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From the Laboratory to the Field: Evaluating User Experience in Virtual Reality for Tomorrow's Metaverse

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Résumé

En vue de la transformation technologique promise par la Metaverse, ce mémoire par articles a pour objectif d'enrichir le domaine d'étude portant sur la Réalité Virtuelle (RV) en s'intéressant à l'expérience immersive et émotionnelle de ses utilisateurs. Afin de mener à terme ses objectifs, la recherche déployée consiste à varier différents attributs d'un Environnement Virtuel (EV) par le biais de ses dimensions sensorielles, sociales et interactives et d'en évaluer ses effets sur l'Expérience Utilisateur (UX). Une première phase de recherche en laboratoire, utilisant la RV en contextes méditatifs, vise à développer un cadre méthodologique rendant ainsi possible la seconde phase de recherche, cette dernière étant conduite en contextes sociaux directement sur le terrain, hors d'un environnement contrôlé. Dans un premier temps, les résultats démontrent qu'il existe une relation positive entre l'affect positif d'un utilisateur et sa perception de présence dans l'EV. Dans un second temps, les résultats suggèrent que le partage d'une expérience en RV avec un partenaire du monde réel bonifie l'expérience émotionnelle, sans toutefois dégrader l'expérience immersive. De plus, les résultats soutiennent que la RV active, par le biais d'interactions, suscite des niveaux d'immersion sensorielle et d'exploration plus élevés. Par son approche à méthodes mixtes combinant mesures perçues (questionnaires et entretiens) et vécues (activité électrodermale, cardiaque, cognitive, de mouvement), cette recherche offre d'importantes contributions méthodologiques. Par l'entremise d'une haute validité écologique, les résultats obtenus permettent de guider les développeurs de RV en appuyant son potentiel hautement social, et surpassant les contextes d'utilisation communément solitaires de cette technologie émergente.

Mots-clés: Réalité virtuelle, Environnements virtuels partagés, Expérience multisensorielle, Interactivité, Présence, Immersion, Expérimentation en laboratoire, Étude de terrain, Méthode mixte

Abstract

This thesis explores the User Experience (UX) behind Virtual Reality (VR). Precisely, it investigates the impact of varying different attributes of a Virtual Environment (VE), namely its sensory, social, and interactive dimensions, on lived and perceived UX. Given the novelty and complexity of VR as a technology, this research unfolds in a multiphasic approach. First, it develops and assesses a mixed methodological paradigm by measuring lived UX in meditative VR contexts, a fundamental step in reaching its second and end-goal: evaluating VR in social contexts directly into the field, away from controlled laboratory environments. The first study suggests a significant relationship between users' positive affect and their sense of presence in the VE. The second study supports that shared active VR generates greater positive affect; while presence, immersion, flow and state anxiety are unaffected by the co-presence of a real-world partner. Additionally, it confirms that active VR elicits greater sensory immersion and exploration behavior regardless of the social context. Altogether, notable methodological contributions emerge from the successful use of a mixed methods approach for measuring lived and perceived UX in VR. Theoretically, the suggestion that VR can be shared with a real-world partner without hindering the immersive experience emerges as a surprising, yet compelling finding. Through its high ecological validity, this thesis offers practical directions for VR developers not only to promote active VR for greater exploration and immersion, but also to design these experiences to be shared, therefore surpassing the ubiquitous solitary contexts of use of this promising technology.

Per the multiphasic nature of this thesis, the first research phase consisted of a laboratory-based study developing a methodological framework to evaluate lived UX in VR. Considering its main purpose to assess the feasibility of the methodology and tools chosen, a small sample size was prioritized at this stage. The successful outcome of this former part of research provided a strong foundation for the follow-up study to be carried out in the field, away from controlled laboratory settings, with a central aim to extend preliminary results to more ecologically valid contexts of use. Throughout both phases, this research leveraged a mixed methods approach combining conventional UX measures of perceived experience, i.e., self-report surveys and user interviews, and innovative measures of lived experience, i.e, electrodermal, cardiac, cognitive, and motion activity. This comprehensive UX assessment served as an important buffer against potential challenges arising from the inherently complex experimental design and equipment combination of a field study. The methods employed to overcome these potential methodological limitations are reviewed in depth in subsequent chapters.

