05
Realism	H, I, S, D	0.124 > 0.05
Possibility to act	H, I, S, D	0.246 > 0.05

Table 4.1-4. Results of ANOVA test for presence questionnaire features between different conditions (H: Haptic, I: isomorphic, S: speed-control, D: direct-weight).

- **Effectiveness of Metaphors**

The effectiveness of metaphors in enhancing SOP is assessed based on participants' feedback and observable changes in behavior and interactions. This research centered on conducting an experiment that examined the experience of lifting an object within a virtual reality (VR) setting. We evaluated four distinct conditions with respect to the perceived and actual movements made by the participants. The haptic condition was used as a reference. We aimed to assess the perception of effort exerted to lift the object under each condition, employing both objective measurements (physical work) and subjective assessments (the Borg CR10 and presence questionnaires).

#### *Displacement and Perception of Weight*

Our study revealed that, as expected, the actual hand displacement feature (disp; see Table 4.1-1 displacement) in the congruous conditions was approximately 1 m due to our pseudo-haptic feedback approaches. However, in the incongruous conditions

(speed-control and direct-weight), the disp feature value increased as the weight of the virtual object was raised.

The two-way ANOVA results further illuminated this, showing that the displacement feature maintained its consistency when subjects were lifting bottles of varying weights in different conditions. However, the hand displacement remained consistent only up to a weight of 1 kg, beyond which heavier bottles resulted in changes in displacements. This observation suggests the existence of a threshold weight of one kg that participants can lift in both VR and real-world environments without discerning any difference in their hand displacements.

#### *Implications for Pseudo-haptic Feedback Approaches*

The consistency in hand displacement until a weight of 1 kg, followed by an increase in displacement for heavier weights, underscores the impact of our pseudo-haptic feedback approaches. In the incongruous conditions, the increase in the weight of the virtual object led to an increase in the disp feature value, suggesting that these pseudo-haptic feedback approaches can significantly influence the perception of weight in a VR setting.

These observations offer critical insights into the design of VR experiences and highlight the potential of pseudo-haptic feedback approaches in enhancing the user's perception of physical properties such as weight. Future research should aim to further explore and refine these approaches to improve their effectiveness and applicability in diverse VR contexts.

#### *Movement Duration and Perceived Fatigue*

Our study also observed the movement duration across congruous and incongruous conditions with different weights. The results from a two-way ANOVA indicated that the movement duration was not consistent across these conditions. This inconsistency suggests that users were attempting to compensate for the perceived weight of the object by increasing the distance their hand moved, which logically led to an increase in the duration of the movement.

The Borg CR10 fatigue questionnaire revealed that users experienced similar levels of fatigue in their hands when lifting real objects in haptic conditions and when lifting virtual bottles in the direct-weight condition. This subjective sense of fatigue was supported by the results of the presence questionnaire, which showed that users in non-haptic conditions experienced the same sense of presence as they did in haptic conditions. Table 4.1-1 further corroborated these findings, showing no significant differences between users' feelings of presence in different conditions. This suggests that users were effectively immersed in the virtual environment, and we were successful in inducing comparable levels of fatigue in the haptic and direct-weight conditions.

#### *Impact of Pseudo-Haptic Approaches on Physical Work*

Despite the considerable differences in physical work between haptic and isomorphic conditions, our pseudo-haptic approaches had a notable impact on the individual's physical work (see Figure 4.10; Figure 4.11). Our formulation, however, did not take

into account the mass of the subjects' arms, which may account for the significant discrepancy. The formula for work (Eq. 1) suggests that work is directly proportional to the weight of an object. Yet, as Figure 4.10 indicates, for some individuals, the value of work decreases when the weights of the objects increased from 2 to 5 kg in the haptic condition. Conversely, all but one user managed to increase the value of their work in response to an increase in the weight of the virtual objects. These findings imply that users modify their lifting behaviors in VR and that our pseudo-haptic methods significantly influence their movement patterns.

#### *Speed-Control Conditions and Visuomotor Conflict*

In speed-control conditions, users could observe the effects of visuomotor conflict on their hand movements. In comparison to the isomorphic condition, visual feedback significantly impacted the work's value. In the speed-control condition, however, the virtual bottle's velocity changes according to the weight of the bottle. For 0.616 kg, there is no statistically significant difference between the isomorphic and speed-control conditions, but for heavier weights (1, 2, and 5 kg), significant differences emerge. This suggests that the integration of multi-sensory conflict influences the acceleration and displacement of the users' hands, leading to more actions performed on the controller. These findings offer valuable insights into how visuomotor conflicts can be manipulated to enhance the user's experience in a VR setting.

#### *Comparing Direct-Weight and Speed-Control Conditions*

By comparing the outcomes between the speed-control and direct-weight conditions, we found that the direct-weight condition was more effective in inducing subjects to increase their perceived weights to 2 and 5 kg (post hoc-Tukey, p-value 0.05). Interestingly, subjects were also able to perceive the difference between 2 and 5 kg in the speed-control condition (post hoc Tukey, p-value > 0.05).

Our direct-weight and speed control methods have been demonstrated to simulate fatigue comparable to haptic conditions (as per the Borg CR10 questionnaire), indicating the success of these methods in enhancing the user's sense of presence.

#### **4.1.6 Conclusion:**

In summary, in this study we tried to measure and enhance subjects sense of presence in the context of interacting with virtual object like lifting virtual bottle. We used pseudo haptic as a metaphor to induce objects' visual weight to the participants.

Overall, the novelty of this work is including:

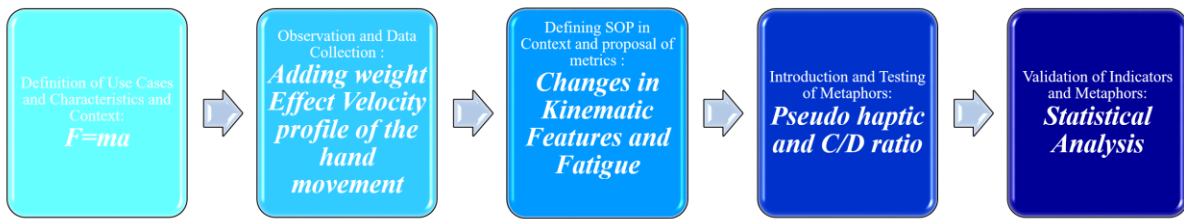
- Designing different manipulation conditions in VR, based on the physical work of expected/targeted objects' weight, to be induced in VR on virtual objects.
- Studying the effect of pseudo-haptic feedback on VR users' lifting behaviors and comparing them to lifting real objects.
- Formalizing the notion of physical work to study different individual behaviors in virtual and real environments by using it as an objective measure of the sense of presence.
- Evaluating relationships regarding the sense of presence between objective (physical work) and subjective measurements (sensation of fatigue).

### *Implications for VR Design*

The findings of this study present several implications for VR designers, particularly those grappling with the challenge of delivering a sense of weight to the user of a VR hand controller. Firstly, our study demonstrates the potential for direct interaction with virtual objects using a VR controller and trackers. Secondly, our experiment was able to induce heavier weights that are more akin to those of objects people interact with in their daily lives, in contrast to previous studies that have primarily focused on objects weighing less than 500 g (Samad, et al., 2019).

Our pseudo-haptic model successfully induced these weights in VR participants without the need for additional haptic devices, as long as the weight of the virtual object was equal to or less than 1 kg. However, for heavier virtual weights (2 and 5 kg), subjects may experience the same fatigue in their hands as they would in the haptic condition. To mitigate discrepancies between visual and kinesthetic cues, the use of supplementary haptic devices is recommended. This approach will help maintain the user's sense of presence in the VR environment.

## 4.2 Use Case2: Lifting virtual bottles; Kinematic Analysis



### 4.2.1 Phase 1: Definition of Use Cases and Characteristics and Context

- *Definition of Use Cases and Contexts*

This work is the extended version of the previous experiment. However, in this work we tried to study the impact of weight and also virtual weight on hand kinematic features.

- *Defining Characteristics and Context*

Previous studies highlighted the impact of weight on kinematic features in the real environment (Bock, 1990) (Atkeson & Hollerbach, 1985) (Gaveau, et al., 2014) (Hoffman & Strick, 1993). In particular, Hoffman et al. (Hoffman & Strick, 1993) showed that the pattern of muscle activity changes by changing the weight of the object.

According to Bock et al (Bock, 1990), an increasing load affected both normalized and non-normalized velocity profiles, but he did not notice the symmetry of the velocity profile shape. Gaveau et al. (Gaveau, et al., 2014), (Papaxanthis, et al., 1998).illustrated that by gaining load, the TPV value (Time to Peak Velocity/movement time) of the hand movement in the upward direction decrease. Here is the equation used to determine time to peak velocity:

$$TPV = \frac{(time_{PV_{movement}} - time_{onset_{movement}})}{(time_{offset_{movement}} - time_{onset_{movement}})}$$

Where  $time_{PV_{movement}}$  is the time at which peak velocity occurs,  $time_{offset_{movement}}$  is the time at the end of the movement and  $time_{onset_{movement}}$  is the starting time of the hand movement.

On the other hand, Atkeson and Hollerbach (Atkeson & Hollerbach, 1985) showed that the velocity of hand movement increased when the weight decreased.



#### 4.2.2 Phase 2: Observation and Data Collection

- *Selection of Participants:*

Twenty right-handed users (6 women and 14 men, ranging from 18 to 44 years with a mean age of  $26.24 \pm 7.98$  SD) participated in our experiment. All were healthy and had no neurological, muscular, or cognitive disorders, with normal or corrected-to-normal vision. Users' heights ranged from 156 to 185 cm, with a mean height of  $173.74 \pm 6.57$  cm. Users from different backgrounds, either from inside or outside the university, agreed to participate voluntarily without compensation

- *Behavioral Observation*

When lifting an object in an upward direction, the weight of the object affects various aspects of hand kinematics and body posture:

**Maximum Velocity:** Lifting a heavier object requires more force, and the muscles cannot produce this force as quickly as for a lighter object. Consequently, the maximum velocity during the lift is usually lower for heavier objects.

**Duration of the Movement:** It generally takes longer to lift a heavier object. The increased time is due to the need to generate more force and the decreased maximum velocity.

**Amplitude:** The amplitude, or the height to which the object is lifted, may be reduced for heavier objects. With greater weight, it is harder to generate sufficient force to lift the object through the same range of motion as a lighter object.

**Time to Peak Velocity:** With heavier weights, the time to reach peak velocity can increase. This is because more time is required for the muscles to generate the additional force needed to accelerate the object.

**Posture:** The posture of the individual lifting the object is also affected by its weight. For heavier objects, people often bend their knees and lower their center of gravity to engage larger muscle groups like the legs and back in addition to the arms. This is a more efficient and safer way to lift heavy objects. Also, the spine might be kept more vertical to minimize shearing forces on the lower back.

**Grip:** The grip might change based on the weight of the object. For lighter objects, a simple grip may suffice, but for heavier objects, the individual might employ a firmer grip involving more of the hand and even the forearm. The type of grip (e.g., overhand, underhand, mixed) might also change based on the object's weight and shape to ensure better control during the lift.

It's important to note that proper technique is crucial, especially when lifting heavy objects, to reduce the risk of injury. The body's kinematics during a lift is

influenced by individual factors such as strength, experience, flexibility, and the biomechanics of the person's body.

- *Data Collection*

The primary data, consisting of temporal details, hand positioning and velocity in a three-dimensional VR space, were gathered from the VR hand controller under VR reference and direct weight conditions, as well as from VR hand trackers in real-life scenarios. Post-collection, the raw data were processed using a Butterworth low-pass filter with a cut-off frequency of 6 Hz, which helped derive a smooth velocity profile for the hand movement.

#### 4.2.3 *Phase 3: Defining SOP in Context and proposal of metrics*

- Development of Context-Sensitive Indicators

An array of features were computed from the raw data, including Movement Duration (MD), Maximum Velocity (MaxV), and Time to Peak Velocity (TPV).

***Movement Duration (MD):*** It was determined as the temporal interval of the hand movement when the velocity attains 5% of its peak velocity.

***Time to Peak Velocity (TPV):*** It was calculated as the ratio of acceleration duration to the total duration of hand movement. TPV has been validated in previous studies as an effective measure of movement timing and an estimation of planned timing movement, with significant dependence on direction (Berret, et al., 2008).

Moreover, we also considered the unimodal, bell-shaped velocity profile as an additional kinematic feature (Abend, et al., 1982) (Morasso, 1981)

***Movement Direction Considerations:*** We acknowledged that the velocity profiles for hand movements vary depending on the direction of movement—upward, downward, or horizontal—as per findings from (Gentili, et al., 2007) (Berret, et al., 2008). Given the focus on upward movement in this study, we primarily used the velocity profile of the subject's hand movement in the upward direction, which assumes an asymmetric bell shape when the subject's hands are free of additional weight (with the acceleration phase being shorter than the deceleration phase).

Beside all these objective measurements we used Borg CR10 as a subjective measurement.

***Borg CR10 Scale:*** As previously discussed, the Borg CR10 Scale is a subjective rating scale for measuring perceived exertion. This tells you how hard the participants feel they are working during the activity.

#### 4.2.4 Phase 4: Introduction and Testing of Metaphors

- Identification of Metaphors

As in the previous study, this study uses the same metaphor, protocol, and environment. Additionally, we kept the same subject as in the previous work and asked them to lift the bottle in VR environment. Unlike the previous work, we removed the bottle with 5 kilograms' weight from all conditions (Real and virtual) and one condition as well. Our metaphor was pseudo haptic.

- Testing of Metaphors

In order to better understand this work, we will explain the conditions and the way that we used metaphor in the following paragraphs.

**Conditions:**

**Condition R:** Real condition. We developed this condition as our reference condition of real lifting, i.e., without perceiving any conflict between somatosensory feedback and visual information, but perceiving weight effect related to the mass of the real bottle lifted. An exact correspondence between real bottle and virtual bottle was provided through a precise tracking of the real one. Indeed, to avoid any difference due to a possible effect of our VR environment between conditions, the lifting of real object was also done in VR. In this condition we used 2 HTC Vive hand trackers, one fastened on the surface of the real bottle and the other fastened on the wrist of the dominated hand of the subjects. The hand trackers were activated as soon as subjects grabbed the bottle, recording the kinematic data of their hand movements.

**Condition V:** VR reference condition. This condition did not consider any pseudo-real feedback. This condition was developed so that subjects would perform a lifting task with HTC Vive hand controller without perceiving any conflict between their somatosensory feedback and visual information, but also without perceiving any weight effect, except the VR controller mass ( $m=0.31$  kg).

**Condition P:** Pseudo-haptic condition. Finally, we introduced here a technique that manipulated the control/display (C/D) ratio of subject's hand movement to modulate the virtual object's heaviness perceived by visual input. We applied a C/D ratio value that had an inverse relation to the weight of the virtual object. Our formula applied a displacement ratio between the real and the perceived (visually, in VR) displacement of the bottle ranging from 0.5 to 1, depending on the "virtual weight" that we wanted to induce. This means that when the ratio was close to 1, it was easier to move virtual objects, with less difference between real and perceived displacements and motions, and oppositely it was harder when close to 0.5. This value was chosen to make users feeling conflicts between somatosensory and visual input, but not enough to break presence felt in the environment, and their lifting objective.

Considered object masses: we proposed to use three different masses: 0.61, 1, and 2 kg, for all lifting technique conditions.

#### 4.2.5 *Phase 5: Validation of Indicators and Metaphors*

- Statistical Analysis

Statistical analysis is conducted to validate the developed indicators, ensuring that they accurately represent SOP in different contexts.

##### Two-Way ANOVA Analysis

The two-way analysis of variance (ANOVA) was conducted to examine the interaction effects between the independent variables "condition" and "weight". The "condition" variable comprised three levels; Condition R, Condition V, and Condition P. Similarly, the "weight" variable also had three levels; 0.61, 1, 2kg. The level of significance was set at  $\alpha = 0.05$ .

##### Posthoc Analysis:

Post-hoc analysis in statistics refers to additional tests that are conducted after an initial analysis (like an ANOVA) in order to make multiple comparisons between groups. Post-hoc tests are usually done when an initial test indicates that there are significant differences among groups, but doesn't tell you which groups are different from each other. In this work we employed Tukey's Honestly Significant Difference (HSD). This is one of the most common post-hoc tests. It is used to compare all possible pairs of means. Tukey's test is particularly useful when the sample sizes are equal for each group.

##### **Movement Duration (MD) Comparison across Conditions**

Fig. 4.2-1 and Table 4.2-1 provide a detailed overview of the movement duration (MD) for the weight-lifting tasks under the real (R), VR reference (V), and pseudo-haptic (P) conditions. These tasks were executed under three different weight loads: 0.66, 1, and 2 Kg.

##### **Weight Impact on MD**

A two-way ANOVA analysis on the collected data revealed no significant interaction effect of weight and lifting conditions on MD ( $F(4, 162) = 2.04, p > 0.05$ ). However, the main effect of weight on MD was found to be statistically significant ( $F(2, 162) = 3.36, p < 0.05$ ). This is evident in the real and pseudo-haptic conditions where the MD increased as the weight of the object increased. The post-hoc Tukey tests further underscored these findings by revealing significant differences in the MD for 0.6 and 2 kg ( $p < 0.05$ ), as shown in Figure 4.12.

##### **Condition Impact on MD**

The MD in the VR reference condition was notably consistent across different weights, unlike the real and pseudo-haptic conditions. The two-way ANOVA analysis affirms that the main effect of the condition on MD was significant ( $F(2, 162) = 14.71, p < 0.05$ ). Specifically, the MD for lifting 2 kg under the pseudo-haptic condition was significantly longer than the corresponding MD under the real and VR reference conditions.

The Tukey post hoc analysis revealed significant differences between the direct weight and VR reference conditions ( $p = 0.002$ ) and between the VR reference and real conditions ( $p = 0.0001$ ). However, no significant difference was found between the pseudo-haptic and real conditions ( $p = 0.16$ ).

In conclusion, the weight factor significantly influences MD, with heavier loads leading to longer durations. The condition of the lifting also significantly impacts MD, with the pseudo-haptic condition resulting in a longer MD for a 2 kg weight lift compared to the real and VR reference conditions. The consistency of MD in the VR reference condition across different weights is an intriguing finding, suggesting that VR experience might be modulated to mimic real-world kinematics more closely.

	VR reference			Real			Pseudo-haptic		
	0.6 kg	1 kg	2 kg	0.6 kg	1 kg	2 kg	0.6 kg	1 kg	2 kg
<b>MD (s)</b>	1.32± 0.46	1.20± 0.44	1.19± 0.46	1.86± 0.10	1.95± 0.11	2.24± 0.14	1.46± 0.55	2.17± 0.11	4.49± 0.21
<b>Max V (m/s)</b>	1.57± 0.46	1.70± 0.46	1.70± 0.47	1.14± 0.52	1.02± 0.23	0.82± 0.10	1.38± 0.32	1.24± 0.42	1.07 ±0.42
<b>TPV</b>	0.43± 0.04	0.43± 0.03	0.43± 0.03	0.46± 0.06	0.49± 0.10	0.50± 0.11	0.44± 0.04	0.46± 0.09	0.48± 0.11

Table 4.2-1 The mean and standard error for the kinematic features of 20 subjects at different conditions and weights

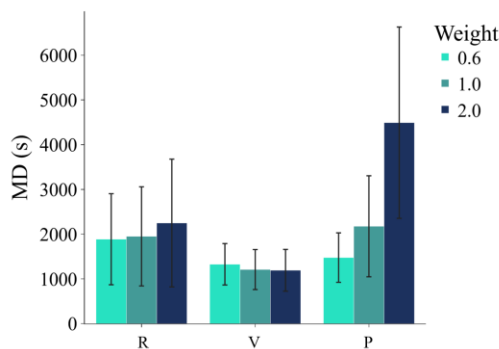


Figure 4.12. MD mean±SE value (N=20) for each condition. R: real, V: VR reference, P: pseudo-haptic

### Maximum Velocity (MaxV) Analysis across Conditions

For a more nuanced understanding of the impact of different conditions on the weight-lifting movements, the maximum velocity (MaxV) was analyzed in detail across the real, VR reference, and pseudo-haptic conditions.

Figure 4.13 and Table 4.2-1 present the mean value and standard deviation of MaxV for the three weight categories lifted under the three conditions by all subjects.

#### Weight Impact on MaxV

In the real condition, MaxV decreased as the weight of the lifted object increased. In contrast, the MaxV remained consistent in the VR reference condition across all trials. Interestingly, under the pseudo-haptic condition, the MaxV of simulated movements tended to decrease as the lifted object became heavier, in line with the findings from the real condition. This pattern indicates that the control/display (C/D) ratio model, as implemented by the directed-weight model, successfully mirrored the scaling of MaxV for lifting movements in the real-world scenario.

#### Condition Impact on MaxV

Despite these observations, the two-way ANOVA analysis showed that neither the interaction effect of condition and weight on MaxV ( $F(4, 162) = 0.148, p > 0.05$ ) nor the main effect of weight on MaxV ( $F(2, 162) = 0.86, p > 0.05$ ) were statistically significant. There was also no statistically significant difference in MaxV across the different conditions ( $F(2, 162) = 0.17, p > 0.05$ ).

However, the post hoc analysis did not show any difference between real and pseudo-haptic conditions in MaxV ( $p = 0.97$ ). This suggests that while the changes in MaxV were perceptible in the pseudo-haptic and real conditions with respect to weight variations, these changes were not statistically significant. This intriguing outcome could have implications for how lifting movements are simulated in virtual environments.

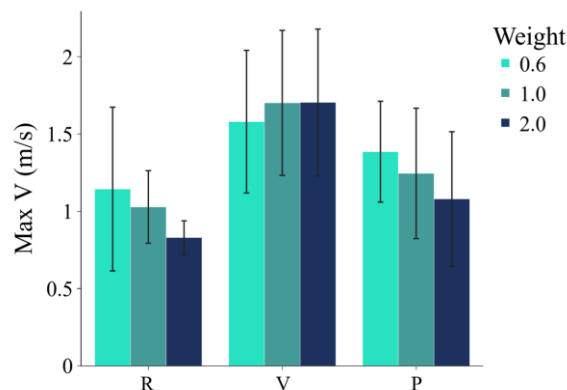


Figure 4.13 MaxV mean  $\pm$  SE value ( $N=20$ ) for each condition. R: real, V: VR reference, P: pseudo-haptic

### **Analysis of Bell-shaped Velocity Profile**

We further assessed the movement timing of weight-lifting movements through the time to peak velocity to total movement duration ratio (TPV). This assessment helped provide a deeper understanding of the shape of the velocity profiles under different conditions and weights.

Figures 4.14, 4.15, and 4.16 present the typical shapes of velocity profiles (normalized by duration and MaxV) for the real, VR reference, and pseudo-haptic conditions, respectively. These profiles were produced by a typical subject under the experimental conditions while lifting weights of 0.6, 1, and 2 kg.

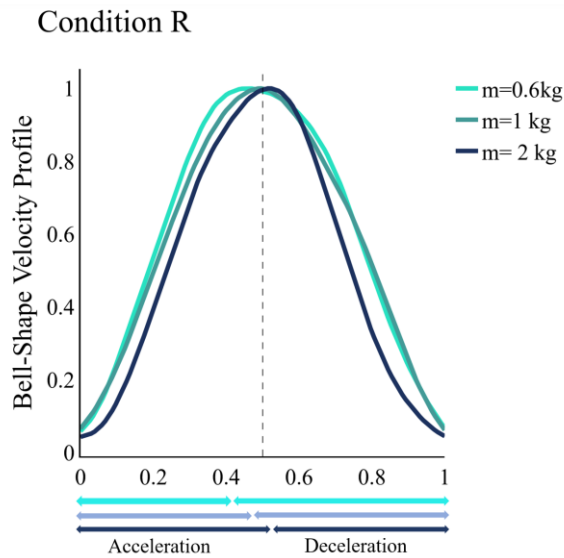
### **Asymmetry in Velocity Profile**

Under the real condition (as shown in Figure. 4.14), the movement of lifting light weights (for instance, 0.6 kg) is characterized by an asymmetric velocity profile. In such instances, the acceleration phase of the movement is shorter than the deceleration phase.

### **Real Condition and Velocity Profile**

Interestingly, as the weight of the object increases, the asymmetry in the velocity profile diminishes and starts to resemble a more symmetric profile. The ratio of the acceleration duration to the total movement duration was found to increase from 0.42 (with the 0.6 kg weight) to 0.5 (with heavier weights). This shift indicates that when subjects lift heavier loads, the acceleration duration, in relative terms, increases.

These findings suggest a dynamic adaptation in the movement strategy of the subjects as the weight of the object changes, reflected in the evolution of the velocity profile from an asymmetric to a more symmetric shape. This nuanced understanding of the movement dynamics can guide the development of more realistic simulations of weight-lifting movements in VR.



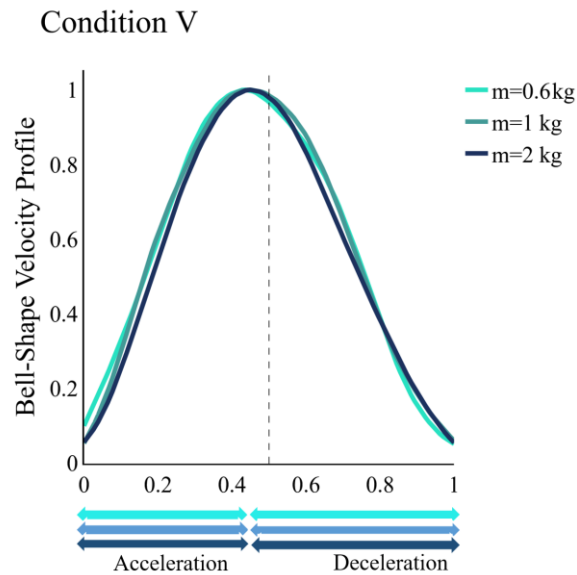
*Figure 4.14 The velocity profile produced by one subject's hand movement in real condition. According to the bottle weight, colored arrows represent velocity acceleration and deceleration*

### **VR Reference Condition and Velocity Profile**

When examining the VR reference condition, as illustrated in figure 4.15, the velocity profile of the non-loaded arm for the upward movement exhibited an asymmetric pattern. This observation was consistent across all weight categories, suggesting that the weight of the object does not have a substantial impact on the velocity profile in the VR reference condition.

The velocity profile under this condition maintained an asymmetric bell shape throughout, with the acceleration phase being shorter than the deceleration phase. This finding underscores the contrast between the VR reference and real conditions and indicates a potential area of development for VR simulations to closely mimic the real-world kinematic changes that occur with different weights.





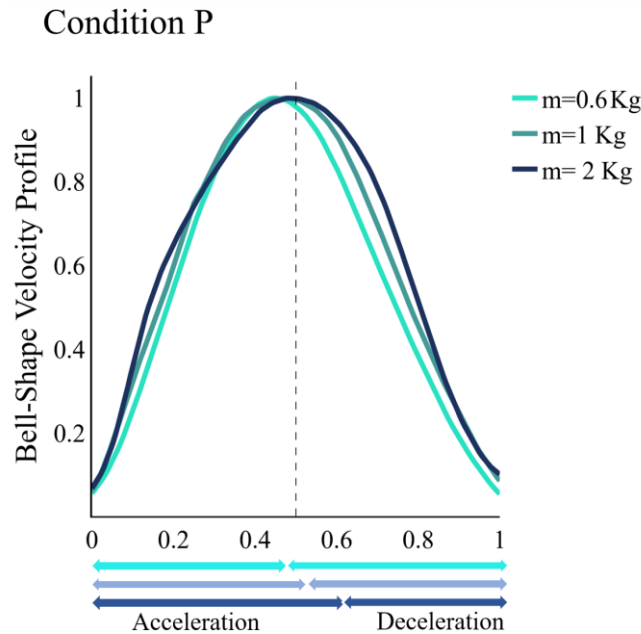
*Figure 4.15. Velocity profile produced by subject's hand movement in VR reference condition. Colored arrows represent acceleration and deceleration in the velocity profile made by the subject's hand according to the different perceived virtual bottle weights in VR reference condition.*

### **Pseudo-haptic Condition and Velocity Profile**

In the pseudo-haptic condition, as depicted in figure 4.16, the velocity profiles exhibit an interesting trend. As the delay of the virtual movement relative to the actual arm movement increases (i.e., as the virtual weight of the object increases), the subjects tend to extend the acceleration phase of the movement.

This suggests that, under the pseudo-haptic condition, the subjects intuitively adapt their movements to compensate for the perceived increase in the weight of the virtual object. They elongate the acceleration part of the velocity profile, which is a dynamic adaptation similar to what was observed under the real condition with increasing weights.

In conclusion, these observations confirm that while the VR reference condition maintained a consistent velocity profile irrespective of the weight, both the real and pseudo-haptic conditions demonstrated adaptive changes in velocity profile symmetry and acceleration duration with increasing weights. This highlights the potential of pseudo-haptic feedback to induce realistic kinematic adaptations in VR environments.



*Figure 4.16 Velocity profile produced by subject's hand movement in pseudo-haptic condition. Coloured arrows represent acceleration and deceleration in the velocity profile made by the subject's hand according to the different perceived virtual bottle weights in pseudo-haptic condition.*

#### TPV:

Following the previous observation in a typical velocity profile, we statistically analysed the TPV values with respect to different weights and conditions which are represented in figure 4.17. According to this, TPV increases with increasing weight under real and pseudo-haptic conditions. Based on mean TPV values in real condition, the acceleration duration ranged from 45% of movement duration during lifting the weight of 0.6 kg to 49% of MD during the 2 kg-weight lifting. In contrast, TPV does not change when weight increases in VR reference. The mean and SD of TPV shows in table 4.2-1. In VR reference, the TPV value for 0.6 kg, 1 kg, and 2 kg is 0.43, while in real condition, the values are 0.46, 0.49, 0.50. Accordingly, the pseudo-haptic condition TPV keeps an increasing trend, and for 0.6, 1, and 2 kg, the TPV is 0.44, 0.46, and 0.48, respectively.

The result of the two-way ANOVA shows that the interaction effect of weight and condition on TPV was not significant ( $F(2,162) = 2.17, p < 0.05$ ). Moreover, the ANOVA analysis revealed that TPV was not weight-dependent ( $F(2,162) = 2.54, p > 0.05$ ). Despite this, there was a significant main effect of the condition on TPV ( $F(2,162) = 6.00, p < 0.05$ ). Tukey post hoc results confirm there is a significant difference between pseudo-haptic and VR reference ( $p < 0.05$ ) and real and VR reference ( $p < 0.05$ ). However, Tukey post hoc analysis did not show any statistical differences between real and pseudo-haptic ( $p > 0.05$ ). These results confirmed that our proposed model, based on pseudo-real model, can simulate a lifting behaviour (pseudo-haptic) that is similar to the real one (real condition), in terms of kinematic features.

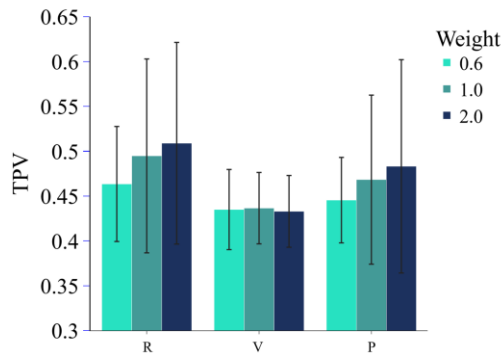


Figure 4.17 TPV mean  $\pm$  SE value (N=20) for each condition. R: real, V: VR reference, P: pseudo-haptic

### Borg CR10:

The Borg CR10 questionnaire provided insights into participant fatigue under varying conditions, as presented in figure 4.18. The mean and standard deviation (SD) of fatigue scores for the 20 participants revealed that individuals experienced greater fatigue in real and pseudo-haptic conditions compared to the Virtual Reality (VR) reference condition. The reported fatigue scores were  $3.65 \pm 2.66$  for the real condition,  $3.65 \pm 2.41$  for the pseudo-haptic condition, and  $0.95 \pm 1.19$  for the VR reference condition.

A one-way ANOVA analysis demonstrated significant differences in fatigue scores across the conditions ( $F(2, 58) = 10.624, p < 0.0001$ ). Further exploration via Tukey's post hoc analysis revealed significant differences in fatigue between the real and VR reference conditions ( $p < 0.05$ ), and between the pseudo-haptic and VR reference conditions ( $p < 0.05$ ).

However, no significant difference in fatigue levels was found between the real and pseudo-haptic conditions ( $p > 0.05$ ). This suggests that the fatigue experiences in the real and pseudo-haptic conditions were comparable, despite the different nature of these environments.

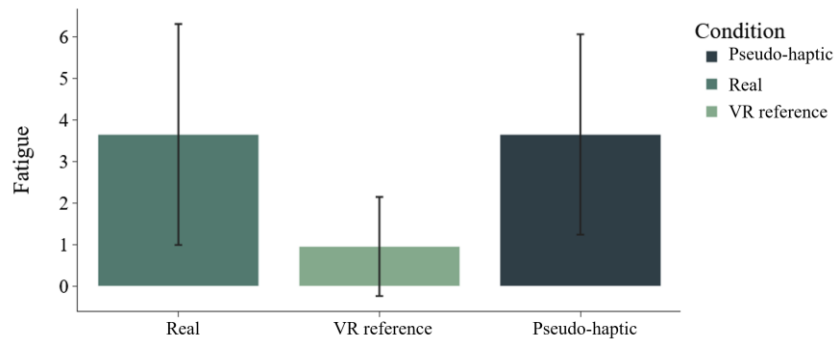


Figure 4.18. Results of the Borg CR10 Questionnaire for our conditions, considering all bottle weights

- Effectiveness of Metaphors

This research was dedicated to exploring the influence of a unique illusory technique, termed pseudo-real feedback, on the perception of a virtual object's weight in Virtual Reality (VR). The aim was to understand the kinematic patterns of a single-joint upward lifting movement (rotating around the shoulder) performed by subjects' arms in distinct experimental conditions: lifting a virtual bottle using a hand controller without any real, lifting actual bottles with genuine weights, and lifting virtual bottles with a modified visual feedback via the Control/Display (C/D) ratio method to induce a vision-somatosensory conflict.

Kinematic attributes provide a quantitative means to examine lifting behaviour in different environments. Past research has indicated that kinematic features, including the velocity profile of hand movement, vary according to movement direction and are sensitive to this factor (Papaxanthis, et al., 1998). For instance, in a downward movement (favoring gravity), the velocity profile is generally symmetric, whereas it skews towards the beginning of the movement during upward motion against gravity. This asymmetry illustrates that the Central Nervous System (CNS) incorporates gravity into motion planning. Additionally, (Gaveau, et al., 2014) highlighted that the effects of gravity could be amplified by adding weights to the subjects' arms, causing the velocity profile to skew towards symmetry during upward movement.

To facilitate the comparison of results between VR and the real world, a VR reference condition was designed. In this condition, the shape of the velocity profile mirrored that of non-loaded arm motion in the real world. Importantly, the velocity profile of hand movement under the VR reference condition was similar to that of non-loaded hand movement in the upward direction, which was in line with previous findings (Berret, et al., 2008) (Sciutti, et al., 2012). The light weight of the hand controller ( $m=0.31$  kg) could explain the negligible impact on the hand's velocity profile in the VR reference condition.

To understand the effect of gravity on 3-dimensional arm movement in a VR environment, subjects were instructed to lift bottles of varying real weights while fully immersed in VR. Our results confirmed that with increased weight, TPV increased, and the velocity profile was no longer asymmetric, closely mirroring

findings in real-world settings (Gaveau, et al., 2014). Moreover, maximum velocity (Max V) and movement duration (MD) were also influenced by the effects of the loads, with heavier objects moving slower and taking longer to lift.

In the pseudo-haptic condition, the impact of virtual weight, created by the pseudo-real model using C/D ratio manipulation, on kinematic features and velocity profile was assessed. Despite no significant difference in TPV value between the real and pseudo-haptic conditions, a significant difference was found between the real and VR reference conditions and the pseudo-haptic and VR reference conditions. This suggests that the real model managed to deceive subjects' brains and reproduce a similar effect to the real condition.

Lastly, the Borg questionnaire results were consistent with the kinematic features. In both real and pseudo-haptic conditions, participants experienced similar levels of fatigue, indicating that the pseudo-haptic condition affected both kinematic features and participants' sensation of fatigue by altering the CNS and changing motion planning.

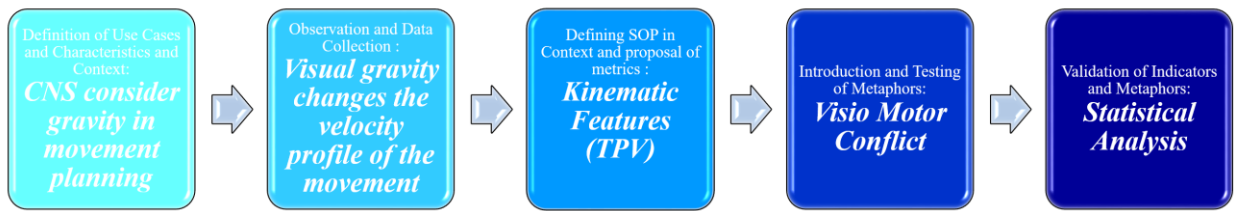
In our study, we observed that the Time to Peak Velocity (TPV) of hand movement under a load tended to increase proportionally with the weight of the load. This phenomenon can be attributed to the body's need to exert more force to overcome the inertia of the load and accelerate it to a specific velocity, thus prolonging the duration required to achieve peak velocity.

This understanding finds its roots in Newton's second law of motion, which posits that the force required to accelerate an object equals the product of the object's mass and its acceleration ( $F=ma$ ). When moving the hand without a load, less force is required for acceleration. However, as weight is added, a greater force is needed to achieve identical acceleration. If the muscles are unable to generate this additional force instantly, it will take longer to reach peak velocity.

Nonetheless, several other factors also come into play, such as muscular strength and endurance, coordination, and the nature of the movement being executed. For example, individuals with stronger muscles may be able to generate the extra force necessary to move a heavier load more swiftly, thus diminishing the increase in TPV.

Furthermore, the relationship between load and TPV is not necessarily linear. For lighter loads, the increase in TPV may be relatively insignificant. However, as the load becomes heavier, the increase in TPV might become more conspicuous. This specific relationship can fluctuate based on individual strength, technique, and other factors. Understanding this relationship and the factors that influence it can provide crucial insights into designing more effective and realistic VR simulations. This research contributes to our understanding of these dynamics and sets the groundwork for future studies to explore them further.

### 4.3 Use Case3: Effect of Gravity on Hand Movement:



#### 4.3.1 Phase 1: Definition of Use Cases and Characteristics and Context

- Definition of Use Cases and Contexts

To perform a movement the central nervous system (CNS) pays regard to the different (inertia,...) and extrinsic (gravity, Coriolis,...) strength on our body and our environment and foresees the aftereffects. (figure 4.19) among them we choose a sense of gravity because our world is gravity-dependent ; therefore gravity field is present everywhere and in everything we perceive. This force seems to be taken in consideration by the CNS while we interact (Demougeot & others, 2009) with the environment.

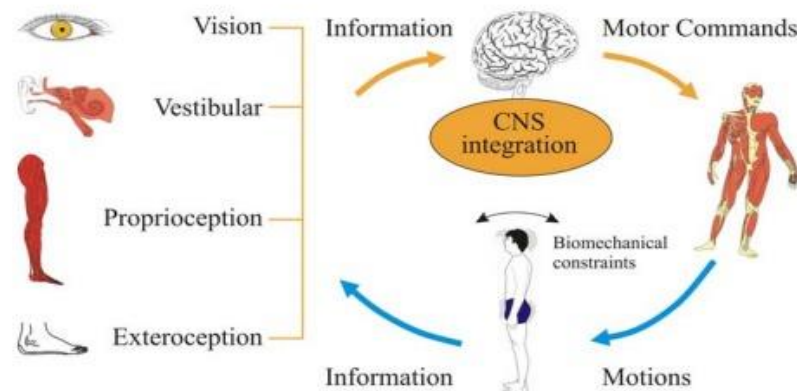


Figure 4.19 CNS perceives environmental variables and plan and control the movement.

As mentioned above, in performing a movement, the central nervous system (CNS) takes into account internal (inertia,...) and external (gravity, Coriolis,...) factors and anticipates the effects afterward (Demougeot & others, 2009). According to previous studies (Sciutti, et al., 2012) (Le Seac'h & McIntyre, 2007) hand kinematics are gravity-dependent. According to (Pozzo, et al., 1998), (Papaxanthis, et al., 1998), robust differences can be observed in hand velocity profiles during upward, downward, and horizontal movements. As a matter of fact, the acceleration duration is longer than the deceleration duration for downward movements, equivalent for horizontal (left or right) movements, and shorter for upward movements. Several studies (Berret, et al., 2008) (Papaxanthis, et al., 1998), (Papaxanthis, et al., 1998) (Papaxanthis, et al., 1998), (Papaxanthis, et al., 2003), (Papaxanthis, et al., 2003) demonstrated that these asymmetries are a result of the optimization of arm movements (by minimizing energy expenditures) through a direction-dependent planning process.

- Defining Characteristics and Context

Visual information plays a key role in the sensorimotor integration of gravity and how it affects movement control and motion planning. In these studies, the protocols were designed to address the issue of the effect of visual input on the hand velocity profile, i.e. TPV (time to peak velocity). According to TPV, there is a strong difference between conditions where subjects' hand movements are aligned with their visual input in terms of direction. In contrast, subjects move their hands in one direction and perceive rotated visual input. For instance (Sciutti, et al., 2012) showed that when one has to perform vertical (up and down) single-joint arm movements while visually perceived incongruent vertical movements (respectively, down and up) adaptation to a visuomotor rotation produces a significant change in the motor plan, i.e., changes to the symmetry of velocity profiles. This changes mostly represents by Acceleration duration over movement duration (AD/MD) parameter of hand kinematic. We in text we call AD/MD parameter Time to Peak Velocity (TPV).



Figure 4.20A: schematic of hand movement conflict, B: Alternation of the AD/MD value during a visual conflict (Sciutti, et al., 2012)

We propose that hand kinematics has better chance to be in accordance between real and virtual world if the perception of virtual environment is good, leading to a good sense of presence. In that consideration, the hand kinematics can be an indicator of sense of presence.

#### 4.3.2 Phase 2: Observation and Data Collection

- Selection of Participants:

We asked 20 participants including eighteen right-handed and two left-handed subjects, ranging in age from 19 to 35 to take part in the experiment. All participants were recruited through word of mouth. No compensation was given after the experiment. Before the experiment, a brief training was provided to let the subjects understand their main task in the virtual environment. It is important to note that they were in good health and had never undergone a vision or neurological or muscular surgery. The subjects with different backgrounds, either inside or outside the university, voluntarily participated in the study.

- Behavioral Observation

Visual gravity affects the kinematic features of hand movements because it provides cues for predicting how objects move in the environment and how forces such as gravity act on them. When planning and executing movements, the brain takes into account the perceptual information received, including visual gravity, to adjust motor commands. This can affect several kinematic features of the movement, such as maximum velocity, duration, time to peak velocity, and amplitude:

**Maximum Velocity:** When an object appears to be influenced by gravity, the brain may anticipate the need for a faster response to catch or interact with it effectively. This could lead to an increase in the maximum velocity of the hand movement. For instance, if you try to catch a ball falling due to gravity, your hand might move faster compared to a situation where the ball is moving horizontally at the same speed.

**Duration of the Movement:** The total time taken to complete a movement could change depending on visual gravity. For example, when reaching for an object that is falling, the brain might plan for a shorter movement duration to ensure that the hand reaches the object before it falls too far. Conversely, if gravity seems to have less effect on an object, the brain might plan for a longer, more controlled movement.

**Time to Peak Velocity:** Visual gravity can also affect when in the movement the hand reaches its maximum speed. In response to a falling object, the hand might need to accelerate more quickly, leading to an earlier time to peak velocity. Conversely, if the object is moving slowly or not influenced by gravity, the time to peak velocity may occur later as the movement can be more controlled.

**Amplitude:** The amplitude of the movement, or the distance covered by the hand, can also be affected by visual gravity. If the object is falling quickly, the brain might plan for a larger movement amplitude to ensure that the hand can reach the object in time. In contrast, when gravity's effect is perceived as less pronounced or absent, the brain might plan for a smaller amplitude since the object is not expected to move as much vertically.

Therefore, visual gravity can influence the kinematics of hand movements by affecting the planning and control of these movements. These adjustments are essential for efficiently interacting with objects in an environment where gravitational forces are at play. The brain uses the visual information to predict the object's motion and adapts the motor commands to optimize the hand's trajectory, speed, and timing.

- Data Collection

There are multiple kinematic measurements recorded during the experiment (in x, y, z axis format) such as Position, Velocity, Acceleration and beside these we recorded the time. The acceleration ( $m/s^2$ ), speed ( $m/s$ ), position ( $m$ ). Subjects hand movement trajectory can be plotted to visualize and verify by using x and y and z coordinates. We gathered all these data through VR hand controllers during the experiment into a CSV file. Data analysis was performed by using Python and all statistical analysis in this section were performed by using IBM® SPSS® Statistics version 26 (SPSS Inc., Chicago). Selected statistical test and assumptions will be described in detail at each measurement section. Before data analysis we applied data cleaning using Butterworth low pass filter with a cut off frequency 6Hz. For data cleaning, the velocity profile of each movement was visually checked, and only movements showing a single peak were considered.



4.3.3 Phase 3: Defining SOP in Context and proposal of metrics

- Development of Context-Sensitive Indicators

From the raw data we extracted kinematic features including: movement duration (MD) which is time interval in which velocity was superior of 5% of its peak, movement amplitude (Amp) which is angular amplitude of the rotation around the shoulder joint, maximum velocity (V max), and time to peak velocity (TPV) which is an index of the timing of movement velocity profiles, which has been shown to be significantly direction dependent (Berret, et al., 2008); (Crevecoeur, et al., 2009); (Gentili, et al., 2007); (Le Seac'h & McIntyre, 2007).

The formula relevant to extract each of these features are explained in below:

Movement duration :  $(T_{end_{pos}} - T_{start_{pos}})$

Movement amplitude :  $(ending\ position - starting\ position)$

Maximum velocity: Max (Velocity)

Time to peak velocity =  $(time_{V_{max_{movement}}} - time_{starting_{movement}}) / (time_{ending_{movement}} - time_{starting_{movement}})$

Where  $time_{PV_{movement}}$  is the time at which peak velocity occurs,  $time_{offset_{movement}}$  is the time at the end of the movement and  $time_{onset_{movement}}$  is the starting time of the hand movement.

The AD/MD values showed normal distribution (Kolmogorov-Smirnov test) and therefore could be subjected to t-test analysis and to the analysis of variance (ANOVA).

Raw data	Extracted Features
Time	MD (s), TPV(-)
Position (m)	Amp(m)
Velocity (m/s)	Vmax(m/s)
Acceleration(m/s <sup>2</sup> )	

Table 4.3-1 Raw Data VS. Extracted Features

4.3.4 Phase 4: Introduction and Testing of Metaphors

- Identification of Metaphors

In a previous study, (Sciutti, et al., 2012) evaluated the visual weight of arm movement planning using a linear model. Upon to their study, using a simple linear model, the

relative importance of visual context in arm movement planning was assessed. There are two types of directional information associated with each incongruent movement: the direction specified by the visual context (or visual direction) and the direction of the movement the subject actually performs with the arm (or nonvisual direction).

There is a specific velocity profile for each arm movement direction, characterized by TPV. In particular, the adopted kinematics would be determined by an internal model of gravity, which determines the optimal features of the velocity profile based on movement orientation and direction.

$$VP_{Tot} = F(\text{dir\_of\_motion}) \quad \text{Equation 4-17}$$

For a specific motion direction,  $VP_{Tot}$  is the optimal velocity profile, and  $F(\text{dir})$  is a (possibly nonlinear) function associated with gravity's internal model.