Keywords: Virtual Reality, User Experience, Shared Virtual Environments, Multisensory Experience, Interactivity, Presence, Immersion, Laboratory Experiment, Field Study, Mixed Methods

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List of Acronyms

AR: Augmented Reality
ASD: Autism Spectrum Disorder
BPM: Beats Per Minute
EEG: Electroencephalography
ERP: Event Related Potential
EDA: Electrodermal Activity
GAD: Generalized Anxiety Disorder
HMD: Head-Mounted Display
HR: Heart Rate
HRV: Heart Rate Variability
ICA: Independent Component Analysis
MBCT: Mindfulness Based Cognitive Therapy
MMT: Mindfulness Meditative Training
MUVE: Multi-User Virtual Environment
REB: Research Ethics Board
SVE: Shared Virtual Environment
UX: User Experience
VR: Virtual Reality
VE: Virtual Environment
VRET: Virtual Reality Exposure Therapy

Foreword

The present work was completed as part of the student's Masters in User Experience at HEC Montreal. This thesis has been the object of evaluation and approval by the administrative management of the M.Sc. program at HEC Montreal. To ensure compliance with requirements outlined in the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans, all phases of research performed as part of this thesis went through an extensive ethical review prior to beginning data collection. Approval was granted by the Research Ethics Board at HEC Montreal under the certificate number 2022-4458 (Appendix D). Accordingly, all stages of research involving humans as participants were completed ethically, with informed written consent obtained from all participants. Additionally, the authorization to write this thesis in the form of articles, in English, was provided by the program director (Appendices E and F). Hence, this thesis encompasses 4 chapters. While the first and last chapters introduce the topic and reiterate important research takeaways, respectively, middlemost chapters present the scientific articles that have been written in relation to the different research phases of this project.

Chapter 2 presents the first phase of research that was performed in laboratory settings. An abridged version of this study, available in Appendix A, was presented at the 20th Annual Workshop of the Association for Information Systems Special Interest Group on Human Computer Interaction (AIS SIGHCI) in Austin, Texas. The related scientific article, *Evaluating User Experience in Multisensory Meditative Virtual Reality: A Pilot Study,* was published in the AIS Conference Proceedings and was awarded Best Paper by SIGHCI on December 12th 2021, an award that was received for the first time at the Tech3Lab. The complete version of the study, including results pertaining to users' emotional arousal as presented in Chapter 2, has not been published yet.

Chapter 3 presents the second phase of research that was carried out in field settings. This second phase of research, evaluating the user experience of a notorious Montreal-based VR exhibition *l'Infini* in October 2021, has been the subject of newspaper articles published by Le Devoir & La Presse among others. A succinct version of this study entitled *Take My Virtual Hand: An Evaluation of User Experience in Shared Interactive Virtual Reality*, available in Appendix B, has been submitted to the journal of Cyberpsychology, Behavior, and Social Networking for consideration in their special issue on "Virtual Emotions: Understanding Affective Experiences in the Metaverse." The article, submitted on July 31st, 2022, is currently under review by the journal. All forms of publications were made in agreement with collaborative partners and in the respect of co-authors (Appendix G).

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First and foremost, none of the work presented in this thesis could have seen the day without the valued mentorship of my research directors. I feel truly privileged to have benefited from their supervision, not only to learn from them as brilliant researchers, but also as compassionate mentors. Their resilience, optimism, and brilliant outlook on taking UX research remotely through these challenging times have been eye-opening. Constantinos, Pierre-Majorique, and Sylvain, my most sincere thanks for making this path the most fulfilling undertaking of my academic journey. I wish to extend my gratitude to my co-authors, Jared, Théo, your expertise and guidance on the experimental design for Chapter 2 was consequential.