Based on both visual and nonvisual directional information, the CNS determines the velocity profile of the next movement by combining both. The simplest hypothesis is a linear combination of the direction suggested by the visual context and the nonvisual direction:

$$VP_{Tot} = F[\alpha \times \text{dir}_{vis} + (1 - \alpha)\text{dir}_{non\_vis}] \quad \text{Equation 4-18}$$

The direction of the visual feedback is represented by  $\alpha$  parameter that represents its relative weight. Assuming as well that the function relating the optimal velocity profile to each given motion direction is linear, as a first-order approximation implies, The previous equation will be rewritten to:

$$VP_{Tot} = \alpha F(\text{dir}_{vis}) + (1 - \alpha)F(\text{dir}_{non\_vis}) \quad \text{Equation 4-19}$$

According to the congruent condition  $\text{dir}_{vis} = \text{dir}_{non\_vis}$ , the previous equation becomes

$$VP_{Tot} = F(\text{dir}_{vis}) = VP_{vis} \quad \text{Equation 4-20}$$

As a result, we can measure the components  $F(\text{dir}_{vis})$  during the congruent condition where movement takes place in  $\text{dir}_{vis}$  and  $F(\text{dir}_{non\_vis})$  during the incongruent condition where movement takes place in  $\text{dir}_{non\_vis}$ . Using the velocity profile adopted in any incongruent condition, we can determine the weighting factor, which identifies the relative importance of the visual and non-visual motion directions for determining the next movement's motor plan.

$$VP_{Tot} = \alpha VP_{vis} + (1 - \alpha)VP_{non\_vis} \quad \text{Equation 4-21}$$

We measured  $VP_{Tot}$  in term of TPV in particular incongruent condition. To explain it in a simpler way we let's give an example. For instance, in O-u where the hand motion was performed in outward direction while visual feedback presented in upward direction,  $VP_{vis}$  will be then the velocity profile typical of a congruent upward motion (because upward is the movement direction associated to the visual feedback), and  $VP_{non\_vis}$  will be the velocity profile measured during a congruent outward

movement (because Outward is the nonvisual movement direction). To solve the equation 4-21 and find  $\alpha$  we used least squares solution for incongruent condition. To understand that the visual weight related to different environment, we found different  $\alpha$  for each subject during different incongruent conditions (U-d, D-U, O-u) in each environment ( B&W, City ).

- Testing of Metaphors

In order to better understand this work, we will explain the conditions and the way that we used metaphor in the following paragraphs.

To examine this hypothesis inspiring by Sciutti et al. experiment we designed our environment in a way that:

- Designing a visual motor manipulation as a metaphor.
- Designing a simple B&W environment, where it doesn't have any visual elements except a movement of a simple dot which represents subjects hand movements in VR.
- Designing a VR environment where is rich in terms of visual elements and it induce sense of gravity to the VR users.
- Ask VR users to move their hand in both environments under different conditions.

In following we explain this procedure in detail.

Two different visual scenes were designed with the aim of finding the effect of visual input in motor planning (B&W and City). As part of this study, subjects were asked to move their hands in both congruent and incongruent conditions. Table 4.3-2 shows different conditions and visual feedback and related hand movement and also their abbreviation that we used to show them in the text. We explained each condition in the following:

Congruent condition (vertical or horizontal movement):

In this condition, the visual feedback is in the same vertical or horizontal direction of the arm movement. For instance, when a subject performs upward, downward, inward, and outward arm movements (s) he observes that the dot representing hand in the virtual environment is also going in the same direction.

Incongruent Conditions

In this condition, the visual feedback of the arm movement (the dot that represents the arm of the subjects) moves in conflict with the actual arm movement. Therefore, the initial position of the dot will be located at the top zone if the hand movement is upward, it will be located on the bottom zone if the hand movement is downward. In this phase, subjects saw that the dot moving in the reverse direction or orientation of his actual hand movement but with the same velocity of his hand movement. We managed 2 different kinds of conflicts including:1) incongruent Vertical and 2) incongruent Horizontal. In the following, we will explain them in more detail.

### Incongruent Vertical

In this kind of conflict, the actual arm movement and its related visual feedback have the same orientation but not the same direction. For instance, upward hand movement is associated with downward visual feedback, this phase is including 1) upward hand motion with downward visual feedback (U-d condition) and the initial point of the dot was top zone. 2) downward hand motion with upward visual feedback (D-u condition) and the initial point of the dot was the bottom zone of the circle (Figure 4.21 D-u).

### Incongruent Horizontal

In this condition, the hand motion and related dot movements are orthogonal. When subjects move their dominant hand horizontally, they see the dot moving vertically. In better words, horizontal arm movement is associated with vertical visual feedback. In this phase the hand motion and visual feedback are as follows: 1) move horizontal (outward) and view Upward (O-u condition).

Three conditions were tested, which are summarized in Table 4.3-2. According to this table, there are different actual hand movements and visual feedbacks. Regardless of the direction of the hand movement, horizontal hand movements (both outward and inward) have the same velocity profile (Sciutti, et al., 2012). Due to this reason, we did not ask subjects to perform outward hand motions with inward visual feedback or inward hand motions with outward visual feedback.

During both conditions, subjects were asked to carry out single-joint arm motions at their own natural speed in both environments. In both environments, the subject's hand fingertip is represented by a dot whose diameter is 2 cm and which moves in real time on the screen during the experiment. The subjects were asked to move the finger/dot from one target zone to another (e.g., upwards, downwards, outward/rightward arm movements) during the course of the test (Figure 4.21).

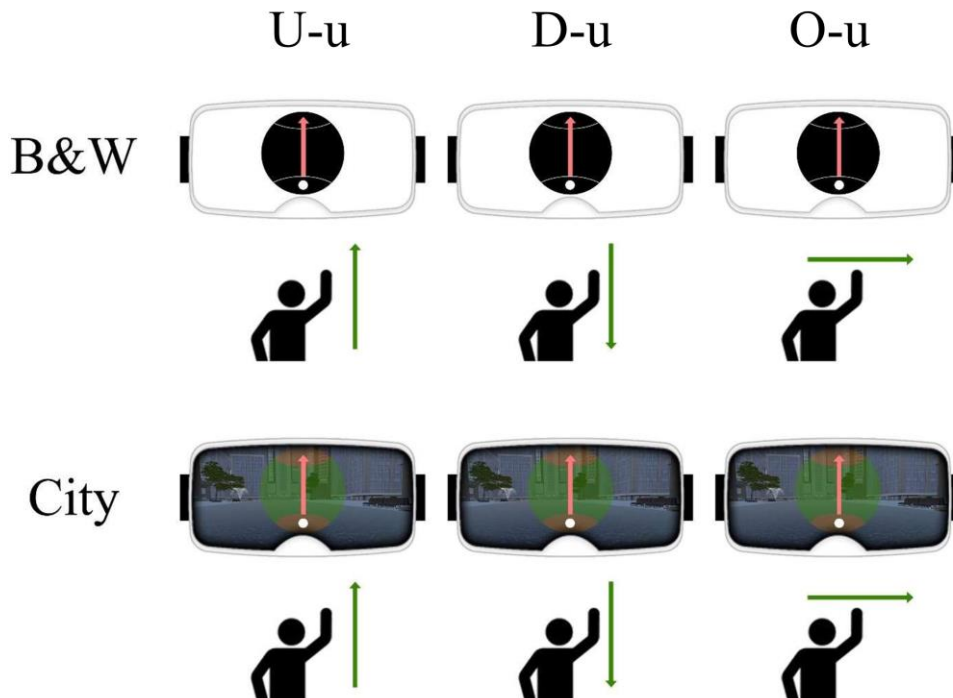


Figure 4.21. Schematic representation of the motor task performed in the B&W and City. U-u: Congruent condition. D-u : Incongruent vertical condition. O-u: Incongruent horizontal condition. A green arrow indicates the subject's hand movement throughout the images, while a red arrow indicates the subject's visual feedback. The white dot represents the subject's hand in the visual scene.

Condition	Actual hand movement	visual feedback	Abbreviations
Congruent Vertical	Upward Downward	upward downward	(U-u) (D-d)
Incongruent Vertical	Upward Downward	downward upward	(U-d) (D-u)
Congruent Horizontal	Outward	outward	(O-o)
Incongruent Horizontal	Outward	upward	(O-u)

Table 4.3-2. Sum-up of the different conditions tested with their abbreviations

Experimental equipment:

There was a resolution of 1440 x 1600 pixels per eye with a field of view of 110 degrees for the headset. It was equipped with Steam VR tracking, g-sensors, gyroscopes, eye comfort settings (IPD), and eye tracking sensors. There was a 120 Hz frequency of output for the data. In order to provide visual feedback about the subject's hand position on the screen, the HTC Vive eye pro controller (joystick) provided feedback about the subject's position on the screen. The joystick was light enough in weight (308 grams) to not compromise the subject's ability to accomplish a task and not wear out his or her hand in the process. However, participants did not report any asynchronous sensation of motion between the arm and dot in both environments.

## Environments:

We designed two environments: a Black and White environment (B&W) and a City environment (see Figure 4.22). When subjects wore the headset, the HMD prevented subjects from seeing their actual hand in the natural environment. The first environment a circular Black area with a white contour, including two target zones, was displayed. This environment reproduced the previous environment (Sciutti, et al., 2012) as a base environment for this study. Each zone covers about 32% of the scene (see Figure 4.22 B&W). The other environment) is a city scene that has lots of visual and audio elements (high buildings, a flying helicopter, fountain, ...) to induce the sense of gravity in the participants (see Figure 23). And we created a transparent circular area with the same zones as the B&W environment; a dot representing the subject's hand in the City environment (see Figure 4.22 City).



Figure 4.22. HMD Visual display. Subjects perceived a 3-dimensional hand position displayed through a VR headset screen in B&W and City environment.

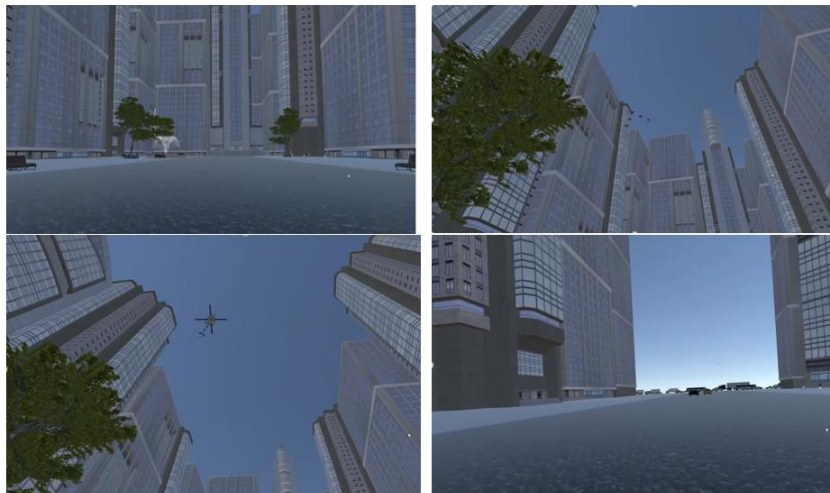


Figure 4.23. Examples of the City environment. During the subjects' presence in City, as they moved their heads, they perceived different visual elements in the city environment, including high buildings, flying helicopters, fountains, tall trees, etc.

## Experimental Procedure:

In the two different visual scenes, each subject performed 360 arm movements (180 arm movements for the scene in B&W, and 180 arm movements for the scene in the city). As part of this study, subjects were asked to move their hands in both congruent

and incongruent conditions. It is important to note that under congruent conditions, hand movement and visual feedback had the same direction or orientation (Figure 4.21 U-u). As compared to this, the arm motion and visual feedback were not in the same direction or orientation in the incongruent phase (Figures 4.21 D-u and 4.21 O-u). In order to conduct this experiment, three conditions were tested, which are summarized in Table 4.3-2.

According to this table, there are different actual hand movements and visual feedbacks. Regardless of the direction of the hand movement, horizontal hand movements (both outward and inward) have the same velocity profile (Sciutti, et al., 2012). Due to this reason, we did not ask subjects to perform outward hand motions with inward visual feedback or inward hand motions with outward visual feedback.

For every ten trials, the experimenter asked subjects to rest with their arms along their trunk for one minute in order to prevent fatigue. Throughout all phases of the experiment, the experimenter initiated arm movements verbally. During the experiment, the experimenter asked the subject to perform a natural, one-shot arm movement without paying attention to absolute precision in order to avoid the final pointing adjustment of the hand. There was a time delay of less than 30 milliseconds between the actual finger motion and the visual feedback in both environments.

Due to the incongruence between actual arm movements and visual feedback (relative observed movements), the subjects were confused and executed the movements incorrectly and this resulted in interference. To ensure that subjects could perform correct incongruent movements, we asked them to perform some incongruent vertical and horizontal movements as a training phase before commencing data collection.

We asked participants to perform eight training movements in order to avoid the interference effect caused by rotated visual feedback. Subjects' hands did not divert from horizontal and vertical movement while watching the dot move in the opposite direction or orientation by allowing a slight deviation from correct movement (less than  $3^\circ$ ). Prior to data collection, we asked subjects to perform eight training movements in order to avoid interference from this failure. Subjects were not permitted to diverge more than  $3^\circ$  from the horizontal or vertical axis. Participants were trained to perform the correct hand movements by performing eight training.

#### 4.3.5 *Phase 5: Validation of Indicators and Metaphors*

- Statistical Analysis

Four features were selected as kinematic features to measure sense of presence of the VR users, in this study. Precisely, which of the kinematic features are significantly different during subjects presence in different VR environments? Average value of the features for three conditions (congruent, incongruent vertical and incongruent horizontal) and two environments (B&W and City) were computed, after data cleaning and preprocessing. All the features passed the Assumption of normality were tested using Shapiro-Wilk test.

In Table 4.3-3, we demonstrate the means and standard deviations of hand kinematic features for 20 subjects in B&W and City environments. A number of features are

involved in this process, including movement duration (MD), movement amplitude (MA), maximum velocity (Vmax), and time to peak velocity (TPV).

According to the results of the 2-way ANOVA, there was no significant interaction effect of conditions and environment on MA ( $F(7, 216) = 0.149, p > 0.05$ ). The visual scene did not have a significant effect on MA ( $F(1, 216) = 4.654, p = 0.32$ ), however, the main effect of conditions was significant ( $F(7, 216) = 8.850, p < 0.0001$ ). As a result, subjects produced the task with the same accuracy regardless of the visual scene that is presented to them.

An analysis of the MD with two-way ANOVA showed that the interaction effect of visual scene and conditions on this parameter is not statistically significant ( $F(7, 216) = 1.388, p > 0.05$ ). MD was not significantly affected by visual scene ( $F(1, 216) = 5.01, p > 0.05$ ). Conversely, conditions had a significant main effect on MD ( $F(7, 216) = 9.44, p < 0.0001$ ). Due to MD results, subjects generated the same MD regardless of the visual scene.

		(U-u)	(D-d)	(O-o)	(U-d)	(D-u)	(O-u)
MD (sec)	B&W	0.94±0.22	0.98±0.30	0.87±0.24	1.10±0.34	1.11±0.38	1.11±0.36
	City	1.00±0.22	1.10±0.35	0.79±0.25	1.21±0.31	1.20±0.26	1.01±0.30
Vmax (m/s)	B&W	1.51±0.36	1.44±0.37	1.81±0.39	1.43±0.36	1.31±0.33	1.51±0.33
	City	1.41±0.35	1.29±0.36	1.76±0.38	1.32±0.23	1.25±0.22	1.62±0.34
MA (m)	B&W	0.69±0.06	0.69±0.07	0.65±0.07	0.67±0.07	0.66±0.07	0.77±0.10
	City	0.72±0.10	0.70±0.09	0.68±0.07	0.70±0.07	0.68±0.08	0.79±0.11
TPV	B&W	0.44±0.04	0.49±0.07	0.51±0.08	0.46±0.09	0.48±0.07	0.49±0.10
	City	0.45±0.03	0.50±0.05	0.50±0.06	0.47±0.06	0.48±0.06	0.47±0.08

Table 4.3-3. The mean and standard deviation for hand kinematics in B&W and city.

#### Effect of the Visual Movement Conflict on Movement Timing

When the arm motion and visual feedback are congruent, the TPV value conforms with the previous studies (Papaxanthis, et al., 2003), (Papaxanthis, et al., 1998) (Sciutti, et al., 2012)). Figure 4.24 represents the value of TPV for each subject in different congruent conditions, including upward, downward, and outward directions in B&W and City environments. TPV value for (U-u) confirms the asymmetry of movement timing ( $0.44 \pm 0.04$  and  $0.46 \pm 0.03$  for B&W and City environments). In this case, the acceleration part of the velocity profile was shorter than the deceleration part. In contrast, the TPV value for D-d (B&W:  $0.49 \pm 0.07$  and VR:  $0.50 \pm 0.05$ ) and O-o



movements (B&W:  $0.51 \pm 0.08$  and City:  $0.50 \pm 0.06$ ), regardless of the environments produced symmetric velocity profiles (see (Papaxanthis, et al., 1998)).

Figure 4.24 (U-d, D-u, O-u) displays a better discrepancy between the mean and individual values of incongruent conditions in different environments. The slope of the gray trend lines indicates personal changes of TPV from B&W to the City environment. The TPV mean values for B&W and City environment for U-d were respectively  $0.46 \pm 0.09$  and  $0.47 \pm 0.06$ ; in comparison for the D-u condition in the B&W environment, the TPV mean value was equal to  $0.48 \pm 0.07$ , and in City, it was  $0.48 \pm 0.06$ . However, the T-test results did not confirm any statistical difference between the two environments in the incongruent vertical conditions.

Figure 4.24 (O-u) illustrates the discrepancy between subjects' behaviors in the B&W and the City environments. In this state, the hand velocity profile was no longer symmetric in both visual environments. Outward pointing movement timing was affected by upward visual feedback. The mean and standard deviation values of TPV for the 20 subjects tested in the B&W and City environment were  $0.49 \pm 0.10$  and  $0.47 \pm 0.08$ , respectively. Statistical results of the group analysis (T-test) showed that the effect of the City environment was more significant than the B&W ( $P - value = 0.0013$ ).

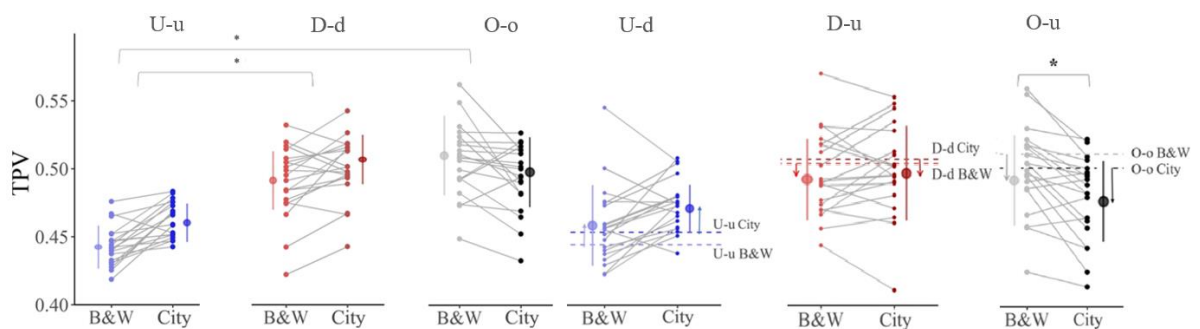


Figure 4.24. Individual and mean TPV of hand movement for congruent conditions (U-u, D-d, O-o) and incongruent conditions (U-d, D-u, O-u) in B&W and City environments. Lighter colors present the subject's behavior in the B&W environment, and darker colors are for City environments. Asterisks show the statistical difference. The arrows show the difference between the mean value of congruent condition and incongruent condition in different environments. The horizontal dashed line represents congruent conditions means value in B&W (light color) and City (dark color).

### Effect of Visual Feedback

Figure 4.25 depict individual TPV ratios (downward: red, upward: blue) measured in conflicting visual feedback plotted against the corresponding TPV ratio congruent visual feedback. The first row represents the (U-d and D-u) in the B&W environment, and the second represents incongruent conditions in the City environment.

Visual feedback impacted actual arm movement in both B&W and City environments (Figure 4.257, column A, column B). Although visuomotor conflict led to a change in

motor planning in both settings, the effect of visual gravity on hand kinematics was more significant in the City environment. Figure 4.25, column C, indicates the impact of incongruent visual feedback on actual hand movement. In both City and B&W environments, upward visual feedback shortened the movement timing of downward hand movement, and downward visual feedback lengthened natural upward hand movement timing. T-test results confirm that in B&W and City environments, there is a statistical difference between D-u and U-d conditions ( $p < 0.05$ ). Finally, the development of the correlation coefficient shows, in the B&W ambience, a moderate relationship between eye and hand movement in the U-d condition ( $r=0.667$ ).

On the other hand, this relationship is weak in the D-u condition and the same environment ( $r=0.286$ ). However, in the City environment, the result of the correlation coefficient does not show any strong relationship between hand and eye in D-u or U-d condition. In the B&W, in the U-d case, 75% of participants are affected by the downward visual feedback while in D-u, the upward visual feedback impacts 40% of subjects. In the City environment, in the U-d condition, 65% of participants were influenced by downward visual feedback. In comparison, 70% of subjects were affected by upward visual input in the D-u condition.

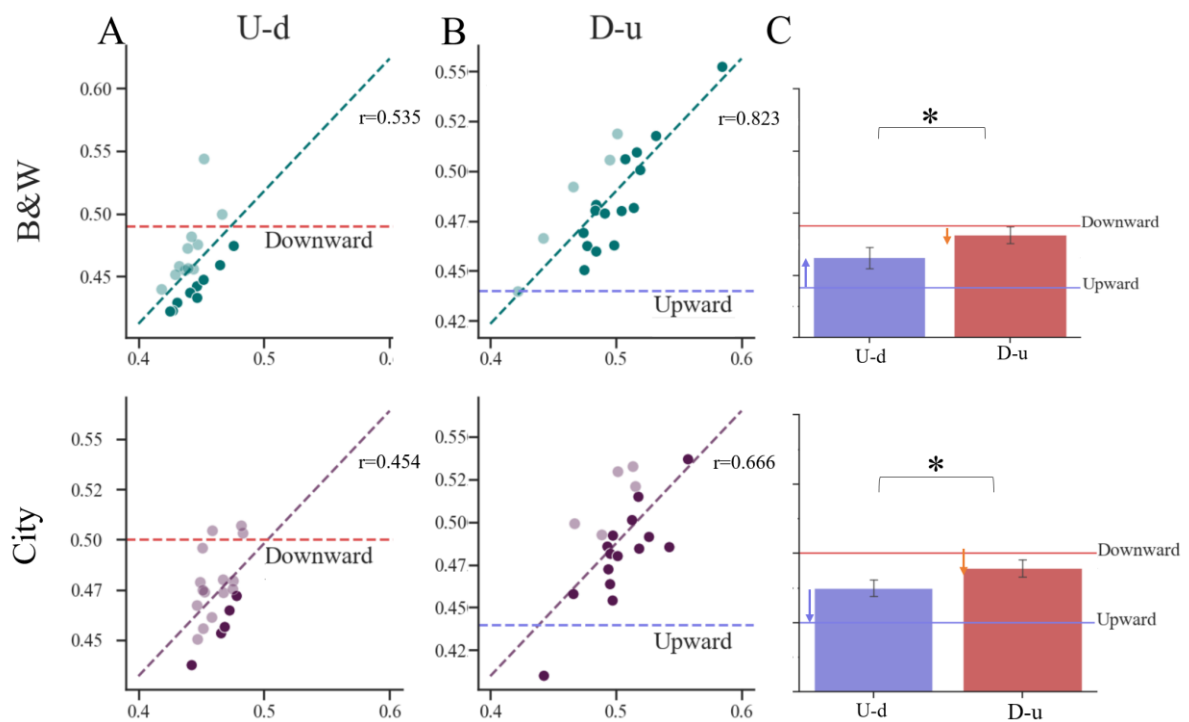


Figure 4.25. Effect of visuomotor conflict on TPV (Motor replanning for incongruent direction conflict): Columns A and B represent results for the state (U-d) and situation (D-u), respectively. An imaginary diagonal line for each dot plot represents where the subjects should place if the conflicting visual feedback does not affect motion planning and whether the movement was performed as expected. The darker dots indicate subjects placed below the diagonal, while lighter dots indicate subjects placed above it. Column C shows the difference between (U-d) and (D-u) conditions in B&W and City. horizontal lines indicate the mean value of U-u (blue) and D-d (red), and red and blue arrows show the effect of incongruent visual conflict on arm movement. Asterisks

indicate the statistical differences obtained by data group analysis.