I am beholden to the operations team and research assistants at the Tech3Lab, whose help and cleverness have fueled this project forward. I am also very appreciative of the Natural Sciences and Engineering Research Council of Canada for providing the financial pillars to this innovative research (NSERC; Grant number DDG-2020-00041). A massive thank you to all participants who provided their time, UX research is human-centered, and they proved this true, especially in a context of pandemic.

To the research team at the Amsterdam Conscious Brain Lab, thank you for being a defining step in my personal journey. Simon, the opportunity you provided me with unlocked the main door to the rest of my academic research adventure. Josipa, Stijn, thank you for showing me the *gezellig* side of scientific research.

To my parents, my sister, I am more grateful than words can express. Thank you for being present at every step of the process, for brightening up my days when most needed, and for believing in me, unconditionally. Your love and support have been driving forces in the completion of this thesis. To my friends, thank you for helping me push through, sometimes consciously, sometimes by your simple presence and *joie de vivre*.

I am extremely thankful for the open-mindedness of Studios PHI and Félix & Paul, who have allowed Chapter 3 of this project to come to life. Marc-André, Julie, Thomas, thank you for allowing me to be part of something I have always been passionate about; your creative lens in pushing the limits of innovation and strengthening the bridge between arts and science is truly inspiring.

Beyond the personal and professional growth that these past two years have been pillars to, if this experience has taught me one thing it is that “your limits are somewhere up there, waiting for you to reach beyond infinity." This Master’s thesis is a hundred-page reminder that with hard work and passion, even the craziest dreams can be fulfilled when you keep sight of the stars you aim to reach. My sincere gratitude to everyone who has contributed, even through a smile or laughter, to this achievement.

Chapter 1: Introduction

1.1 The rise of the Metaverse: VR surfing this emerging technological wave

A 70K design prize, this is what today's leading corporations like NASA are willing to invest to attract the best developers in creating state-of-the-art Virtual Reality (VR) experiences. The agency announced on May 5th that they are looking for outside help in designing "a new virtual reality research, development, and testing environment to help prepare for the experiences and situations that will be encountered on Mars" (Taylor, 2022, para. 2). Surprising isn't it? That one of the most important science & technology leaders lacks the in-house talent and resources to deploy such an experience. Truth is, VR is evolving at lightning speed, bringing along its innovative movement a new, and ever evolving, set of skills and professions. The fact that tech leaders are resorting to crowdsourcing challenges like the above proves that the design of Virtual Environments (VEs) is, as of today, a discipline that cannot be undertaken by merely anyone, especially as the design of optimal VEs still counts many arising challenges.

To remain competitive and with an aim to nurture idiosyncratic missions, innovative initiatives like those of leveraging VR for educational and training purposes are undertaken by several organizations in today's technological era. In fact, the last year has been shaken up by several emerging technological waves, with the Metaverse probably generating the largest of them all; a wave which many companies have decided to surf on. With a mind-blowing forecast estimating the consumer virtual reality market to reach 2.6 billion US dollars in 2020, and a growth beyond 5 billion US dollars by 2023, it is not surprising to witness companies' eagerness to seize this crescendo of opportunities (Alsop, 2022). Boiling down the concept to its due roots, the Metaverse is an alternate universe enabled through Augmented and Virtual Realities (AR / VR) where people can coexist and can do nearly everything they would do in real life, but in an alternate world (Mystakidis, 2022). Actually, VR has opened the doors to this alternate universe decades ago, such that one could say the Metaverse, perhaps in its premature form, has been around for a while now. However, the last few years of evolution of VR have been truly game-changing, not only on a technological standpoint, but also due to its growing acceptance among the general public, which justifies the enthusiasm towards this technology as we speak. Today, in fact, VR transcends its initial entertainment motives as it is introduced in numerous fields and fulfills a variety of functions.