$\alpha$  is an Indicator of SOP:

Figures 4.26, 4.27, 4.28 show calculated  $\alpha$  for each participant under different incongruent conditions (U-d, D-u, O-u respectively) in both visual scenes(B&W, City). As figure 4.26 represents 50% of the participants has a greater  $\alpha$  in City environment during U-d condition. On the other hand the number of the participants who has a greater  $\alpha$  in City environment during D-u condition is increasing. According to figure 4.27 60% of the participants had greater  $\alpha$  under D-u condition in City environment comparing to B&W. While majority of participants sensed greater  $\alpha$  under O-u condition, in City environment according to figure 4.28. During this condition 80% of participants had greater  $\alpha$  in City environment.

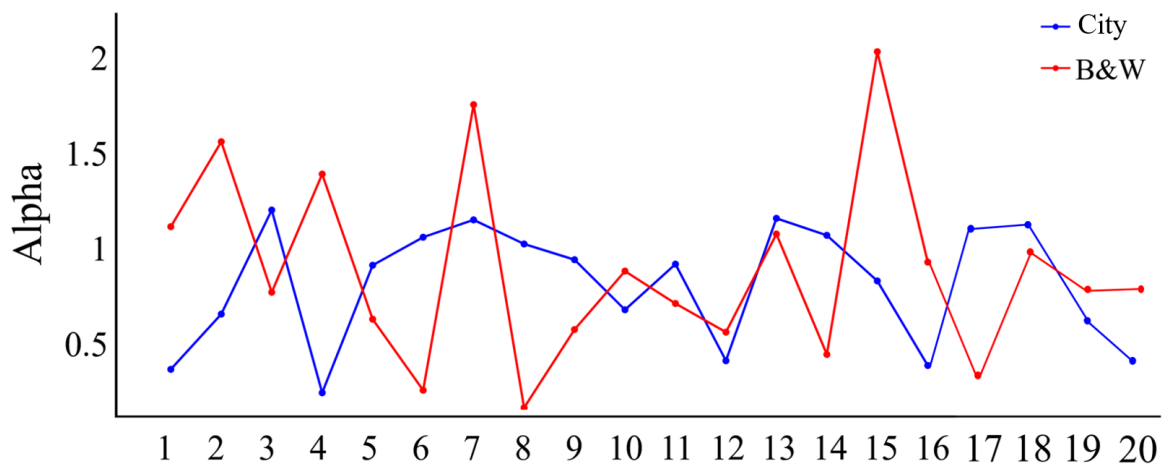


Figure 4.26. Individuals  $\alpha$  during U-d condition in B&W and City conditions. The Y-axis show the  $\alpha$  value for each participants. The X-axis shows the participant,

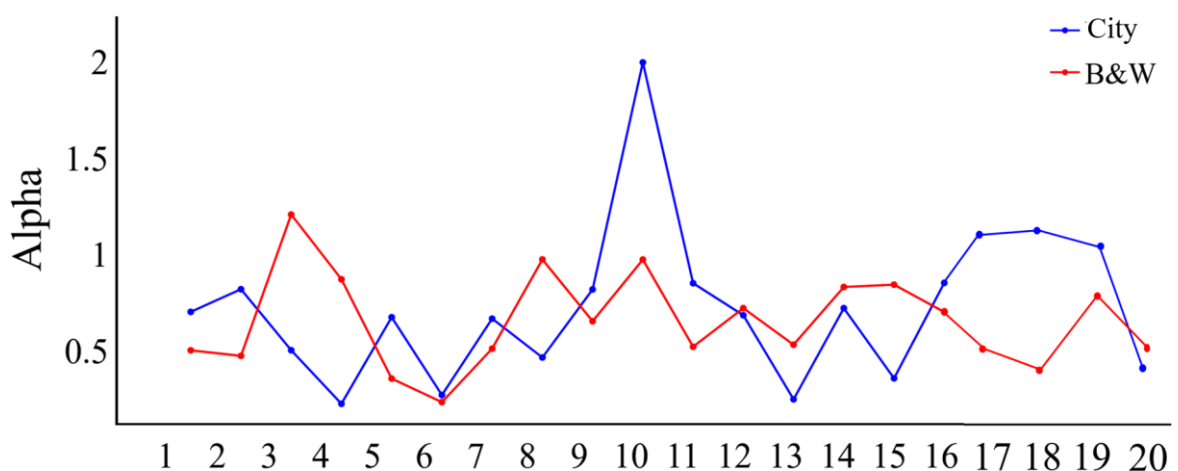


Figure 4.27. Individuals' alpha during D-u condition in B&W and City conditions. The Y-axis show the  $\alpha$  value for each participants. The X-axis shows the participant,

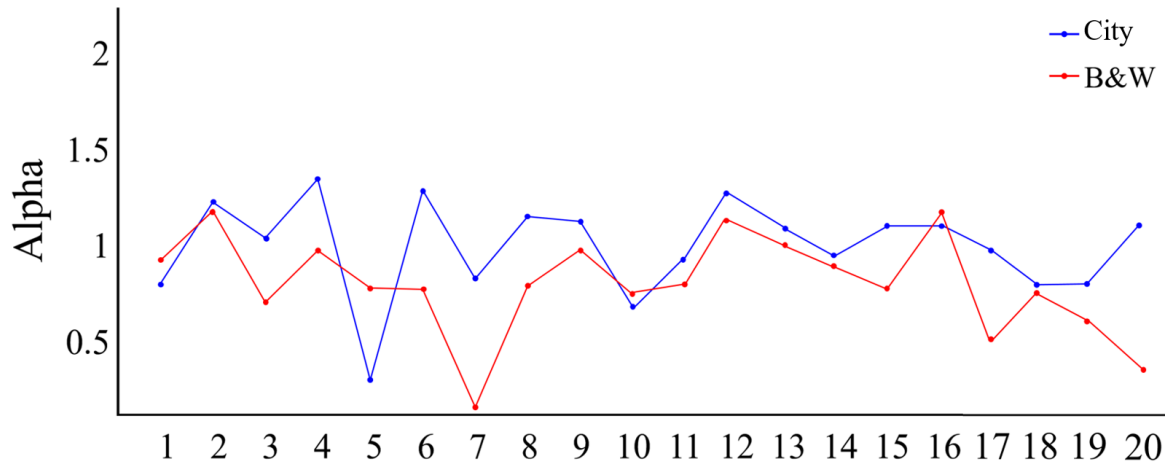


Figure 4.28. Individuals' alpha during O-u condition in B&W and City conditions. The Y-axis show the  $\alpha$  value for each participants. The X-axis shows the participant,

- Discussion

Results show that visual elements change the velocity profile of the hand movement. This alternation can be perceived better when the hand movement and visual feedback are not in the same orientation.

We tried to introduce an objective measurement of the sense of presence in VR environments based on hand kinematics. By inspiring the notions that artificial rotation between hand kinematic and visual feedback affect the motor plan plus the effect of environmental visual elements, the visual information in three-dimension is gravity-dependent and significantly modified arm movement kinematics. This study tried to induce a sense of gravity in subjects by visual information in a VR environment.

The results demonstrate that variations in visual elements influence the velocity profile of hand movements, with notable alterations observable when there's a misalignment between hand movement and visual feedback. Our study aims to introduce an objective measure for the sense of presence in VR environments, relying on hand kinematics as a significant indicator. The alternations in the velocity profile asymmetry across various incongruent conditions in different settings underscore the impact of visual information during the planning phase. This observation is particularly evident when visual feedback aligns with the gravitational axis, further emphasizing the gravity-dependent nature of visual information in three-dimensional spaces, which significantly affects arm movement kinematics. We engaged visual elements in the City environment to evoke a sense of gravity among participants, observing that an increase in visual information correspondingly altered hand kinematics, particularly the subjects' velocity profile. This finding validates our hypothesis that visual elements play a crucial role in planning hand movements in VR, making it a reliable indicator of a user's sense of presence in a given virtual environment. It is the first time the hand movement velocity profile can evaluate the sense of presence to our best knowledge. In the following, we will discuss the role of VR environment richness in arm motion planning on incongruent visual feedback on the movement execution.

The influence of visual information on the temporal pattern in the B&W environment

In the B&W environment, the first experimental phase was the congruent condition when the hand movement has aligned with visual feedback. While subjects couldn't see the position of their real hand in the real environment, a dot represents the hand of the subject in the B&W environment. Hand velocity profile revealed that the value of the time to peak velocity (TPV) for acceleration is less than the deceleration phase for the upward condition. On the other hand, the velocity profile was symmetric in downward and outward conditions.

In the second experimental phase (incongruent condition) in the B&W environment, subjects had to perform arm movement in a vertical plane and see the arm motion in the opposite direction, or execute arm movement in the horizontal plane and see the arm motion in a different orientation. Defining this experimental protocol presents a large discrepancy and sensory conflict between limb trajectory in visual space and movement direction and orientation. While subjects were completely aware of the consequence of their arm motion, they couldn't modify their velocity profile. For instance, after long practice, subjects could not neglect the visual information and subconsciously reconcile movement timing different from the one adopted in the congruent condition. While previously it is shown that in visuomotor conflict condition, reconstruction of the arm trajectory along vertical axis does not strongly rely on visual information and after some practicing subjects can modify their arm trajectory.

When horizontal arm motion was associated with upward visual feedback, the subject's speed profile was no longer symmetric than horizontal arm movement's congruent condition. However, it becomes similar to upward arm motion in the congruent condition. Since previous studies demonstrated that motion kinematics were modified by visual feedback in the vertical direction (Sciutti, et al., 2012), we decided to choose this outward direction coupled with upward visual feedback.

### **Gaining the richness of the VR environment and its efficacy in motor planning**

Understanding that visual vertical has a stronger influence on motor planning leads us to design a VR environment with lots of visual elements that remind subjects of the gravity force and induce them the sense of gravity. Repeating the same experiments in the City environment, the velocity profile results are changing more strongly, especially during incongruent conditions.

During the first experiment in the VR environment (congruent condition), results show that by increasing the richness of the environment, the velocity profile follows the rules of being asymmetric for upward movement and symmetric for other directions (downward, outward).

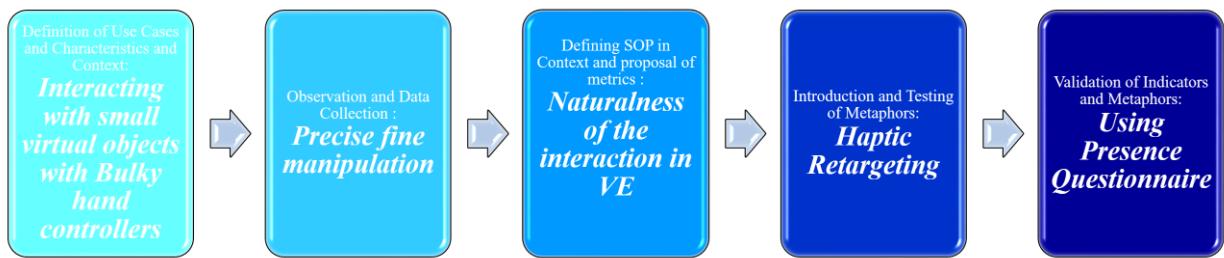
During the second experimental phase, when subjects perform hand movement on the vertical axis and perceive visual feedback in a different direction, the velocity profile of the hand movement is not symmetric anymore, and it gets more asymmetric.

Compared to the B&W environment, the alternation of a velocity profile for horizontal hand motion coupled with vertical visual feedback was statistically meaningful; therefore, in this condition, visual feedback has a stronger influence on temporal features of the arm motion.

Among all the velocity profile parameters, the TPV parameter had the most significant alternation between the two environments, while amplitude and duration were almost constant. Therefore, this parameter represents the degree of richness in VR environments and can be used as an index of immersion in the VR environment.

Considering a simple linear model that combines the visual and planned movement information between the VR environment and B&W environment led us to calculate the relative visual weight between the 2 different environments.  $\alpha$  results show that between 2 different environments, the relative visual weight for the incongruent upward motion was about 50% and for incongruent outward motion 80%. This shows that the most effect of visual input on hand kinematic is the time that hand movement and visual feedback are orthogonal. And comparing environmental visual weight alpha value reaches to its maximum during O-u condition in city environment. These results confirm that hand kinematic reflect the artificial visual input. Therefore, when a VR user present in a virtual environment their hand kinematic could be affected by visual elements. Since in VR environment most of the user perception is through their visual sensory system, therefore hand kinematic could be a new indicator for measuring user's sense of presence.

#### 4.4 Use Case4: Endotracheal Intubation Process



##### 4.4.1 Phase 1: Definition of Use Cases and Characteristics and Context

- Definition of Use Cases and Contexts

VR technology can be used to create realistic simulation environments where medical professionals can practice endotracheal intubation without the risk of harming actual patients. Through VR training, they can familiarize themselves with the equipment, the anatomy of the airway, and the procedure itself. They can repeatedly practice the intubation process in a controlled environment, and receive real-time feedback on their performance. This helps in building muscle memory, improving reaction times, and enhancing decision-making skills under stress. Additionally, VR can simulate various complications and scenarios that might not be easily replicable in traditional training settings, further preparing them for real-life emergencies.

Given the importance of endotracheal intubation in saving lives, especially in emergency situations, and the challenges in training professionals in this procedure, VR emerges as a highly effective tool. By utilizing VR for training, medical professionals can gain the necessary skills and confidence to perform endotracheal intubation more efficiently and safely, ultimately contributing to better patient outcomes.

- Defining Characteristics and Context

Indeed, the current limitations of VR technology, such as using bulky hand controllers, may not fully replicate the tactile sensation and dexterity required in handling small and delicate instruments like a laryngoscope in the operating room. This is a valid concern and highlights an area where VR technology needs to evolve to offer more realistic training experiences.

##### 4.4.2 Phase 2: Observation and Data Collection

- Selection of Participants:

Seven participants (4 males and 3 females aging range from 22- 36) took part in this experiment. Subjects from different backgrounds, either from inside or outside the university, agreed to participate voluntarily and without any compensation in the experiment. None of them had any physical or neurological disorders

- Behavioral Observation

During the process the Anesthesiologists demonstrates correct handling of the laryngoscope and endotracheal tube and visualize the vocal cord. The endotracheal tube is passed between the vocal cords into the trachea. The Anesthesiologists checks tube placement in the trachea, not esophagus, through visualization, auscultation, and/or end-tidal CO2 detection.

- Data Collection

- Subjective Measurements (Presence Questionnaire) :

- For subjective measurements, we utilized a Presence Questionnaire, a tool designed to assess the participant's sense of 'presence' within the virtual environment. This questionnaire is primarily employed to measure the participant's perceived involvement, immersion, and realness of the virtual experience.

- Realism: This factor assesses the extent to which the participant feels that the virtual environment replicates the complexity and detail of a real-world equivalent. It evaluates how authentically the sensory cues, spatial properties, and environmental interactions in the virtual world mirror those in reality.
    - Possibility to Act: This element captures the perceived ability of the participant to interact with the virtual environment. It gauges the extent to which the participants feel they can execute actions, manipulate objects, and influence the events within the virtual setting.
    - Quality of the Interface: This component assesses the usability and intuitive design of the virtual reality interface. It considers aspects like ease of navigation, control responsiveness, and overall user-friendliness.
    - Self-Evaluation of Performance: This component is a self-assessment from the participant, where they rate their own ability to accomplish tasks within the virtual environment. It gauges their perceived competence and efficacy in executing the intended tasks within the virtual setting.

- These four components of the Presence Questionnaire serve to provide a comprehensive understanding of the participant's experience, feelings of immersion, and perceived proficiency within the virtual environment. The responses from the Presence Questionnaire provide subjective data, enabling the analysis of individual's perceptual and psychological experiences during the virtual reality experiment.

#### 4.4.3 *Phase 3: Defining SOP in Context and proposal of metrics*

Naturalness of interaction in Virtual Environments (VE) as a metric for Sense of Presence (SoP) is critical in the training for procedures like endotracheal intubation. Sense of Presence refers to the user's psychological sense of being "inside" or "part of" the virtual environment. The more natural the interactions feel in the VE, the higher the sense of presence, which can be essential for effective training in complex medical procedures like endotracheal intubation. Development of Context-Sensitive Indicators

- Development of Context-Sensitive Indicators

- Here's how naturalness can be evaluated as a metric:



- *Realism of Tools and Environment*: The visual and tactile representation of the tools, such as the laryngoscope, and the environment, like the patient's anatomy, should be as realistic as possible. The ability to manipulate the laryngoscope with similar dexterity and responsiveness as in real life is crucial for naturalness.
- *Haptic Feedback*: A natural interaction should involve the sense of touch. By integrating haptic technology, the user can feel physical feedback while handling virtual instruments, adding to the sense of presence. The closer the haptic feedback resembles the sensation of handling real instruments, the more natural the interaction.
- *Latency and Responsiveness*: In a natural interaction, the virtual tools and environment should respond to the user's movements and actions without noticeable delay. High responsiveness and low latency are crucial for simulating the time-sensitive and precise nature of endotracheal intubation.
- *Degree of Freedom in Movements*: The user should be able to move and manipulate instruments in the VE with the same range and complexity of movements as in real life. This includes rotations, translations, and subtle adjustments, which are vital for endotracheal intubation.
- *Ergonomics of Controllers*: The physical controllers used for interaction in the VE should be ergonomically designed to resemble the feel and handling of actual medical instruments.

#### 4.4.4 Phase 4: Introduction and Testing of Metaphors

- Identification of Metaphors

In the real-world setting, medical personnel must use both hands to perform endotracheal intubation promptly. However, in the virtual environment, due to the patient's mouth being small while the Vive controllers (joystick) are bulky, the controllers will bump together and ruin the sense of presence and immersion. To address this, we turned to the concept of haptic retargeting (Azmandian, et al., 2016).

To solve this problem, we benefit from the idea of haptic retargeting as a metaphor. Based on the premise of this study, which posits that visual input supersedes proprioceptive feedback, we were able to devise a solution for the collision issue.

We formulated a visual-proprioceptive conflict model, which essentially created an offset between the positions of the virtual and real hands. This configuration permitted the virtual hands to appear closer together while maintaining a wider gap between the actual hands. Importantly, users were incapable of detecting this positional discrepancy between the virtual and real hands, thereby preserving the sense of immersion and presence.

- Testing of Metaphors

Procedure:

Upon arrival, participants were requested to sit for a duration of 10 minutes, enabling us to obtain a stable set of physiological data. Subsequently, they were equipped with the HTC Vive headset and instructed to enter the experiment in a standing position. A brief explanation was provided on how they would receive in-experiment instructions.

The participants were then guided to perform the endotracheal intubation procedure on a 3D model of a patient's throat, using the laryngoscope for visualization of the vocal cords and simultaneous insertion of the endotracheal tube. Following the successful insertion of the tube into the patient's lungs, the laryngoscope was removed, the tube's cuff inflated, and a CO2 monitor was applied to verify patient breathing through the tube. Lastly, the tube was attached to a holding mask to ensure its stability.

### Protocols

To assess the efficacy of the haptic retargeting model, we introduced two distinct scenarios.

### Reference Condition

In this scenario, participants did not experience any visual-proprioceptive conflict. Their virtual hands corresponded accurately with their actual hands, with an offset of zero between the two. Participants did not encounter any perceptual conflict in this condition.

### Retargeting Condition

In contrast, this scenario involved an alteration in the offset between the virtual and real hands to a measure of 6 centimeters. This specific offset was chosen as it represented the maximum discrepancy that participants could tolerate without perceiving a disassociation between their virtual and actual hands. Although the virtual hand maintained the same speed as the real hand, its position was varied.

### Experimental Device:

Participants were standing in an empty and calm space during the experiment. They were equipped with an HTC Vive eye pro headset and controllers. The headset's resolution was 1440\*1600 pixels per eye with 110 degrees of field-of-view. The device was equipped with eye tracking, a g-sensor, gyroscope, proximity, and eye comfort setting (IPD).

### Environments:

When a user wears the 3D headset, they are immersed in a simulation environment that replicates a realistic medical environment for practicing hooking up the patient to a ventilator. This environment contains multiple medical objects such as a surgical table, monitors, lights, etc (see figure 4.29). There is a smaller table (see figure 4.30) in the environment to the left of the user that has various medical tools on it, such as a laryngoscope, endotracheal tube, CO2 monitor, etc. To induce anxiety in the user we have added telephone noises, pager noises, as well as nurses who talk in the environment.



Figure 4.29 Virtual surgical environment.

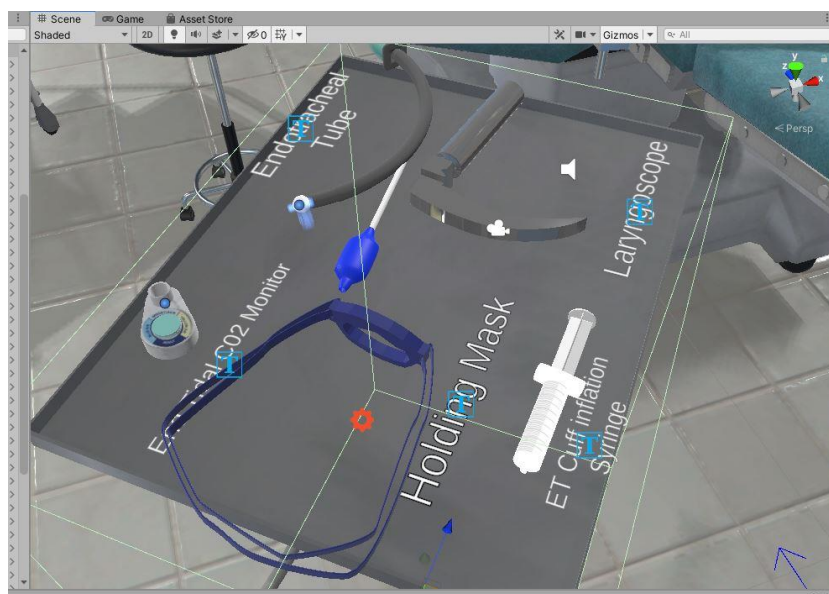


Figure 4.30. Medical tools table

#### 4.4.5 Phase 5: Validation of Indicators and Metaphors

- Statistical Analysis

Fig. 4.31, shows the mean value of the presence questionnaire for different 7 participants. According to this image, subjects sense more realism in retargeting conditions compared to the reference condition. Moreover, subjects perceived more possibility to act in the retargeting condition. However, the quality of the interface was almost the same in both conditions. Finally, they estimated in the retargeting conditions they had a better performance and sense of presence. T-test analysis did not show any significant different between real and retargeting condition.

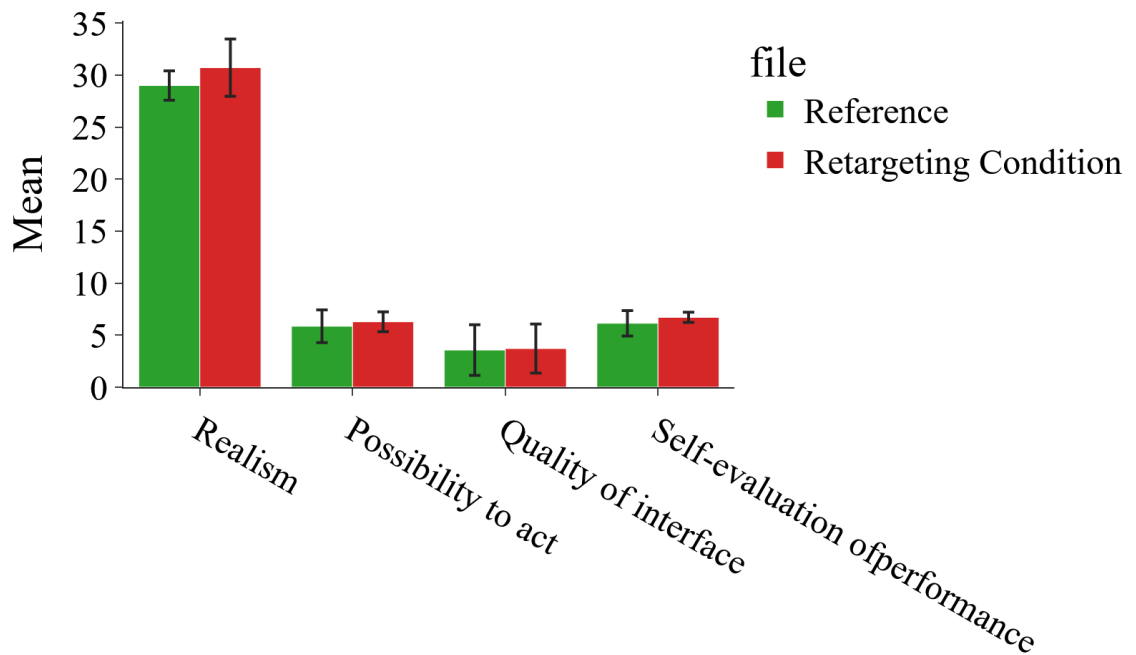


Figure 4.31. Analysis of the presence questionnaire in different conditions.

- Effectiveness of Metaphors

The accessibility and usage of virtual reality in other fields of science, made scientists in different fields pay noticeable attention to the use of this application. One of the most sensitive fields of science is the medicine which requires a high concentration and low reaction time of the doctors and participants. Endotracheal intubation is one of the most sensitive procedure procedures in medical science which demands highly focused nurses and must be done in a short amount of time. Therefore, training nurses have special importance. Virtual reality by providing a realistic and believable environment is a good alternative solution to train novice medical students and nurses.

In this study, we aimed to train nurses in the intubation process using virtual reality. To achieve this goal, we provided a surgical environment similar to the real one, and we asked novice people to join the experiment.

In the Endotracheal Intubation Simulation, there was a significant problem that affected the quality as well as the usability of the simulation. The problem is that when performing the simulation, the controllers end up bumping together and breaking the immersion. Two major factors caused this problem. The first is that the simulation requires you to have both hands in the patient's mouth at the same time. The second is that the HTC Vive controllers are significantly bigger than the mouse of the virtual patient.

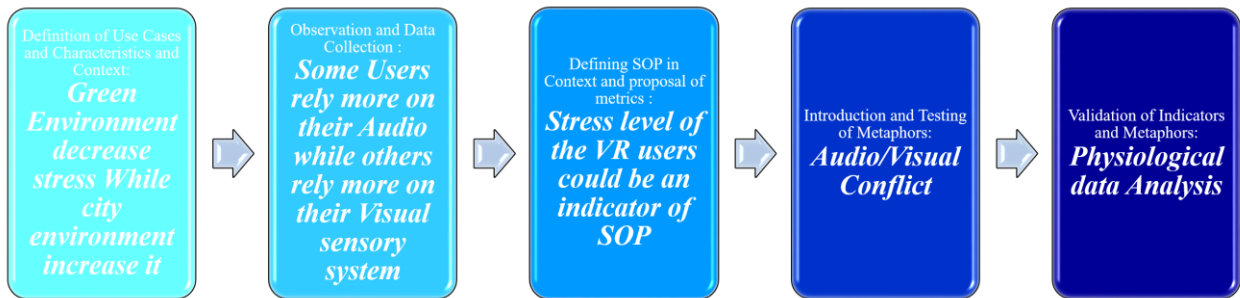
The solution to this problem that was implemented was setting an offset value to the virtual position of the controllers to the real-world position of the controllers. In most conventional virtual environments, the goal is to match the controllers exactly where

they are in the real world. However, for the needs of our simulation, it was beneficial to make the virtual positions of the controllers closer together and offset them by a small but significant amount towards each other. We chose a distance close to this measure to make sure that users of the simulation would be unable to notice that the controllers were offset from their physical real-world positions. If the distances were too large that they would be noticeable, it would be incredibly disorienting for the user, however, if it was too small it would not be enough to fix the main problem described earlier.

The distance we found was a great compromise and was able to solve the main problem while keeping the offset hidden from the user. This solution was inspired by a concept called Haptic Retargeting, however, it differs moderately from the original concept, as it operates purely in the virtual environment and does not involve the physical world outside of the Vive controllers. Our results of the presence questionnaire, specifically the realism and possibility to act responses in the questionnaire, confirm that by using this solution, participants experienced a better sense of presence in the environment, leading to better performance.

The solution we found was successful and is a technique that could be implemented in other Virtual Reality programs if those programs had problems similar to the Endotracheal Intubation simulation.

#### 4.5 Use Case5: Effect of multisensory feedback on stress level



##### 4.5.1 Phase 1: Definition of Use Cases and Characteristics and Context

- Definition of Use Cases and Contexts

The use of Virtual Reality (VR) in therapy has been a promising development in the healthcare sector, particularly in the context of mental health and well-being. VR can be used in various therapeutic contexts, including the management of stress.

- Defining Characteristics and Context

Stress and anxiety have a tight connection and they have overlapping neural substrates of psychological states as well as intertwined behavioral and neural structures (Daviu, et al., 2020), (Chrousos, 2009), (Seinfeld, et al., 2016). Dysfunctionality and hypersensitivities of the stress system are associated with anxiety disorders (Seinfeld, et al., 2016). Due to the overlapping structure between stress and anxiety, placing in a stressful situation can intensify anxiety (Grillon, et al., 2007). It has also been shown that anxiety and stress have an impact on individuals' physiological responses such as heart rate and skin conductance and blood pressure (Min, et al., 2020).

Human emotions can be influenced by its environment whether feeling stress when stuck in a traffic jam or delighted when relaxing in a nice place after a long weekday. Clearly, the elements of the environment such as lighting, level of noise, control of the situation, can affect human's emotion and wellbeing.

Different researches have shown that green environments like forests and nature alleviated tension and stress relief (Grahn & Stigsdotter, 2003) (Annerstedt, et al., 2013). And humans prefer a natural environment compared to an urban one. Naturalness, lightning, and weather type in a virtual environment have significant effects on users' emotional states. For instance, humans have a significant preference to stay in a light scene compared to a dark scene, as well as a sunny scene compared to an overcast scene (Beute & de Kort, 2013). (Lederbogen, et al., 2011) also showed that living in a city environment will negatively affect the brain responses to stress compared to towns and rural, and it makes people feel stressed easily (Yeung, et al., 2013) (Bilgin, et al., 2019), experimented with a sunny forest as the calm environment and a roller coaster ride as the dynamic environment for a comparative study of mental states in 2D and 3D virtual environments using electroencephalogram (EEG). In addition, a scene with warm and bright light, peaceful audio, and natural environments are the most helpful in calming participants (Tarrant, et al., 2018)

#### 4.5.2 *Phase 2: Observation and Data Collection*

- Selection of Participants:

20 healthy participants (6 women and 14 men, with a mean age of  $26.24 \pm 7.98$  SD) participated in the experiment. All of them had normal vision and never presented with neurological or cognitive disorders. Subjects' heights ranged from 156 to 195 cm, and the mean height was  $174.2 \pm 11.64$  cm. Subjects from different backgrounds, either from inside or outside the university, agreed to participate voluntarily and without any compensation in the experiment.

- Behavioral Observation

Similar to the real world, in a virtual environment human beings perceive information through their sensory modalities such as vision, audio, and haptic. The notion of multisensory integration refers to the coherent and relevant interaction of the multi-sensory stimuli. Among all research on audio-visual integration, some studies indicated that audio-visual integration can lead to more intense emotional responses (Pan, et al., 2019).

One of the most important questions in VR was always about, which sensory system is more dominant. To answer this question various studies focused on the impact of sound and audio on different fields of virtual reality such as mass and material perception, (Fleming, 2014) or visual perception (Bowman, et al., 1999) or game experience (Rogers, et al., 2018).

It is a common belief that vision is the dominant sensory input system, however, in multisensory conflict conditions, it can be manipulated by other sensory systems such as audio (Bowman, et al., 1999) (Shams, et al., 2000).

Our research is trying to study the behavior of the subject in a stressful and calm environment and analyze the sense of presence for the optimization of virtual immersion. Besides that this research wants to study the anxiety response of VR users to audio-visual stimuli and their reaction to visual-sound conflict conditions.

- Data Collection

In this study, we employed the Empatica E4 device to capture and analyze the physiological data of our participants across various conditions and environments. The Empatica E4 is a wearable sensor device capable of measuring parameters such as heart rate, electrodermal activity, skin temperature, and accelerometer data. By utilizing this device, we aimed to obtain objective physiological indicators that could shed light on the participants' experiences.

Furthermore, we utilized the State-Trait Anxiety Inventory (STAI) to assess the participants' stress levels throughout the study. The STAI is a widely accepted and validated self-report questionnaire that measures both state anxiety (temporary emotional condition) and trait anxiety (long-standing predisposition). The inclusion of the STAI allowed us to capture participants' subjective experiences of stress during the different conditions and environments.

Additionally, to evaluate the participants' sense of presence and susceptibility to cybersickness, we administered specific questionnaires designed for these purposes. The presence questionnaire aimed to gauge the extent to which participants felt immersed in the virtual environment. Meanwhile, the cybersickness questionnaire aimed to assess any symptoms of discomfort or sickness experienced during virtual reality exposure.

By incorporating these measures, our study aimed to investigate the potential relationship between stress levels and the sense of presence in virtual reality (VR) experiences. Our hypothesis is that subject stress levels could serve as a new indicator for measuring the sense of presence in VR. Through the integration of physiological data from the Empatica E4 device, stress measurements from the STAI, and responses from the presence and cybersickness questionnaires, we sought to conduct a comprehensive analysis of the data to explore this relationship further.

#### **4.5.3 Phase 3: Defining SOP in Context and proposal of metrics**

- Development of Context-Sensitive Indicators

Stress, as an indicator to measure the sense of presence in Virtual Reality (VR), is based on the notion that when individuals are truly immersed and feel present in a virtual environment, their psychological and physiological responses are similar to what they would be in a similar real-world situation.

Here's how stress can be an indicator of measuring the sense of presence:

- **Psychological Stress Responses:** If an individual's psychological stress responses in a virtual environment are similar to those experienced in real life under similar circumstances, this could indicate a high sense of presence.
- **Physiological Stress Responses:** Physiological responses such as increased heart rate, sweating, and changes in skin conductance can also indicate stress levels. In a virtual environment, if these physiological responses are triggered by events or scenarios that would also cause stress in real life, this can be indicative of a high sense of presence.
- **Behavioral Indicators:** Stress can also be assessed through behavioral indicators. If individuals in a virtual environment exhibit avoidance behavior, startle responses, or other stress-related behaviors that are consistent with how they would react in real life, this could indicate a sense of presence.
- **Self-Reported Stress:** Users can be asked to self-report their stress levels or emotional states while engaged in the virtual environment. This can provide valuable data on how realistically they are responding to the virtual environment, and thus, how present they feel within it.

#### **4.5.4 Phase 4: Introduction and Testing of Metaphors**

- Identification of Metaphors



Using audio-visual conflict as a metaphor to study the effect of environmental sounds and visual elements on VR users' stress levels is an intriguing approach. Audio-visual conflict refers to a situation in which the auditory and visual stimuli in a virtual environment are inconsistent or contradictory. This conflict can be used as a metaphor to understand how discrepancies in sensory information can affect the users' stress levels in VR.

- Testing of Metaphors

To test the effect of our metaphor we designed the environments and procedure as following:

#### Experimental Device and Environments

The VR environments (city and forest) were designed in Unity 3D software and it was carried out in a quiet room and participants were comfortably seated on a chair. We used the HTC Vive Pro headset, tracked by an HTC Vive camera. The headset's resolution was 1440\*1600 pixels per eye with 110 degrees of field-of-view. The device was equipped with, a g-sensor, gyroscope, proximity, and eye comfort setting (IPD). Besides that, we utilized Empatica E4 bracelets for measuring physiological data. To induce or reduce subjects' anxiety we designed different environments such as cities and forests. The city environment is filled with stressful elements such as loud and chaotic city sound coming from cars, ambulance, rain, and also from the barking of a fierce dog. Moreover, the buildings are on fire, heavy rain, and a lot of running pedestrians makes the city looks very crowded imitating a very intense and chaotic city environment. The lighting of the city is set to be a moody and dim environment which let the participants experience nightlife in a chaotic city environment (see Figure.4.32).

On the other hand, the forest environment is designed with a calm forest element including the sound and the visuals of its surrounding. The environment is filled with the sound of the forest, lake, and also wind sound. Moreover, with the presence of the flying birds, participants will be able to hear the sound of flying birds around them in various directions. Besides, it has a hut with a lake view, another hut with a forest view, and also a furnished cabin where all of the elements are connected with a pathway. The lighting of the forest is designed to be a bright environment which lets participants experience a relaxing sunny day in the forest (see Figure. 4.33).

To make sure that each participant spends a fixed time in each environment and passes the same road and faces the same happening in the virtual scenes we developed an automatic navigation system using an animator system instead of using teleportation or other navigation systems. This system allows us to study the fixed effect of the environments on the subjects.

#### Experimental Protocol

Each subject was presented with a set of reference conditions followed by a sound conflict condition. Subjects spent 3.5 minutes per experimental phase. They rest about 2 minutes before entering the other environment. Our experiment is divided into 2 different phases including reference conditions and conflict conditions.



*Figure 4.32. City environment: This environment is loaded with stressful elements like burning buildings, angry dogs, running people, dark smoky rainy weather, and traffic jams.*

#### Reference Condition

In this condition, participants did not perceive any conflict between the visual elements and audio in the city and forest scenes. When participants presented in this condition they perceived the visual elements like fire in the city, barking dogs, and running people with their relative sounds, in the same way, in the forest environment when they observed lake and birds they heard the relative sound of water and sound of the birds.

#### Conflict condition

To investigate subjects' physiological reactions to the audio and also to test the subject's sensitivity to the audio elements in the virtual environment, we designed audio conflict conditions where the sounds of the two environments were interchanged. In this condition, while subjects perceived the visual elements of the chaotic city environment they heard the audio of the forest scene and vice versa.

#### Pre-experiment condition

Before starting the experiment, we asked subjects to sit comfortably on a chair for 10 minutes in a calm environment. After that, we recorded the pre-experiment physiological data of the participants before entering the experiment. During this condition and recording the pre-experimental data we asked subjects to avoid performing sudden acts and movements.



Fig. 4.33. Forest environment: In this environment green elements like trees and plants and other elements like water, mountains, etc. were used to induce calmness in the participants.

#### 4.5.5 Phase 5: Validation of Indicators and Metaphors

- Statistical Analysis

In the following section, we will provide a detailed report of our findings by analyzing the heart rate (HR) data of the participants in different environments and conditions.

In an attempt to compare the different influences of environmental element effects (such as sound and visual) on the subject's HR, we plotted the HR mean of all subjects using a bar plot and also the individual's HR (dots) to monitor the subject's HR alternation due to different conditions.

Figure 4.34 shows the mean value of 12 subjects' heart rates that participated under different experimental conditions. In the reference condition, the mean value of HR in the city environment is (equal to 72.08) higher than the pre-experiment condition (equal to 69.7), while in the forest environment the mean value of HR of 12 participants decreased (equal to 68.6). On the other hand in the conflict condition, changing the audio of the experiment caused to change in the mean value of HR for 12 participants in the environments (see figure 4.34 - Conflict). Compared to reference conditions, in the sound conflict, during the city environment, the subject's HR decreased (mean =70.57), while in the forest environment increased (71.53). However, the one-way repeated measure ANOVA test did not indicate any statistical differences between city and forest environments during different conditions ( $p$ -value  $> 0.05$ ).

As figure 4.34 illustrates, some subjects' behaviors were modified during the conflict condition. Nonetheless, to monitor these changes in the individual's behavior we plotted the HR of each participant.

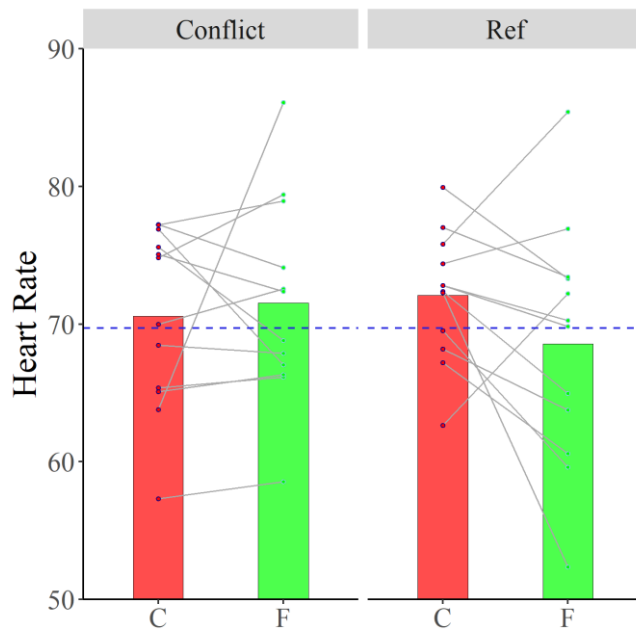


Figure 4.34. Individual's and mean value of HR in the city (C) and forest (F) environment under experimental conditions. The gray line shows the trend of subjects' behavior in city and forest environments.

Figure 4.35 shows typical HR trends produced by one random subject in different environments under experimental conditions. The highest trend for HR is related to the city environment in the Ref condition, while the lowest trend corresponds to the forest environment in the Ref condition. On the other hand, the effect of sound is significantly visible in the city environment during the conflict condition. However, the visual elements in the city environment caused to increase in the HR trend but the effect of sound is eye-catching in this condition compared to the city environment in the Ref condition. Similarly, in the forest environment under conflict condition sound effects leads to incrementing the HR trend.

To investigate the influence of the sound on each subject's behavior figure 4.36 demonstrates an increasing or decreasing trend of HR means value during Ref or Conflict conditions. As figure 4.36 shows 58 % of the subjects in conflict conditions experienced higher HR values in the forest compared to the city, while in the Ref condition they experienced lower HR in the forest compared to the city. On the other hand, 48% of the subjects kept their trend and didn't react to the sound.

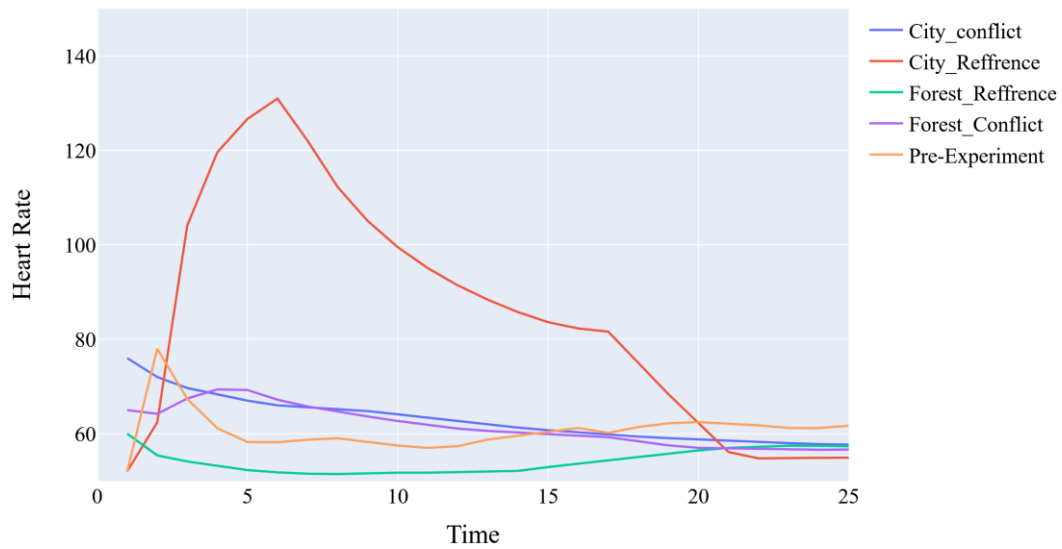


Figure 4.35. The HR trend of one typical subject over time during different experimental conditions.

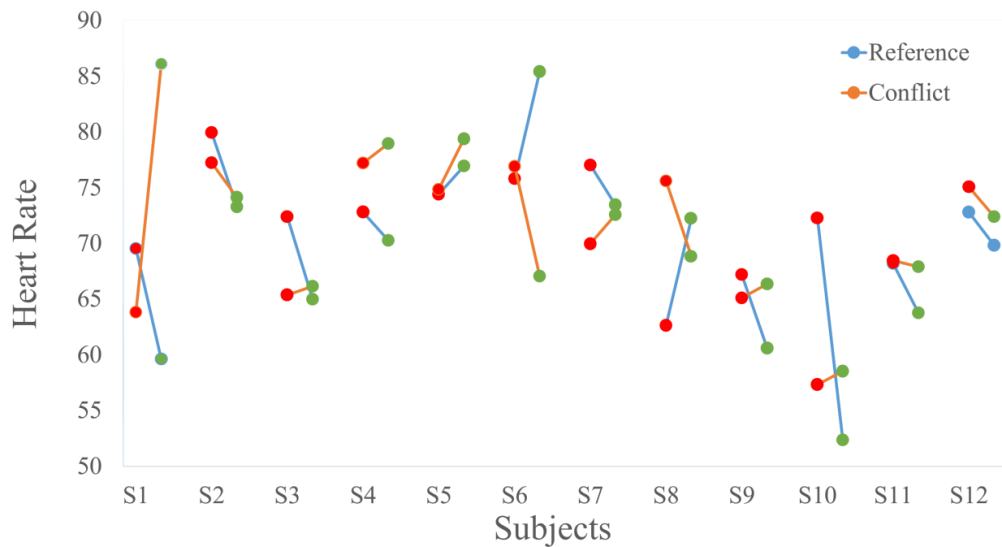


Figure 4.36. Individual's HR behavior in the city (red dots) and forest (green dots). Blue lines indicate subjects' HR modification during reference condition and the orange line represents HR transformation during sound conflict condition.

- Effectiveness of Metaphors

Due to the fact that virtual reality provides the opportunity to separate its users from the real world and transfer them to a virtual one, enhancing user experience in the virtual world has special importance. The main purpose of this research conducted to study subjects' behavior under multi-sensory conflict conditions to understand which sensory

input is more dominant. Moreover, we were interested in pursuing the effect of environmental elements on subjects' stress and anxiety level.

There is a common belief that in a multi-sensory conflict condition visual sensory input is a dominant sensory system. However, some studies (Shams, et al., 2000) (McGurk & MacDonald, 1976) showed that audio input can manipulate the visual sensory system. In this study, we compared the relative effect of sound on individuals' stress and anxiety level by means of the heart rate (HR) of the participants.

Previous studies showed that green environmental elements like the forest can reduce tension and anxiety (Annerstedt, et al., 2013), while (Lederbogen, et al., 2011) showed that the urban environment elevates human anxiety and stress levels. These findings are fundamental to our research. Therefore we tried to induce stress by means of urban environmental elements or decrease it by rural elements. To investigate the influence of the audio in the conflict condition we changed the audio of the city environment with the forest environment and vice versa.

To evaluate our findings we used HR as an objective measurement to quantify our results.

Although the result of the group analysis did not show statistical differences between different environments under both conditions, the trend of elevating HR in the city and demoting HR in the forest environment is attracting attention (see figure 4.34 – Ref). One of the reasons that we didn't observe significant differences between different environments could be due to the lack of participants.

However, the effect of the sound is significantly visible in subjects' HR. Figure 4.36 demonstrated that in conflict conditions subjects react differently to the sound modifications and 42% of them kept their previous behavior under the sound conflict condition while the rest of them were influenced by auditory manipulation. This finding shows that some subjects are more visual dependent in the multi-sensory conflict condition and mostly they rely on their visual input while some of them rely more on their auditory sensory system.

Our results are important findings and could be helpful for VR developers who want to increase the degree of immersion in VR users. By profiling VR users into audio-dependent and visual-dependent groups, they can develop environments and focus on one sensory modality instead of two modalities and gain better results in elevating subjects' sense of presence.

## Chapter 5 Conclusion and Perspective

### CONTENT:

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### 5.1 General conclusion:

This thesis has aimed to provide a comprehensive investigation into the vital concept of "sense of presence" (SoP) in the domain of Virtual Reality (VR). This body of work has demonstrated that SoP is integral to the VR experience and has a direct impact on user pleasure, satisfaction, and perceived benefits.

Over the course of this research, we have detailed the intricate nature of SoP, its definition, classification, and measurement. We discovered that the feeling of 'being there' or personal presence, one of the types of SoP, is fundamental to all forms of VR formats. In addition to the theoretical exploration, a significant portion of this thesis was devoted to devising a context-specific methodology for measuring SoP, addressing the concern that a universal measure could ignore vital individual and environmental factors.