1.2 The distinctive nature of VR: Its promising use in numerous fields of application

Virtual reality is a next-generation technology that allows users to be fully immersed in three-dimensional virtual environments (Albus et al., 2021). These immersive VEs, enabled through a head-mounted display (HMD), trigger a user's senses by delivering three-dimensional images and spatial audio, giving life to virtual experiences that mimic those experienced in real life (Xiong et al., 2021; Bell & al., 2022). By replicating real-world environments through the delivery of highly multisensory experiences, the key distinctive feature of VR, among other technologies, is the sense of presence and immersion it generates (Yang et al., 2019). In fact, when discussing VR, these two constructs are rarely mentioned without one another; the reason being their unique complementary nature. On one hand, presence fluctuates as a function of the attentional and perceptual resources allocated by a user to the sensory inputs incoming from a given environment (Steuer, 1992). In simpler terms, presence refers to the subjective sense of "being there" in an environment, even when one is physically situated in another (Witmer & Singer, 1998). While presence tends towards the subjective end of the spectrum, immersion, on the other hand, is more so related to the objective nature of the associated feeling. Specifically, immersion refers to the degree to which a user's sensory channels are engaged by the virtual simulation; these senses being stimulated by the technical attributes of VR such as image resolution, image quality, sound fidelity, and field of view (Kim & Biocca, 2018; Parong et al., 2020).

Thus, considering its intrinsic nature as a multimodal and distinctively engaging media, and given the nearly endless opportunities afforded by this technology in recreating real-world or imaginary environments, VR holds a promising future in a variety of domains. Additionally, the potential functions to be fulfilled by VR are extremely versatile considering that content can be communicated through a combination of sensory stimuli, rather than words solely (Carrozzino & Bergamasco, 2010). Accordingly, VR is now used for fundamental purposes, ranging from physical and mental health, all the way to education and training, and is no longer limited to that of pure entertainment.

In the health sector, VR gained exponential interest in the last years as a response to the "mental health pandemic" that was experienced worldwide. Hence, a window of opportunities in utilizing VR for mindfulness training has been seized; research in this line has shown that meditative content delivered through VR can indeed help patients suffering from Generalized Anxiety

Disorders (GAD) in alleviating their symptoms of anxiety (Tarrant et al., 2018). The application of VR towards mental health has been further extended to more specific uses of the technology, namely for the treatment of phobias using Virtual Reality Exposure Therapy (VRET) and the treatment of addictive habits such as smoking related behaviors (Botella et al., 2017; Tamburin et al., 2020). Building upon mental well-being, research also placed VR at the service of fundamental underexplored emotional and social questions. For instance, VR simulations have been used to induce specific emotions and evaluate the resulting differences in right and left hemispheric activation (Rodriguez et al., 2013); they have also been used to simulate social dynamics, like those emerging from intergroup helping behaviors, and to investigate the resulting human emotional reactions (D'Errico et al., 2019).

In the educational and training domains, VR has not only shown instances of small-scale interventions, like that of enabling VR-based driving systems to help adolescents with Autism Spectrum Disorder (ASD) in improving their driving skills (Zhang et al., 2017), but also more diffused and applied uses as a successful tool for accompanying health-care professionals in surgical training, military in stress management coaching, and pilots in flight dynamics (Yiannakopoulou et al., 2015; Pallavicini et al., 2016; Wang et al., 2018).

Although serving insightful and novel purposes, VR remains an important player in the domain to which it owes its initial roots; that of entertainment. As such, in the gaming sector, virtual reality continues to revolutionize social gaming dynamics by unlocking novel ways to play. For instance, progress towards communicating players' emotions virtually is underway, as VR-based systems are currently developed to capture and share players' facial expressions through their avatars in the virtual gaming space (Hart et al., 2018). This progress is also seen in the artistic domain, as VR is increasingly integrated in museums and exhibition centers. In fact, recent studies demonstrated that VR can be an innovative tool in delivering information about museum collections interactively, therefore rendering the overall experience more enjoyable and boosting the intention to revisit the venue (Lee et al., 2020).