By investigating the influence of individual traits and environmental characteristics on SoP, we discovered that these elements could both enhance and detract from the sense of presence in a virtual environment. Thus, our proposed measurement method takes these factors into account, providing a more accurate and tailored assessment of the SoP.

Answering the research questions postulated at the start of this thesis brings us to a pivotal point in our discussion:

Q1: Is it possible to define a dedicated SOP in the context of the user's experience?

Yes, it is. As this study demonstrates, the SoP, being a context-dependent phenomenon, should not be assessed solely through traditional questionnaire methods. The necessity to explore and develop novel measurement approaches that can capture the immediate, subjective, and context-specific nature of presence has been emphasized. Such methodologies have the potential to provide a richer and more nuanced understanding of presence, aligning with the actual experiences users have within virtual environments. Hence, the development of context-sensitive measures is crucial for the more valid and reliable assessment of presence in VR.

Q2: How to measure SoP?

For this study, the primary focus has been on individual behavior and the sensation of performing specific tasks within particular contexts. We introduced a methodology for quantifying the SoP, which we believe is applicable for different use cases and virtual contexts. A mixed-methods approach has been employed to provide a comprehensive analysis of SoP.

The initial step in this method is to identify the use case of the virtual environment, followed by characterizing and specifying the use case. The subsequent step involves observing users' behavior and defining the SoP in the context of that use case. By defining the SoP within the use case context, we were able to introduce objective or subjective indicators to quantify users' sense of presence.

Q3: How to enhance SoP?



Through this work, we introduced different metaphors as a novel approach to enhance the SoP of VR users. These metaphoric interventions, tailored to the context of the VR experience, have shown promising results in augmenting the SoP, thereby creating a more immersive and engaging VR experience.

The contributions of this work are manifold and advance the field of Virtual Reality (VR) by focusing on the concept of Sense of Presence (SoP). Here are the key contributions:

***Proposal of the concept of adaptive SoP:*** This thesis marks a profound shift in how we understand and interpret the SoP in VR. It presents a conceptualization of SoP as a deeply subjective and context-dependent phenomenon, challenging and moving away from the traditional view of it as a universal or monolithic experience. This fresh perspective emphasizes the unique experiential reality of each individual user, acknowledging that SoP can vary based on numerous factors including the user's engagement with the VR environment, the nature of the tasks they perform, and even the particular moment of their experience. This research opens new pathways for understanding and studying.

***Contextual Measurement Methodology:*** Complementing the novel conceptualization of SoP, a new methodology was proposed for measuring SoP that underscores the importance of the context in which the VR experience takes place. Rather than relying solely on self-reporting questionnaire methods, this approach integrates both subjective and objective indicators to provide a comprehensive understanding of a user's SoP. It considers the individual behaviors and sensations linked to specific tasks within the VR environment, thereby enriching the granularity and depth of SoP measurement.

***Metaphoric Interventions for SoP Enhancement:*** This work has also innovatively introduced the use of metaphoric interventions for enhancing SoP. This new perspective focuses on strategies to deepen the user's engagement and connection with the VR environment rather than concentrating solely on the technical aspects of VR. The metaphoric interventions proposed act as bridges, connecting the user's perception with the virtual world, thus amplifying their SoP.

***Emphasizing Individual Differences:*** The research has recognized and underscored the importance of individual differences in experiencing SoP. It brings attention to the user's personal traits and abilities that can affect their sense of presence, thereby suggesting that VR experiences should be more personalized, adapting to the unique requirements of each individual.

***Multidimensional Exploration of SoP:*** The study embarked on a multifaceted exploration of SoP, delving into different types of presence such as personal, social, and environmental. This comprehensive approach broadens our understanding of the concept of SoP and its various dimensions.

***Experimental Validation:*** The research has also included an experimental validation of the proposed methods. This robust validation serves as a solid foundation for future researchers to apply, test, and further develop these methodologies.

***Foundational Contribution to VR Applications:*** By enhancing the understanding, measurement, and amplification of SoP, this work contributes new insights to VR. This

knowledge could potentially have far-reaching implications for a variety of applications in sectors such as education, healthcare, entertainment, and beyond.

### 5.2 Limitation:

This research, although extensive and thorough, does come with some inherent limitations when it comes to the evaluation and development of SOP measurement and enhancement methods.

1. **The Complex Nature of Subjectivity:** We have emphasized throughout that SOP is an intensely subjective experience, with variations across different individuals. Despite our best efforts to create a comprehensive measurement methodology, certain aspects of the SOP experience may remain unaccounted for or not fully represented due to this inherent subjectivity.
2. **Emphasis on Individual Differences:** Although recognizing individual differences is a strength of this study, it also presents a challenge as it complicates measurement outcomes and can introduce potential variability. Our findings might not be universally applicable and might need careful individual-specific interpretation.
3. **Time Constraints:** Due to the time constraints of a thesis project, some aspects of the research might not have been explored as deeply as they could have been. The development and refinement of our proposed methods may require further iterative research and long-term studies to fully validate and optimize them.

Despite these limitations, it's important to note that this research contributes to the understanding, measurement, and enhancement of SoP, serving as a valuable groundwork for future researchers to build upon.

### 5.3 Perspective and Future work:

There is a wide range of possibilities and opportunities for our next steps in this fascinating journey into VR's heart. In this thesis, we established proposals that will allow us to delve deeper and explore further. We will focus our future research on two areas.

We plan to incorporate machine learning and data analysis techniques to enhance the virtual environment's 'sense of presence'. Due to its powerful predictive and analytical capabilities, machine learning can help us understand users' behavior patterns and preferences. In this way, an adaptive virtual environment can be created which adjusts in real time, increasing the SoP by providing a more personalized and immersive VR experience.

Our ability to gain meaningful insights from user-generated data can further assist us in fine-tuning VR environments and experiences. As we continue to refine our methodologies, we can produce more precise SoP measurements and a more engaging user experience.

Our second research focus will be on VR experiences that promote multi-sensory conflict. It is possible for users to experience discrepancies between their seeing and feeling in a virtual environment as the result of multi-sensory conflict. VR's immersive illusion can be disrupted by these conflicts, so resolving them is crucial to improving the system.

The VR experience can be enhanced if we improve our understanding of how to resolve sensory conflicts. By doing so, we can offer users a seamless and captivating virtual experience that is more convincing, , and immersive. Our investigation will involve various techniques and methodologies for identifying, mitigating, and resolving these conflicts. We can create multi-sensory experiences that are harmonious by developing dynamic, adaptive systems that respond in real-time.

In future research endeavors, it would indeed be highly beneficial to conduct comparative studies using various technical devices, including different types of VR headsets. Each headset comes with unique specifications, designs, and weights, all of which can subtly or substantially influence the user's experience and sense of presence in a virtual environment. For instance, the comfort level, field of view, resolution, and even the weight distribution of a headset can play crucial roles in how users perceive and interact with virtual objects, potentially affecting the efficacy of pseudo-haptic feedback mechanisms.

By extending the study to encompass a variety of devices, we would be able to gain deeper insights into how these factors interplay with users' muscular morphology and contribute to or detract from the sense of presence. Understanding these dynamics can pave the way for more personalized and optimized virtual reality experiences, taking into account the diverse needs and preferences of users.

In subsequent studies, we plan to incorporate these elements, comparing and contrasting the results obtained from different devices. This approach will not only help to validate the robustness and generalizability of our findings but also shed light on the device-specific considerations that practitioners and developers need to take into account when implementing pseudo-haptic feedback in virtual reality applications.

For the world of virtual reality, these are indeed exciting times! By combining machine learning, data analysis, and a focus on multisensory conflicts, we are confident that we can continue to move the field forward and create even more compelling, immersive, and satisfying VR experiences. So, let's continue this journey together, pushing the boundaries of what's possible, and revolutionizing how we interact with virtual worlds.

### **5.4 Scientific publications:**

The research results were presented in the following scientific publications, including journals and international conferences and some of them are under review and under manuscript:

#### **Journal Paper**

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1. **Moosavi, M.S., Raimbaud, P., Guillet, C., Plouzeau, J. and Merienne, F., 2023.** Weight perception analysis using pseudo-haptic feedback based on physical work evaluation. *Frontiers in Virtual Reality*, 4, p.973083. DOI : <https://doi.org/10.3389/frvir.2023.973083>
2. **Moosavi, M et al. 2022,** Enhancing Weight Perception in Virtual Reality: An Analysis of Kinematic Features . Manuscript submitted for publication to *Journal of Virtual reality*. (Submitted)

3. **Moosavi**, M, Guillet , C. Pozzo , T. , Merienne, F. (2021) defining an objective measurement of the immersion based on hand kinematic data [*Under manuscript*].Institute Image , École nationale supérieure d'arts et métiers (ENSAM)
4. **Moosavi**, M, Guillet , C. Hu, Y. Merienne, F. (2021) The Influence of Audio Sensory Input on the Anxiety Level of the VR Users toward EEG analysis [*Under manuscript*].Institute Image , École nationale supérieure d'arts et métiers (ENSAM)

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# A. Appendix : Résumé substantiel en langue française

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## A.1 Introduction :

Au fil des âges, les humains ont toujours rêvé de saisir et de refléter la réalité. Les artistes ont exprimé ce désir de diverses manières - dans la littérature, la peinture, la sculpture, le théâtre et l'opéra. La représentation des personnes est devenue plus populaire ces dernières décennies grâce à la photographie, au cinéma et à la télévision. Avec les progrès rapides de la puissance de calcul, des graphiques informatiques interactifs, des écrans immersifs et de la transmission numérique, nous sommes capables de simuler la réalité avec une telle fidélité qu'il est difficile de distinguer ce qui est réel de ce qui ne l'est pas. Peu importe à quel point nos technologies de représentation évoluent, leur véritable valeur est intrinsèquement liée aux attentes, aux engagements et aux réactions de leurs utilisateurs. À l'instar du Picturephone dans les années 1970, la technologie a échoué parce qu'elle ne répondait pas aux besoins des utilisateurs ou n'ajoutait pas de valeur à leurs expériences. La mesure de ces expériences et réactions n'est pas seulement importante, elle est essentielle. D'une part, cela nous guide vers des directives de conception qui rendent les technologies de représentation plus faciles à utiliser. D'autre part, cela facilite le développement de méthodes de mesure psychologique fiables, valides et robustes. Nous pouvons développer une compréhension théorique complète et mener des investigations empiriques des constructions pertinentes en explorant les mécanismes qui guident les expériences et les réactions des utilisateurs en utilisant ces méthodologies. Tant que nous restons concentrés sur ces deux piliers, nous pourrions suivre l'évolution des besoins des utilisateurs. Dans la réalité virtuelle (RV), les expériences sont fortement influencées par le sentiment de "présence", qui à son tour gouverne le plaisir, la satisfaction et les bénéfices. Comme le dit (Sheridan, 1992), la présence est le sentiment d'être physiquement présent à travers des affichages visuels, auditifs ou de force générés par ordinateur. Cet état psychologique se produit lorsque les utilisateurs oublient que les médias qu'ils perçoivent proviennent de la technologie, ou même lorsqu'ils ont l'impression que c'est une extension de leur corps (IJsselsteijn, 2004). Dans le domaine virtuel, un sens puissant de présence amplifie le sentiment d'immersion de l'utilisateur, lui permettant d'agir comme il le ferait dans le monde réel. De plus, la présence se présente sous trois formes : personnelle, sociale et environnementale (Schuemie, et al., 2001). La présence personnelle se rapporte au sens individuel d'"être là", tandis que la présence sociale et environnementale englobe la perception qu'a un individu de l'environnement virtuel - ses habitants ou la réactivité de l'environnement. L'un des principaux axes de cette recherche est la notion de présence personnelle, qui est la plus basique et universellement applicable à tous les types de formats de RV. Considérant que la présence est principalement une expérience subjective, c'est un concept difficile à définir et une condition difficile à mesurer. Au cours des dernières décennies, les chercheurs ont étudié la présence en profondeur et ils ont découvert qu'elle a de nombreuses facettes. En tant qu'outil de mesure auto-déclaré pour quantifier la présence, (Schubert, et al., 1999) ont développé le questionnaire de présence de l'Igroup. (Sheridan, 1992) soutient que la présence est un concept subjectif qui ne peut pas être facilement défini ou mesuré d'un point de vue physiologique. Bien que Sheridan ne rejette pas les mesures objectives de la présence, il indique que les rapports subjectifs sont la mesure de base la plus utile de la présence (Sheridan, 1992). En fonction des différences individuelles et des caractéristiques des EV, nous pensons que le degré de présence ressenti dans un EV varie. La présence d'un EV donné peut être influencée par les caractéristiques, traits et capacités de l'individu. De même, diverses caractéristiques de l'EV peuvent améliorer le sentiment de présence, interférer avec lui ou le diminuer. Compte tenu de ces différences, les mesures de présence devraient être conçues de manière à prendre en compte à la fois les caractéristiques de l'EV et leurs différences individuelles.

Il y a eu des progrès significatifs dans la technologie de la Réalité Virtuelle (VR), entraînant un changement de paradigme significatif dans divers domaines, y compris l'éducation, les soins de santé, le divertissement, et plus encore. En tant que fondement de ces applications, le "sentiment de présence" (SoP) fait référence à l'expérience subjective d'être présent dans un environnement virtuel. Malgré le rôle fondamental joué par le SoP en VR, la recherche est toujours en cours sur comment le mesurer et l'améliorer avec précision. Cette thèse présente une nouvelle méthode pour mesurer le SoP en VR, ainsi que des stratégies qui peuvent être utilisées pour l'améliorer, avec un accent particulier sur les interventions métaphoriques. La recherche suggère que les facteurs environnementaux et les expériences individuelles ont des influences significatives sur le SoP perçu, malgré le fait que le SoP soit contextuellement dépendant ne soit pas universellement reconnu. Nous soutenons qu'une approche de mesure universelle du SoP pourrait négliger des nuances critiques et des interprétations subjectives de l'expérience VR, qui sont souvent spécifiques au contexte. Cette question est abordée en proposant une méthodologie pour mesurer le SoP de manière objective, basée sur le contexte de la RV. De plus, améliorer le SoP est essentiel pour améliorer l'engagement des utilisateurs et l'efficacité globale des applications VR. Contrairement à de nombreux travaux de recherche, qui se concentrent principalement sur l'amélioration des aspects technologiques de la VR, notre travail suggère des interventions métaphoriques comme une perspective intéressante. Nous émettons l'hypothèse que ces interventions, adaptées au contexte de la VR, peuvent augmenter significativement le SoP et créer une expérience utilisateur plus immersive et significative.

### **Contributions :**

Cette thèse, consacrée à l'exploration et à l'avancement du Sens de Présence (SoP) en Réalité Virtuelle (RV), a pour objectif principal le développement de nouvelles conceptualisations, méthodologies et interventions pour le SoP, qui renforceront l'immersion des utilisateurs dans les environnements virtuels. Le champ d'application de ce travail traverse plusieurs domaines, notamment les fondements théoriques du SoP, sa nature dépendante du contexte, l'expérience personnalisée, et une validation empirique des approches développées. Nos propositions ont pour ambition d'explorer les questions du sens de présence et contribuer par une vision synthétique du problème. Nous allons introduire une série d'efforts de recherche, y compris le développement théorique, les études sur les utilisateurs, et la validation pratique, afin de construire un SoP plus adapté au contexte. À la lumière de cela, la thèse apporte plusieurs contributions concernant les développements scientifiques et techniques :

- Revue approfondie de la littérature sur le SoP en RV, y compris ses différents types et impacts sur l'engagement et l'expérience des utilisateurs. Établissement d'une nouvelle méthode pour évaluer le SoP, prenant en compte les comportements individuels et les sensations spécifiques à la tâche tout en abordant les déficiences des mesures existantes. Nous développons des interventions métaphoriques pour améliorer le SoP, une approche novatrice qui privilégie l'engagement des utilisateurs et les expériences immersives par rapport aux aspects techniques de la RV.

- Un examen rigoureux du rôle des différences individuelles dans le SoP, soulignant la nécessité d'expériences en RV personnalisées qui répondent aux traits et capacités uniques des utilisateurs.

- Une validation empirique des méthodes proposées, fournissant une base solide pour que les futurs chercheurs puissent appliquer, tester et affiner davantage ces approches.



- Des contributions substantielles aux applications de la RV, en améliorant la compréhension, la mesure et l'amélioration du SoP, et potentiellement en impactant un large éventail d'applications, comme l'éducation, les soins de santé, le divertissement, et plus encore.

### **Structure de la Thèse :**

Un aperçu de la structure de la thèse est fourni ci-dessous, résumant chaque chapitre et son contenu :

Chapitre 2 - Revue de la littérature : Dans ce chapitre, nous menons une revue de la littérature complète sur le sens de l'immersion, la présence, et les méthodes pour mesurer le sens de la présence des sujets en réalité virtuelle. Nous analysons les méthodologies actuelles et leurs inconvénients, établissant ainsi le contexte de l'approche innovante que nous proposons dans les chapitres suivants.

Chapitre 3 - Proposition de méthodologie : Sur la base des comportements individuels, de la tâche à réaliser en RV et de l'environnement RV, nous proposons une méthodologie pour définir, mesurer et améliorer le sens de présence en RV. Nous utilisons des métaphores spécifiques pour améliorer la présence dans le cadre de cette méthodologie.

Chapitre 4 - Études expérimentales : Ce chapitre décrit comment la méthodologie proposée a été testée dans une variété de contextes de RV. Notre méthodologie est évaluée à l'aide de preuves empiriques, qui soutiennent son efficacité.

Chapitre 5 - Conclusions et Perspective : Le dernier chapitre fournit un résumé de nos conclusions générales et une perspective sur les travaux futurs résultant de cette thèse. Nous discuterons des extensions potentielles de la recherche, des améliorations possibles de la méthodologie proposée, et des nouvelles pistes d'exploration offertes par nos résultats. En déroulant séquentiellement notre étude sur le SoP en RV, de la revue de la littérature, de la proposition de méthodologie, de la conception et de l'exécution expérimentales, jusqu'aux conclusions finales et aux perspectives futures, nous visons à construire une compréhension complète du SoP et de son amélioration dans les environnements immersifs.

## **A.2 Etat de l'art :**

### **Aperçu de la littérature pertinente sur l'immersion virtuelle, le sens de présence, et les différences individuelles dans la perception et la cognition**

#### **Immersion et Sensation de Présence**

La technologie VR, remontant aux années 1960 avec l'introduction du Telesphere Mask de Morton et du Sensorama (Bown, et al., 2017), a évolué de manière significative au fil des ans, devenant plus accessible et diversifiée dans ses applications, qui vont du divertissement et de l'éducation à la visualisation scientifique et aux simulations de formation (Hamad & Jia, 2022). La VR peut être largement catégorisée en expériences immersives et non immersives (Wohlgenannt, et al., 2020). La VR non immersive entoure généralement l'utilisateur d'écrans affichant des informations virtuelles, tandis que la VR immersive utilise des affichages portables (comme des casques) qui suivent le mouvement de l'utilisateur et présentent des

informations VR en fonction de la position de l'utilisateur, permettant une immersion totale à 360 degrés dans l'environnement virtuel (Slater & Sanchez-Vives, 2014).

L'aspect clé de la VR est la création d'une expérience réaliste, faisant sentir aux utilisateurs qu'ils sont pleinement engagés et faisant partie du monde virtuel (Coelho, et al., 2006). Cela est réalisé grâce à l'immersion, qui donne un sentiment de présence dans l'environnement virtuel. Le SoP est généralement considéré comme un facteur crucial en VR, affecté par diverses caractéristiques des médias et des utilisateurs (Schubert, et al., 2001).

Les caractéristiques des médias peuvent être liées à la forme des médias, comme la façon dont l'information sensorielle est obtenue et manipulée, et au contenu des médias qui inclut des objets, des acteurs ou des événements. Les caractéristiques des utilisateurs peuvent aller de facteurs démographiques tels que l'âge et le sexe à des capacités cognitives, des expériences antérieures et des préférences personnelles (Baños, et al., 2004). Plus l'environnement virtuel est immersif et réaliste, plus le sentiment de présence est élevé.

De plus, l'immersion et le SoP peuvent avoir un impact sur les réponses cognitives et émotionnelles de l'utilisateur (Cadet & Chainay, 2020). Une immersion élevée et une crédibilité peuvent améliorer le rappel de mémoire de l'expérience et même influencer les attitudes et les comportements dans le monde réel.

Malgré les progrès dans la compréhension de l'immersion et du SoP, il existe des limitations, comme les différences individuelles dans les expériences sensorielles et les attentes, qui peuvent affecter le degré d'immersion et de SoP (Loomis, et al., 1999). Des recherches supplémentaires sont nécessaires pour explorer les effets à long terme de ces facteurs sur le comportement et les attitudes des utilisateurs.

Différents cadres ont été proposés pour comprendre les facteurs influençant le SoP, mettant l'accent sur diverses dimensions comme l'immersion sensorielle, l'implication émotionnelle, l'absorption cognitive, l'interactivité, la fidélité sensorielle, le récit et la socialité (Heeter, 1992); (Slater & Wilbur, 1997); (Lombard & Ditton, 1997); (Biocca, 1997); (Witmer & Singer, 1998); (Loomis, et al., 1999).

Enfin, il convient de noter que si certaines études proposent que la présence est déterminée par le degré de réalisme d'un médium (Heeter, 1992); (Welch, et al., 1996) (Lombard & Ditton, 1997); (Bystrom, et al., 1999), les définitions traditionnelles du SoP mettent l'accent sur l'expérience d'être présent dans un environnement médiatisé. Cela montre que le concept du SoP en VR est multifacette, et une simple définition pourrait ne pas capturer toutes ses complexités.

### **La perception et la cognition individuelles**

La perception et la cognition individuelles sont essentielles à la manière dont les gens interprètent et interagissent avec leur environnement. La perception concerne l'interprétation des données sensorielles, tandis que la cognition englobe les procédures mentales impliquées dans la pensée, la résolution de problèmes et la prise de décisions. La différenciation entre les états perceptifs comme voir un objet ou entendre un son, et les états cognitifs comme discerner la justesse de la justice, est cruciale (Beck, 2018). Plusieurs facteurs influencent la perception, y compris les composants environnementaux physiques (Luppicini, 2003), les expériences antérieures (Robinson, et al., 1964), et le contexte culturel (Bossuoy, et al., 2014). Les

processus cognitifs tels que l'attention, la mémoire, la perception, le langage et le raisonnement sont vitaux pour l'interprétation des informations et la résolution de problèmes (Brown & Gallimore, 1995). Les différences individuelles en cognition influencent de manière significative la façon dont les gens perçoivent et interagissent avec le monde.

Le domaine de la réalité virtuelle (VR) offre une plateforme unique pour l'étude de la perception et de la cognition individuelles. La VR fournit un environnement où les chercheurs peuvent manipuler l'information sensorielle reçue par les participants. La qualité des visuels et de l'information auditive, le niveau d'immersion et de présence ressentis par l'utilisateur, et les expériences antérieures de l'individu avec la VR sont tous des facteurs qui influencent la perception en VR (Billger, et al., 2004). Les indices émotionnels en VR dépendent des simulations perceptuelles, mais des études récentes suggèrent que l'incorporation d'éléments narratifs en VR peut améliorer les expériences émotionnelles (Bouchard, et al., 2008); (Gorini, et al., 2011); (Mühlberger, et al., 2012) (Peperkorn & Mühlberger, 2013). Les exigences cognitives, les niveaux d'engagement, l'interactivité de l'environnement VR, et l'expérience préalable avec des tâches similaires influencent la cognition en VR. Par exemple, les individus ayant une expérience de jeux vidéo pourraient mieux performer dans des tâches nécessitant une navigation spatiale et une résolution de problèmes.

La cognition joue un rôle crucial dans les expériences VR, influençant la perception de l'utilisateur et l'interaction avec l'environnement virtuel (Sreena & Ilankumaran, 2018). Des facteurs tels que l'interactivité, l'imagerie complexe, l'audio 3D, et le suivi de la tête sont cruciaux pour une immersion profonde (Pimentel & Teixeira, 1993). La charge cognitive, ou l'effort mental requis pour une tâche, peut influencer l'engagement et la performance de l'utilisateur. Si la charge est trop élevée, les utilisateurs peuvent se sentir dépassés et se désengager; si elle est trop faible, l'ennui pourrait s'installer (Bueno-Vesga, et al., 2021). Les attentes et les croyances de l'utilisateur concernant les expériences en VR peuvent également avoir un impact sur leurs perceptions et leurs interactions avec l'environnement (Makransky & Petersen, 2021). Les facteurs cognitifs peuvent également affecter l'expérience émotionnelle en VR, les interprétations et évaluations des utilisateurs de l'environnement VR influençant leurs réponses émotionnelles (Sas & O'Hare, 2003). Critchley (Critchley, et al., 2000) a suggéré que des mesures physiologiques comme l'activité électrodermale (EDA) pourraient être utilisées pour évaluer les effets émotionnels liés aux états cognitifs. Comprendre les aspects multiples de la perception et de la cognition en VR peut aider à créer des expériences VR plus engageantes et efficaces.

### **L'évaluation de l'immersion et du sentiment de présence en réalité virtuelle (RV)**

L'évaluation de l'immersion et du sentiment de présence en réalité virtuelle (RV) a principalement employé deux méthodes : les mesures subjectives et objectives. Les mesures subjectives s'appuient sur les expériences et les émotions auto-rapportées, généralement recueillies par le biais de questionnaires ou d'entrevues après l'exposition aux stimuli de la RV (Oliveira, et al., 2018); (Trindade, et al., 2018); (Estupiñán, et al., 2014); (Ma, et al., 2018); (Livatino & Koffel, 2007). Cependant, cette approche est souvent influencée par des biais individuels et des facteurs situationnels. En revanche, les mesures objectives dans les évaluations de la RV, qui incluent des réponses comportementales et physiologiques, présentent une alternative plus quantifiable et moins intrusive (Coelho, et al., 2006). Par exemple, des changements de rythme cardiaque ou de conductance cutanée pendant l'exposition de l'utilisateur aux stimuli de la RV peuvent fournir des informations précieuses sur l'état cognitif et émotionnel de l'utilisateur (Oliveira, et al., 2018).

Néanmoins, les mesures objectives ont leurs propres limites. Par exemple, les réponses physiologiques ou comportementales peuvent être interprétées différemment en fonction du contexte, et nombre de ces mesures nécessitent des outils spécialisés, augmentant la complexité et le coût de la recherche. Les mesures comportementales, bien que précieuses, peuvent ne pas capturer pleinement la complexité des expériences du monde réel, se concentrer sur des aspects étroits de l'expérience utilisateur et fournir un aperçu limité des expériences subjectives (Anderson, et al., 2013); (Tio, et al., 2019); (Orne, 1962); (Wallach, et al., 2009); (Rock, et al., 2022). Les mesures physiologiques, bien qu'elles puissent être invasives ou inconfortables, peuvent être coûteuses et longues à administrer, et sont généralement limitées à des réponses physiologiques spécifiques (Clemente Bellido, 2014); (Sadowski & Stanney, 2002).

Par ailleurs, les mesures subjectives, malgré leur vulnérabilité aux biais personnels et au biais de réponse, offrent des informations précieuses sur les pensées et les sentiments des utilisateurs (Slater, 2003). Cependant, ces mesures ne sont efficaces que si l'utilisateur est capable d'exprimer avec précision ses expériences. Des méthodes couramment utilisées, comme les questionnaires, peuvent être influencées par le biais de réponse ou le biais de désirabilité sociale, et négligent souvent d'autres aspects cruciaux de l'expérience en RV, tels que l'engagement émotionnel ou la présence spatiale (Slater, et al., 1998); (Slater & Usoh, 1993) (Usoh, et al., 2000) (Graf & Schwind, 2020); (Kaminska & Foulsham, 2016); (Tcha-Tokey, et al., 2016). En conséquence, l'évaluation de l'immersion et du sentiment de présence en RV nécessite une approche équilibrée qui combine les points forts des mesures objectives et subjectives tout en étant consciente de leurs limites.

## **Révision des modèles existants d'interaction en VR et de leurs limitations :**

### **Manipulation directe:**

La manipulation directe est un modèle d'interaction répandu dans la réalité virtuelle (RV), permettant aux utilisateurs de s'engager avec des objets virtuels d'une manière qui simule l'interaction du monde réel. Comme décrit par (Shneiderman, 1982), ce concept comprend une représentation précise de l'objet, des actions tangibles ou des boutons étiquetés pour remplacer la syntaxe complexe, et des opérations rapides, incrémentales et réversibles reflétant leur impact sur l'objet. Ces propriétés se retrouvent également dans des applications telles que les jeux vidéo et les systèmes de conception assistée par ordinateur. La manipulation directe renforce l'immersion et la présence, car elle permet aux utilisateurs de sentir le poids des objets, d'expérimenter des contraintes virtuelles et de percevoir les interactions avec les objets virtuels comme authentiques (Bryson, 2005). De plus, les changements de position ou d'orientation des objets peuvent fournir des informations dans l'environnement virtuel, comme le démontrent les recherches de (Zhao, et al., 2017) et (Lopes, et al., 2015).

Cependant, la manipulation directe en RV a aussi ses limites. L'un des principaux défis est l'absence d'attributs physiques tels que le poids et la texture dans les objets virtuels, ce qui peut conduire à la frustration et la confusion de l'utilisateur (Sutcliffe & Kaur, 2000). Les contraintes spatiales limitent également la capacité à interagir physiquement avec les objets virtuels, surtout dans des environnements encombrés ou étroits (Slater & Usoh, 1993). Enfin, l'effort physique requis pour des manipulations directes prolongées pourrait entraîner de la fatigue et de l'inconfort, détournant le sujet de l'expérience globale de la RV (Bowman & Wingrave, 2001).

### **L'interaction basée sur les gestes:**

Un autre modèle d'interaction significatif en RV est l'interaction basée sur les gestes, qui implique l'utilisation de mouvements physiques, principalement les mains et les doigts, pour interagir avec les appareils numériques. Cette interaction a été présentée dans des consoles de jeux comme la Nintendo Wii et la Xbox Kinect, et des smartphones tels que l'iPhone d'Apple et la série Galaxy de Samsung (Saffer, 2008). L'interaction basée sur les gestes est considérée comme flexible et intuitive, trouvant des applications en RV, les commandes robotiques, et la réalité augmentée (Norman, 2010). Diverses recherches, comme celles de Céspedes-Hernández et al. (2018), (Pop & Sabou, 2017), et (Raees & Ullah, 2019), ont utilisé l'interaction basée sur les gestes pour améliorer la présence et l'expérience utilisateur en RV, ouvrant la voie à un développement supplémentaire dans ce domaine (Yang, et al., 2019).

### **Retour haptique :**

Le retour haptique en Réalité Virtuelle (RV) a humanisé et rendu nos interactions avec les environnements virtuels plus tangibles en simulant un retour tactile et/ou de force (Burdea & Coiffet, 2003). Il offre un sentiment d'immersion et d'authenticité accru dans le monde virtuel et conduit à des interactions plus réalistes avec les objets virtuels (Kuchenbecker, et al., 2006). Cette forme de retour simule les sensations de toucher ou de résistance des objets physiques à travers des vibrations ou des signaux de pression en utilisant des dispositifs portables tels que des systèmes portables ou des gants de données (Sato, et al., 2007). La profondeur et le réalisme des environnements de RV sont renforcés lorsque le retour haptique est combiné avec des indices visuels et auditifs (Srinivasan & LaMotte, 1995). Des avancées technologiques comme les moteurs de vibration, les capteurs de force, et les actionneurs électro-tactiles ont conduit au développement du retour haptique en réalité virtuelle. Ces technologies sont intégrées dans des dispositifs portables ou des contrôleurs pour donner aux utilisateurs des sensations tactiles similaires à celles éprouvées dans le monde réel (Wang, et al., 2006).

De nombreux travaux ont étudié l'effet du retour haptique sur l'expérience en RV. Mousavi et al. (Mousavi & Aziz, 2008) ont fourni un examen complet de la technologie de retour haptique pour les applications de RV dans l'industrie manufacturière, soulignant les avantages potentiels pour l'amélioration du réalisme et de l'utilisabilité. Kreimeier et al. (Kreimeier, et al., 2019) ont exploré l'effet de différents types de retour haptique sur les performances et la présence de l'utilisateur dans les environnements de RV, constatant que les dispositifs combinant à la fois le retour tactile et kinesthésique donnent les meilleures performances. De manière similaire, Lécuyer et al. (Lécuyer, et al., 2004) ont constaté que le retour haptique améliorait significativement la perception de mouvement humain dans les environnements de RV.

Cependant, malgré son importance, le retour haptique présente plusieurs défis. (Burdea, 2000) a discuté de ces problèmes comprenant les problèmes de latence (Azmandian, et al., 2016), les contraintes de résolution (Culbertson, et al., 2018), la complexité d'utilisation (Jones & Berris, 2002), les difficultés d'intégration (Prattichizzo, et al., 2012), le coût élevé (Minsky, 1995), la complexité technique (Follmer, et al., 2012), l'inconfort (Jang, et al., 2016), l'effet de la vallée de l'étrange (Berger, et al., 2018), les limitations inhérentes (Brooks Jr, 1999), et les défis concernant la perception du poids dans les environnements virtuels (Ernst & Banks, 2002); (Aman, et al., 2010). Chacun de ces facteurs peut potentiellement perturber l'immersion virtuelle des expériences de RV et présenter des obstacles à une adoption plus large de la technologie de RV.

### **Interaction multisensorielle :**

Notre système sensoriel, composé de la vue, de l'ouïe, de l'odorat, du goût et du toucher, est crucial pour notre survie, notre communication et notre compréhension de l'environnement. Chaque sens fournit un canal d'information unique et vital : la vue nous permet de percevoir notre environnement (Ackerman, 2018), l'ouïe nous permet de détecter les vibrations et les changements de pression (Moore, 2012), l'odorat et le goût contribuent significativement à notre plaisir de manger (Shepherd, 2006), et le toucher facilite notre interaction avec le monde (Gallace & Spence, 2014). Notre cerveau intègre les informations sensorielles de ces différentes sources pour créer une représentation cohérente et complète de notre environnement (Stein, et al., 2014).

La réalité virtuelle (VR) améliore le modèle existant d'interaction en simulant un environnement multisensoriel. Des écrans haute définition et des environnements audio 3D reproduisent les expériences visuelles et auditives, tandis que les dispositifs de retour haptique permettent aux utilisateurs de sentir le monde virtuel. Bien que plus difficile, il existe des recherches émergentes qui tentent de recréer le goût et l'odeur en VR (Lee & Xu, 2000). Des études suggèrent que l'intégration de la vue et du toucher dans la VR renforce l'immersion et a des applications potentielles dans le divertissement, l'éducation et la formation médicale (Wu & others, 1996). Choi et al. (2016) ont constaté que des retours visuels et tactiles cohérents renforçaient l'illusion de la main virtuelle, suggérant une voie pour améliorer la conception de la VR.

Une plateforme de VR intégrant la vue, le son et le toucher a été développée et testée, révélant des utilisations potentielles dans de multiples domaines (Noccaro, et al., 2020). D'autres études ont découvert des liens entre l'intégration multisensorielle et les expériences de VR telles que l'instabilité de scène, la présence et le cybermalaise (Kim & others, 2020). Bien que la présence multisensorielle dans la VR soit très prometteuse, des limitations existent dans la simulation de certains sens et l'obtention d'une synchronisation en temps réel des retours visuels, auditifs et haptiques (Fröhlich & Wachsmuth, 2014). Des avancées futures dans les systèmes de retour sensoriel sont nécessaires pour progresser davantage dans ce domaine.

### **Le Conflit Multi-Sensoriel (CMS) :**

Le Conflit Multi-Sensoriel (CMS) est une divergence entre les entrées sensorielles qui peut distordre la perception d'un individu, potentiellement provoquant une surcharge cognitive, le mal des transports, et la désorientation (Howard & Templeton, 1966) (Reason & Brand, 1975). D'un point de vue neuroscientifique, le CMS résulte de la difficulté du cerveau à réconcilier les différentes entrées sensorielles pour former une perception cohérente (Ernst & Bühlhoff, 2004)

Dans la Réalité Virtuelle (RV), l'objectif est d'harmoniser les stimuli visuels, auditifs, haptiques et parfois olfactifs pour créer une expérience cohérente. Cependant, le CMS peut perturber cette cohérence, causant un inconfort ou détruisant l'illusion de présence (Sanchez-Vives & Slater, 2005). Ces divergences, comme le décrivent (Meehan, et al., 2002), peuvent être soit inter-sensorielles (entre les sens) soit intra-sensorielles (au sein du même sens). Le CMS peut entraîner un "cybermalaise", similaire au mal des transports, avec des symptômes telles que la désorientation, la nausée et la fatigue oculaire (Keshavarz & Hecht, 2011); (LaViola Jr, 2000). De plus, le CMS peut induire des effets cognitifs négatifs comme une diminution de la conscience spatiale et de la mémoire, et ces effets peuvent persister même après avoir quitté l'environnement VR (Stanney, et al., 1997); (Duh, et al., 2004).

La RV utilise également des métaphores pour créer des environnements abstraits qui stimulent les fonctions cognitives et affectives des utilisateurs, résultant en des interactions plus intuitives et significatives (Slater & Sanchez-Vives, 2016); (Heeter, 1992). Les expériences métaphoriques en RV, en fournissant un cadre d'interaction alternatif, peuvent réduire le CMS, car toute divergence sensorielle s'aligne mieux avec l'expérience globale de l'utilisateur (Brade, et al., 2017). Ces interfaces métaphoriques, par exemple, peuvent décrire le mouvement et l'interaction, permettant aux utilisateurs de "voler" à travers un environnement VR, compensant ainsi le manque de mouvement physique détecté par le système vestibulaire (Jones & Tan, 2013). Elles peuvent également aider à décharger la cognition, conduisant à une réduction de la charge cognitive et à une amélioration de l'immersion (Risko & Gilbert, 2016).

### **A.3 Méthodologie**

#### **Problématique Scientifique :**

Dans ces travaux, nous proposons de considérer que la présence en réalité virtuelle (RV) est bien plus que le simple fait d' "être là". Comme la technologie de la RV est devenue répandue, il est devenu plus facile d'immerger les utilisateurs dans un environnement virtuel (EV). À cet égard, les jugements sur le réalisme des EV deviennent plus importants. La méthode traditionnelle de mesure du Sens de la Présence (SOP), le questionnaire, ne capte pas la nature globale et contextuelle du SOP. Selon la nature contextuelle du SOP, il est étroitement lié à l'environnement et aux expériences individuelles. Par conséquent, l'utilisation de méthodes généralisées telles que les questionnaires rendrait difficile une bonne évaluation et compréhension du SOP. La conception des questionnaires implique qu'ils sont destinés à généraliser les expériences sur un large éventail de contextes et de profils d'utilisateurs. Il est vrai qu'ils peuvent fournir une mesure quantitative simple, mais ils échouent généralement à capturer la nature individuelle et contextuelle spécifique de la présence en RV. De plus, les questionnaires doivent être remplis après les expériences et interactions en RV, ce qui interrompt le flux et peut provoquer des biais. Il est possible que cette réflexion post-expérience diffère significativement de l'expérience in-situ réelle, ce qui peut entraîner des divergences dans les conclusions tirées de l'étude. En raison de ces limites, la validité des questionnaires en tant que mesure du sens de présence peut être remise en question. De nombreuses méthodes ont été introduites dans la littérature pour améliorer et mesurer le sens de présence en réalité virtuelle. L'objectif de cette recherche est de proposer une méthodologie pour définir le SOP et le mesurer en fonction du contexte de l'EV et des caractéristiques de l'utilisateur, ainsi que d'explorer quelques métaphores pour augmenter le SOP. De plus, nous suggérons que les métaphores peuvent être des outils utiles pour améliorer le SOP. En plus de leur capacité à évoquer des images mentales vivantes et familières, les métaphores peuvent également faciliter l'assimilation cognitive des utilisateurs dans les EV, augmentant potentiellement le sens de présence. Dans ce contexte, les principales questions de recherche que nous souhaitons aborder dans nos travaux de recherche sont les suivantes : Q1 : Est-il possible de définir le SOP de manière objective dans le contexte de l'expérience de l'utilisateur ? Q2 : Comment mesurer le SOP dans un contexte spécifique ? Q3 : Comment améliorer le SOP ? Il y a donc deux aspects à la question de recherche en jeu. Premièrement, cela nécessite l'exploration et le développement de méthodes sensibles au contexte pour mesurer le SOP en RV qui vont au-delà des questionnaires génériques afin de capter les expériences individuelles et nuancées des utilisateurs. Deuxièmement, cela implique une investigation de l'utilisation des métaphores

pour améliorer le SOP, ainsi qu'une compréhension de la façon dont ces outils peuvent être calibrés pour fonctionner dans des contextes spécifiques d'EV.

### **Approche Proposée :**

La littérature a montré que le SOP est très dépendant de l'application et orienté vers la tâche, et que des méthodes générales et non personnalisées comme le questionnaire sont incapables de quantifier le sens de la présence. Sur la base des contraintes mentionnées ci-dessus et également par l'examen de la littérature, nous proposons que la présence, en tant que concept dépendant du contexte, ne devrait pas être évaluée uniquement par des méthodes traditionnelles de questionnaire. Nous devrions explorer et développer de nouvelles approches de mesure qui peuvent saisir la nature immédiate, subjective et contextuelle de la présence. De telles méthodologies pourraient être capables de fournir une compréhension plus riche et plus délicate de la présence qui est en accord avec les expériences réelles que les utilisateurs ont au sein des environnements virtuels. Il est crucial de développer des mesures sensibles au contexte afin d'évaluer la présence en VR d'une manière plus valide et fiable. Aborder les complexités du sens de la présence (SOP) dans les environnements VR nécessite une approche nuancée. Pour cette étude, l'accent sera mis sur le comportement individuel et la sensation d'effectuer des tâches spécifiques dans certains contextes. Dans cette étude, nous avons essayé d'introduire une méthodologie pour quantifier le sens de la présence, qui peut être applicable pour différents cas d'utilisation et différents contextes virtuels. Par conséquent, nous avons utilisé une approche de méthodes mixtes pour fournir une analyse complète du SOP. La première étape de cette méthode consiste à déterminer le cas d'utilisation de l'environnement virtuel, suivi des caractéristiques et des spécifications du cas d'utilisation. Notre prochaine étape est d'observer le comportement des utilisateurs, puis de définir le SOP dans le contexte du cas d'utilisation. En définissant le SOP dans le contexte du cas d'utilisation, nous pouvons introduire des indicateurs objectifs ou subjectifs pour quantifier le sens de la présence des utilisateurs. De plus, nous serons en mesure d'introduire différentes métaphores pour améliorer le SOP des utilisateurs de VR. Voici une description détaillée de chaque étape.

1. Définition des Cas d'Utilisation, des Caractéristiques et du Contexte
2. Observation et Collecte de Données
3. Définition du SOP dans le Contexte et Proposition de Métriques
4. Introduction et Test des Métaphores
5. Validation des Indicateurs et des Métaphores

#### Phase 1 : Définition des Cas d'Utilisation, des Caractéristiques et du Contexte

- Définition des Cas d'Utilisation et des Contextes. Plusieurs cas d'utilisation de la VR, tels que la formation, l'interaction, et la session de thérapie (augmentation et diminution du stress) sont identifiés pour s'assurer que la méthodologie est applicable pour différents contextes virtuels.

- Définition des Caractéristiques et du Contexte. Pour chaque cas d'utilisation, les caractéristiques et les spécifications sont définies. Cela inclut le type de tâches que les utilisateurs sont tenus d'effectuer, les caractéristiques de l'environnement virtuel et les interactions attendues.

#### Phase 2 : Observation et Collecte de Données



- **Sélection des Participants.** Les participants sont sélectionnés en fonction de critères pertinents pour les cas d'utilisation étudiés. La diversité démographique est également prise en compte.

- **Observation du Comportement.** Les comportements, interactions et réponses des participants sont étroitement observés alors qu'ils accomplissent des tâches spécifiques au sein des environnements de RV. Une attention particulière est accordée aux signes qui peuvent indiquer le niveau de présence, tels que l'immersion, l'engagement et la naturalité des interactions.

- **Collecte de Données.** Des données qualitatives (par le biais d'entretiens et de questions ouvertes) et des données quantitatives (par le suivi des mouvements, des temps de réponse et des taux d'interaction) sont recueillies.

### Phase 3 : Définition du SOP dans le Contexte et Proposition de Métriques

- **Définition du SOP dans le Contexte.** Les données recueillies lors de la phase 2 sont analysées pour comprendre comment le SOP est vécu dans différents contextes et tâches. Cela inclut l'identification des points communs et des différences entre les cas d'utilisation.

- **Développement d'Indicateurs Sensibles au Contexte.** Sur la base de l'analyse, de nouveaux indicateurs sensibles au contexte sont développés pour définir et mesurer le SOP. Ces indicateurs sont à la fois objectifs et, si nécessaire, subjectifs.

### Phase 4 : Introduction et Test des Métaphores

- **Identification des Métaphores.** Des métaphores potentielles qui pourraient améliorer le SOP en fonction du contexte sont identifiées. Ces métaphores peuvent être des améliorations visuelles, auditives ou haptiques.

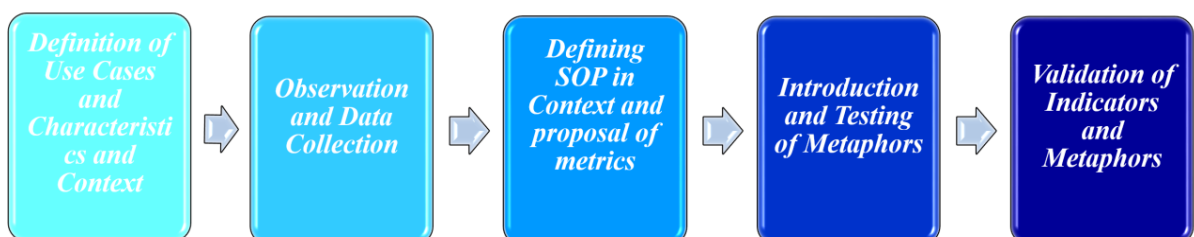
- **Test des Métaphores.** Les participants sont exposés aux métaphores identifiées dans les environnements de RV, et des retours sont recueillis concernant leur effet sur le SOP.

### Phase 5 : Validation des Indicateurs et des Métaphores

- **Analyse Statistique.** Une analyse statistique est effectuée pour valider les indicateurs développés, en s'assurant qu'ils représentent avec précision le SOP dans différents contextes.

- **Efficacité des Métaphores.** L'efficacité des métaphores pour améliorer le SOP est évaluée en fonction des retours des participants et des changements observables dans le comportement et les interactions.

Voici le schéma de la méthode présentée :



## A.4 Études Expérimentales :

### Cas d'Utilisation 1 : Lever de Bouteilles Virtuelles

La figure 0.1 illustre la méthodologie de cette expérience de cas d'utilisation. La phase 1 indique que lorsqu'une personne souhaite soulever un objet, la force qu'elle doit exercer sur l'objet doit être égale ou supérieure au poids de l'objet pour pouvoir le soulever contre la force gravitationnelle qui agit sur lui. Dans la phase 2, nous expliquons que lorsque les participants sont invités à soulever des bouteilles, leurs muscles dépensent effectivement de l'énergie. Dans la troisième phase, nous démontrons que le travail contre la gravité et la fatigue musculaire pourraient être des indicateurs du sentiment de présence dans un environnement où un sujet doit interagir avec un objet virtuel. En phase 5, nous avons introduit le pseudo haptique comme une technique pour évoquer la perception haptique grâce à des indices visuels afin d'induire le sentiment de lourdeur de l'objet aux utilisateurs de la réalité virtuelle, et nous l'avons utilisé comme une métaphore.

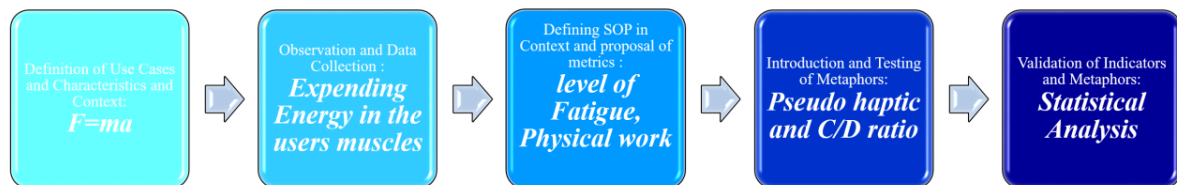


Figure 0.1 Méthodologie de l'expérience de levage de bouteilles en réalité virtuelle

Dans cette étude, nous avons cherché à mesurer et à améliorer le sentiment de présence des sujets dans le contexte de l'interaction avec un objet virtuel, comme le levage d'une bouteille virtuelle. Nous avons utilisé le pseudo-haptique comme une métaphore pour induire le poids visuel des objets aux participants.

Globalement, les apports de ces travaux comprennent :

- La conception de différentes conditions de manipulation en réalité virtuelle, basée sur le travail physique du poids attendu/ciblé des objets à induire sur des objets virtuels.
- L'étude de l'effet du retour pseudo-haptique sur les comportements de levage des utilisateurs de la réalité virtuelle et leur comparaison avec le levage d'objets réels.
- La formalisation de la notion de travail physique pour étudier différents comportements individuels dans des environnements virtuels et réels en utilisant comme mesure objective du sentiment de présence.
- L'évaluation des relations concernant le sentiment de présence entre les mesures objectives (travail physique) et subjectives (sensation de fatigue).

### Cas d'Utilisation 2 : Lever de Bouteilles Virtuelles - Analyse Cinématique

La figure 0.2 présente une autre approche pour mesurer le sentiment de présence en réalité virtuelle lors du levage d'un objet dans un environnement VR. La première phase est la même que dans l'expérience précédente, nous avons montré que lorsqu'une personne veut soulever un objet, la force

qu'elle doit exercer sur l'objet doit être égale ou supérieure au poids de l'objet afin de le soulever contre la force gravitationnelle qui agit sur lui.

Dans la phase 2, nous avons expliqué que lorsqu'on soulève un objet dans une direction ascendante, le poids de l'objet affecte divers aspects de la cinématique de la main et de la posture du corps tels que la Vitesse Maximale, la Durée du Mouvement : Amplitude, Temps pour atteindre la Vitesse Maximale, Posture, Prise.

Dans la phase 3, nous avons introduit les caractéristiques cinématiques comme mesures objectives ainsi que le Borg CR10 comme mesures subjectives.

Dans la phase 4, nous expliquons comment nous avons utilisé le pseudo-haptique comme une métaphore pour augmenter le sentiment de présence des utilisateurs en réalité virtuelle.

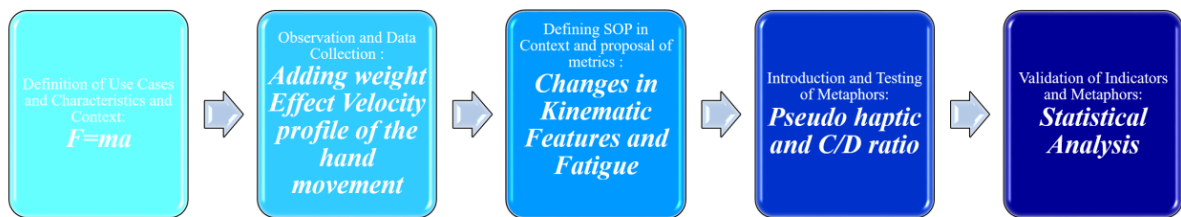


Figure 0.2 une autre approche pour mesurer le sentiment de présence lors d'une tâche de levage d'objet en réalité virtuelle

Et dans la dernière phase, nous avons discuté des résultats de l'expérience et comment ces résultats du retour pseudo-haptique sur la cinématique de la main sont similaires aux caractéristiques cinématiques du levage d'objets réels.

### Cas d'Utilisation 3 : Effet de la Gravité sur le Mouvement de la Main

La figure 0.3 présente la méthodologie de cette expérience sur le cas d'utilisation, à savoir l'effet de la gravité visuelle sur le mouvement de la main.

Dans la première phase, nous discutons de la manière dont le système nerveux central (SNC) prend en compte la gravité pour planifier les mouvements et donc comment la cinématique de la main est dépendante de la gravité.

Dans la phase 2, nous expliquons que la gravité visuelle affecte les caractéristiques cinématiques des mouvements de la main car elle fournit des indices pour prédire comment les objets se déplacent dans l'environnement et comment des forces telles que la gravité agissent sur eux. Lors de la planification et de l'exécution des mouvements, le cerveau prend en compte les informations perceptives reçues, y compris la gravité visuelle, pour ajuster les commandes motrices. Par conséquent, les caractéristiques cinématiques, y compris la vitesse maximale, la durée du mouvement, le temps pour atteindre la vitesse maximale et l'amplitude, sont affectées par la gravité visuelle.

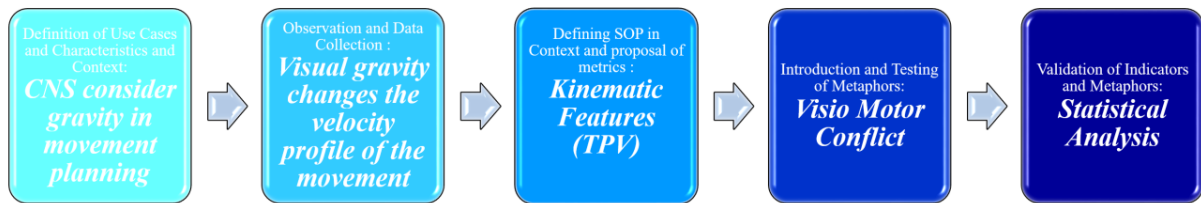


Figure 0.3 la méthodologie de cette expérience sur le cas d'utilisation, à savoir l'effet de la gravité visuelle sur le mouvement de la main

Dans la phase 3, nous avons introduit les caractéristiques cinématiques comme mesures objectives car elles pourraient être représentatives d'une entrée visuelle.

Dans la phase 4, nous expliquons comment nous avons utilisé le conflit visuo-moteur comme une métaphore, et les environnements conçus pour voir l'effet de la gravité visuelle sur le mouvement de la main dans chaque environnement. De plus, nous introduisons un paramètre appelé alpha qui indique le poids visuel relatif dans chaque environnement.

Dans la dernière phase, nos résultats montrent que le temps pour atteindre la vitesse maximale du mouvement de la main des sujets change radicalement dans chaque environnement et est fortement affecté par la perception visuelle. De plus, la valeur alpha (l'importance relative du contexte visuel) change également radicalement dans chaque environnement. Par conséquent, lorsqu'un utilisateur est présent dans un environnement virtuel, la cinématique de sa main pourrait être affectée par les éléments visuels. Comme dans l'environnement VR, la plupart de la perception de l'utilisateur se fait par son système sensoriel visuel, la cinématique de la main pourrait donc être un nouvel indicateur pour mesurer le sentiment de présence de l'utilisateur.

#### Cas d'Utilisation 4: Processus d'Intubation Endotrachéale

La Figure 0.4 représente la méthodologie de cette expérience de cas d'utilisation sur le processus d'intubation endotrachéale.

Dans la première phase, les limitations actuelles de la technologie VR, comme l'utilisation de contrôleurs de main volumineux, peuvent ne pas reproduire entièrement la sensation tactile et la dextérité nécessaires pour manipuler à deux mains des instruments petits et délicats comme un laryngoscope en salle d'opération.

Dans la phase 2, nous avons défini la manipulation fine et expliqué comment les anesthésistes démontrent la manipulation correcte du laryngoscope et du tube endotrachéal et visualisent les cordes vocales. Le tube endotrachéal est passé entre les cordes vocales dans la trachée.

Dans la phase 3, nous avons continué à dire que la naturalité de l'interaction dans les Environnements Virtuels (EV) en tant que mesure du Sens de Présence (SoP) est critique dans la formation à des procédures comme l'intubation endotrachéale. Nous avons expliqué que dans cette expérience, l'utilisation d'un questionnaire de présence pourrait être utile pour mesurer le niveau de présence des sujets dans la VR.

Dans la phase 4, nous avons introduit une méthode appelée réacheminement haptique (« haptic retargeting ») comme métaphore pour résoudre le problème de l'interaction avec des objets fins et petits dans la VR à l'aide de contrôleurs de main encombrants. L'idée de base de

cette métaphore est le conflit de la proprioception visuelle qui offre une perception illusoire dans l'environnement VR.

Dans la dernière phase, nous avons parlé de l'efficacité de la méthode de réacheminement haptique pour améliorer le sens de présence dans la VR et résoudre le problème d'interaction à l'aide de contrôleurs de main encombrants.

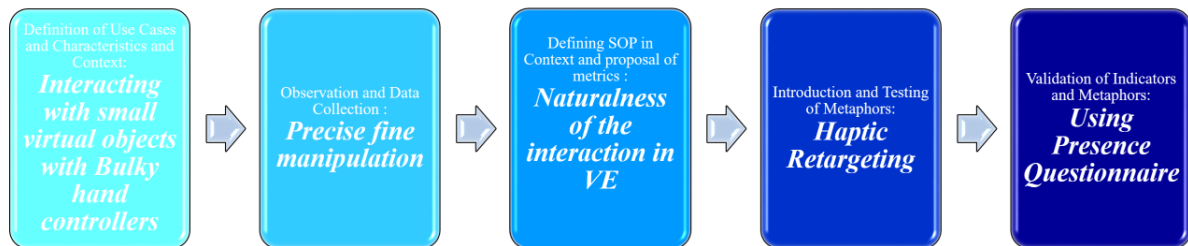


Figure 0.4 la méthodologie d'expérience de cas d'utilisation sur le processus d'intubation endotrachéale

## Cas d'Utilisation 5: Effet de la rétroaction multisensorielle sur le niveau de stress

La figure 0.5 illustre la méthodologie de cette expérience de cas d'utilisation sur l'effet de la rétroaction multisensorielle sur le niveau de stress.

Dans la première phase, nous abordons l'utilisation prometteuse de la réalité virtuelle (RV) dans le domaine de la santé, en particulier en matière de santé mentale et de bien-être. La RV peut être utilisée dans divers contextes thérapeutiques, y compris pour gérer le stress. Le stress et l'anxiété sont étroitement liés, partageant des substrats neuronaux similaires et des structures comportementales et neurales entrelacées. Plusieurs recherches ont montré que des environnements verts tels que les forêts et la nature soulagent le stress (Grahn & Stigsdotter, 2003) (Annerstedt, et al., 2013). De plus, vivre dans un environnement urbain affecte négativement la réaction du cerveau au stress par rapport aux villes et aux zones rurales, ce qui peut augmenter la susceptibilité au stress.

Dans la deuxième phase, nous nous intéressons à la question de savoir quel système sensoriel est le plus dominant en RV. Pour y répondre, diverses études se sont concentrées sur l'impact du son et de l'audio sur différents domaines de la réalité virtuelle, telles que la perception de la masse et du matériau (Fleming, 2014) ou la perception visuelle (Bowman, et al., 1999) ou l'expérience de jeu (Rogers, et al., 2018). Bien que la vision soit généralement considérée comme le système sensoriel dominant, dans des conditions de conflit multisensoriel, elle peut être manipulée par d'autres systèmes sensoriels tels que l'audio (Bowman, et al., 1999) (Shams, et al., 2000).

Dans la troisième phase, nous expliquons que l'utilisation d'un questionnaire de présence pourrait être utile pour mesurer le niveau de présence des sujets en RV. Notre recherche vise à étudier le comportement du sujet dans un environnement stressant et calme et à analyser le sentiment de présence pour optimiser l'immersion virtuelle. De plus, cette recherche souhaite

étudier la réponse à l'anxiété des utilisateurs de RV face à des stimuli audiovisuels et leur réaction aux conditions de conflit visuel-sonore.

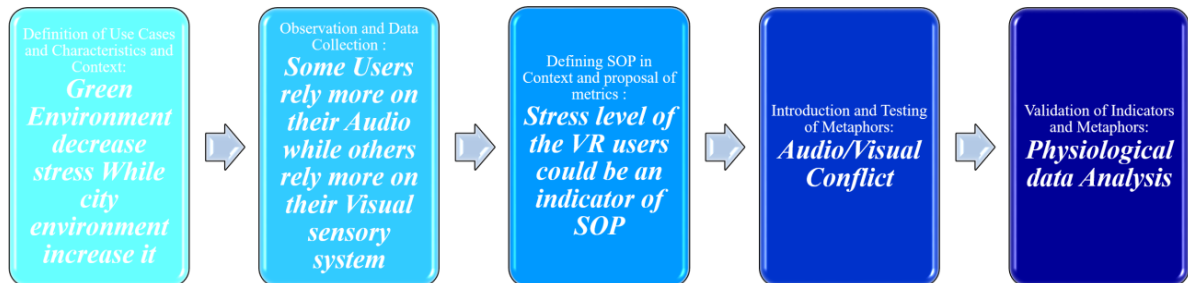


Figure 0.5 la méthodologie d'expérience de cas d'utilisation sur l'effet de la rétroaction multisensorielle sur le niveau de stress.

Dans la quatrième phase, nous expliquons le développement d'indicateurs sensibles au contexte. Dans cette expérience, nous montrons que le stress, en tant qu'indicateur pour mesurer le sentiment de présence en réalité virtuelle (RV), est basé sur l'idée que lorsque les individus sont véritablement immergés et se sentent présents dans un environnement virtuel, leurs réponses psychologiques et physiologiques sont similaires à ce qu'elles seraient dans une situation similaire dans le monde réel. De plus, utiliser le conflit audiovisuel comme métaphore pour étudier l'effet des sons environnementaux et des éléments visuels sur les niveaux de stress des utilisateurs de RV est une approche intéressante. Le principe proposé est de mettre en œuvre un conflit audiovisuel pour lequel les stimuli auditifs et visuels dans un environnement virtuel sont incohérents ou contradictoires. Ce conflit peut être utilisé comme une métaphore pour comprendre comment les disparités dans l'information sensorielle peuvent affecter les niveaux de stress des utilisateurs en RV.

Dans la dernière phase, nous montrons que l'effet du son change significativement la fréquence cardiaque. Nos résultats montrent que certains sujets sont plus dépendants de la vision dans des conditions de conflit multisensoriel et se fient principalement à leur entrée visuelle, tandis que d'autres se fient davantage à leur système sensoriel auditif.

## A.5 Conclusion et Perspectives

### Conclusion générale :

Cette thèse a eu pour objectif de fournir une investigation du concept important de "sentiment de présence" (SoP) dans le domaine de la Réalité Virtuelle (RV). Ce travail a démontré que le SoP est intégral à l'expérience de la RV et a un impact direct sur le plaisir de l'utilisateur, sa satisfaction et les avantages perçus. Au cours de cette recherche, nous avons détaillé la nature complexe du SoP, sa définition, sa classification et sa mesure. Nous avons découvert que le sentiment d'"être là" ou présence personnelle, l'un des types de SoP, est fondamental pour toutes les formes d'expériences en RV. En plus de l'exploration théorique, une partie importante de cette thèse a été consacrée à l'élaboration d'une méthodologie spécifique au contexte pour mesurer le SoP, répondant à la préoccupation qu'une mesure universelle pourrait ignorer des

facteurs individuels et environnementaux essentiels. En étudiant l'influence des traits individuels et des caractéristiques environnementales sur le SoP, nous avons découvert que ces éléments peuvent à la fois améliorer et diminuer le sentiment de présence dans un environnement virtuel. Ainsi, notre méthode de mesure proposée prend en compte ces facteurs, fournissant une évaluation plus précise et adaptée du SoP. Les questions de recherche posées ont pu trouver des éléments de réponse qui sont résumés ci-après :

Q1 : Est-il possible de définir le SoP dans le contexte de l'expérience de l'utilisateur ?

Oui, c'est possible. Comme cette étude le démontre, le SoP, étant un phénomène dépendant du contexte, ne devrait pas être évalué uniquement par des méthodes de questionnaire traditionnelles. La nécessité d'explorer et de développer d'autres approches de mesure qui peuvent capturer la nature immédiate, subjective et spécifique au contexte de la présence a été soulignée. Ces méthodologies ont le potentiel de fournir une compréhension plus riche et plus nuancée de la présence, en accord avec les expériences réelles que les utilisateurs ont dans les environnements virtuels. Par conséquent, le développement de mesures sensibles au contexte est crucial pour une évaluation plus valide et fiable de la présence en RV.

Q2 : Comment mesurer le SoP ?

Pour cette question, l'accent principal a été mis sur le comportement individuel et la sensation d'accomplir des tâches spécifiques dans des contextes particuliers. Nous avons introduit une méthodologie pour quantifier le SoP, que nous pensons applicable à différents cas d'utilisation et contextes virtuels. Une approche mixte a été utilisée pour fournir une analyse complète du SoP. La première étape de cette méthode consiste à identifier le cas d'utilisation de l'environnement virtuel, puis à caractériser et spécifier ce cas d'utilisation. L'étape suivante consiste à observer le comportement des utilisateurs et à définir le SoP dans le contexte de ce cas d'utilisation. En définissant le SoP dans le contexte du cas d'utilisation, nous avons pu introduire des indicateurs objectifs ou subjectifs pour quantifier le sentiment de présence des utilisateurs.

Q3 : Comment améliorer le SoP ?

Grâce à ce travail, nous avons introduit différentes métaphores comme nouvelle approche pour améliorer le SoP des utilisateurs de RV. Ces interventions métaphoriques, adaptées au contexte de l'expérience de RV, ont montré des résultats prometteurs pour augmenter le SoP, créant ainsi une expérience de RV plus immersive et plus engageante.

Les contributions de ce travail sont multiples pour le domaine de la Réalité Virtuelle (RV) en se concentrant sur le concept de Sensation de Présence (SoP). Voici les principales contributions :

*Proposition du concept de SoP adapté :* Cette thèse propose un changement dans notre compréhension et notre interprétation du SoP en RV. Elle présente une conceptualisation du SoP comme un phénomène profondément subjectif et dépendant du contexte, qui remet en question et s'éloigne de la vision traditionnelle du SoP comme une expérience universelle ou monolithique. Cette nouvelle perspective met l'accent sur la réalité expérientielle unique de chaque utilisateur, reconnaissant que le SoP peut varier en fonction de nombreux facteurs, y

compris l'engagement de l'utilisateur avec l'environnement de la RV, la nature des tâches qu'ils accomplissent, et même le moment particulier de leur expérience. Ce nouveau regard permet de nouvelles approches plus pragmatiques et de terrain.

*Méthodologie de mesure contextuelle* : En complément de la nouvelle conceptualisation du SoP, une nouvelle méthodologie a été proposée pour mesurer le SoP, qui souligne l'importance du contexte dans lequel se déroule l'expérience de RV. Plutôt que de se baser uniquement sur des méthodes de questionnaire d'auto-déclaration, cette approche intègre à la fois des indicateurs subjectifs et objectifs pour fournir une compréhension complète du SoP d'un utilisateur. Elle prend en compte les comportements individuels et les sensations liés à des tâches spécifiques dans l'environnement de la RV, enrichissant ainsi la granularité et la profondeur de la mesure du SoP.

*Interventions métaphoriques pour l'amélioration du SoP* : Ce travail a également introduit de manière innovante l'utilisation d'interventions métaphoriques pour améliorer le SoP. Cette nouvelle perspective se concentre sur les stratégies pour approfondir l'engagement et la connexion de l'utilisateur avec l'environnement de la RV, plutôt que de se concentrer uniquement sur les aspects techniques de la RV. Les interventions métaphoriques proposées agissent comme des ponts, connectant la perception de l'utilisateur avec le monde virtuel, amplifiant ainsi leur SoP.

*Accentuation des différences individuelles* : La recherche a reconnu et souligné l'importance des différences individuelles dans l'expérience du SoP. Elle attire l'attention sur les traits personnels et les capacités de l'utilisateur qui peuvent affecter leur sentiment de présence, suggérant ainsi que les expériences de RV devraient être plus personnalisées, s'adaptant aux exigences uniques de chaque individu.

*Exploration multidimensionnelle du SoP* : L'étude a entrepris une exploration multidimensionnelle du SoP, en se plongeant dans différents types de présence tels que personnelle, sociale, et environnementale. Cette approche globale élargit notre compréhension du concept de SoP et de ses différentes dimensions.

*Validation expérimentale* : La recherche a également inclus une validation expérimentale des méthodes proposées. Cette validation sert de base solide pour les futurs chercheurs pour appliquer, tester, et développer davantage ces méthodologies.

*Contribution aux applications de la RV* : En améliorant la compréhension, la mesure, et l'amplification du SoP, ce travail contribue aux connaissances de la RV. Ces connaissances pourraient potentiellement avoir des implications importantes pour une variété d'applications dans des secteurs tels que l'éducation, les soins de santé, le divertissement, et au-delà.

*Limitations* : Bien que cette recherche soit extensive et approfondie, elle comporte certaines limites inhérentes à l'évaluation et au développement des méthodes de mesure et d'amélioration du SoP.

1. *La Nature Complexes de la Subjectivité* : Nous avons souligné tout au long de ce travail que le SoP est une expérience intensément subjective, avec des variations entre différents individus. Malgré nos meilleurs efforts pour créer une méthodologie de mesure exhaustive, certains aspects de l'expérience du SoP peuvent rester non



- comptabilisés ou ne pas être entièrement représentés en raison de cette subjectivité inhérente.
2. **Accent sur les Différences Individuelles :** Bien que la reconnaissance des différences individuelles soit une force de cette étude, elle présente également un défi car elle complique les résultats de mesure et peut introduire une variabilité potentielle. Nos résultats pourraient ne pas être universellement applicables et pourraient nécessiter une interprétation spécifique à chaque individu.
  3. **Contraintes de Temps :** En raison des contraintes de temps d'un projet de thèse, certains aspects de la recherche n'ont pas pu être explorés aussi profondément qu'ils auraient dû l'être. Le développement et l'affinement de nos méthodes proposées peuvent nécessiter des recherches itératives supplémentaires et des études à long terme pour les valider et les optimiser pleinement. Malgré ces limites, il est important de noter que cette recherche contribue de manière significative à la compréhension, à la mesure et à l'amélioration du SoP, servant de base précieuse pour les futurs chercheurs.

### **Perspectives et Travaux Futurs :**

Il existe un large éventail de possibilités et d'opportunités pour nos prochaines étapes dans ce fascinant voyage au cœur de la RV. Dans cette thèse, nous avons établi des perspectives et des fondations qui nous permettront d'aller plus loin et d'explorer davantage. Nous concentrerons nos futures recherches sur deux domaines. Nous prévoyons d'incorporer des techniques d'apprentissage machine et d'analyse de données pour améliorer le "sensation de présence" de l'environnement virtuel. Grâce à ses puissantes capacités prédictives et analytiques, l'apprentissage machine peut nous aider à comprendre les modèles de comportement et les préférences des utilisateurs. De cette façon, un environnement virtuel adaptatif peut être créé qui s'ajuste en temps réel, augmentant le SoP en offrant une expérience de RV plus personnalisée et immersive. Notre capacité à tirer des informations significatives des données générées par les utilisateurs peut également nous aider à affiner les environnements et les expériences de RV. En continuant à affiner nos méthodologies, nous pouvons produire des mesures de SoP plus précises et une expérience utilisateur plus engageante. Notre deuxième axe de recherche concernera les expériences de RV qui favorisent le conflit multisensoriel. Il est possible que les utilisateurs éprouvent des discordances entre ce qu'ils voient et ce qu'ils ressentent dans un environnement virtuel à la suite d'un conflit multisensoriel. L'illusion immersive de la RV peut être perturbée par ces conflits, il est donc crucial de les résoudre pour améliorer le système. L'expérience en RV peut être améliorée si nous améliorons notre compréhension de la manière de résoudre les conflits sensoriels. En faisant cela, nous pouvons offrir aux utilisateurs une expérience virtuelle transparente et captivante qui est plus convaincante et immersive. Notre investigation impliquera diverses techniques et méthodologies pour identifier, atténuer et résoudre ces conflits. Nous pouvons créer des expériences multisensorielles harmonieuses en développant des systèmes dynamiques et adaptatifs qui répondent en temps réel. Pour le monde de la réalité virtuelle, ce sont en effet des temps excitants ! En combinant l'apprentissage automatique, l'analyse de données et une attention portée sur les conflits multisensoriels, nous sommes confiants pour continuer à faire avancer le domaine et à créer des expériences de RV encore plus convaincantes, immersives et satisfaisantes. Alors, continuons ce voyage ensemble, repoussant les limites de ce qui est possible, et révolutionnant la manière dont nous interagissons avec les mondes virtuels.