Further down the artistic road, VR is nowadays used in contexts of double scenography experiences, i.e., experiences that comprise both the physical and virtual environments simultaneously. Accordingly, the development and delivery of such experiences is particularly challenging as it requires VR developers to pay a particular attention to incoming stimuli from two environments, i.e., the real and virtual worlds, that operate in parallel (Bohse Meyer, 2020). This challenge is particularly relevant given the rise of the Metaverse, and its vision to leverage VR to deploy a seamless alternate world. However, before reaching this promising outcome, there are notable challenges in merging physical and virtual worlds that need to be addressed for VR developers to successfully design seamless and optimal VEs; a topic we explore next.

1.3 The design of optimal VEs: Arising challenges yet to be uncovered

Despite its varied uses, there is one common challenge in the use of cutting-edge VR across industries and fields of applications, which has to do with the mobilization of all the virtual space to represent an environment or an object in a realistic and multidimensional way. In that sense, the field of arts, namely those being familiar with rendering experiences that occupy an entire space like theaters and museums, benefits from a head start when it comes to designing three-dimensional environments. In fact, there exists an interesting parallel between theater scenographers and VR developers; both professions require a skill set in the creation of peripheric experiences, one that successfully masters the integration of 360-degree stimuli into seamless experiences. Today, scenography is no longer limited to its traditional form by which the design of a given space should simply assist a specific narrative. Instead, scenography now accounts for the design of the *entire* experience, which is fulfilled by paying a particular attention to multisensorial, material and spatial dimensions (Bohse Meyer, 2020). In light of new emerging technologies, this same attention to details, as seen in today’s theaters, needs to be transposed and accounted for by VR developers when it comes to designing virtual environments. In fact, VR developers need to ensure that three-dimensional VEs respect those experienced in real life, not only in terms of visuals, but also in audio and haptic feedback such that it accurately mimics the way vision, hearing and touch unfolds in the real world. This is fundamental for users to feel optimally immersed in the virtual world, as the opposite would be raising a discrepancy between what they are used to and what they are experiencing in this so-called virtual world, therefore breaking sought feelings of presence and immersion.

This last point, however, is easier said than done. Recreating the real world has never been easy, especially considering the impressive amount and variety of stimuli hitting our senses at every second, in our everyday lives. Still today, the design of VEs is an important challenge given that VR remains a relatively new medium. In fact, as recently as in October 2021, Zuckerberg admitted to the needed progress by sharing how he “think(s) that there (are) aspects of the technology that need to (be) built that just don’t exist today.” (Thompson, 2021, para.23). To fuel innovation, Meta’s vision remains “very focused on just giving creators and developers the tools to build” (Craig, 2021, para.8).

Accordingly, potential uses of VR are nearly endless, and these are simply awaiting to be developed by the most inventive cohort of VR developers. However, before reaching the point of completely seamless virtual experiences, as promised by the Metaverse, there is a need to further investigate and better comprehend the User Experience (UX) behind this immersive technology. This motivation, specifically, was partly responsible for guiding the author of this thesis towards a systematic review of extant literature, the latter following a stepwise method which is detailed in Appendix C. Precisely, a thorough assessment of previous studies showed that the current body of literature lacks insights with regards to the specific factors that influence a user’s immersive and affective journey in VR, and the ones that drive a user’s exploration of their virtual environment. One reason explaining this gap being that the majority of VR research is currently performed in laboratory-based controlled settings, therefore restricting, by default, user movements and preventing results to be extended to ecologically valid contexts of VR (Baka et al., 2018). As a result, avoiding to carry out UX VR research in the field holds off the ecological validity sought by VR developers, and ultimately digs the existing gap deeper by stalling the needed progress in VR.

1.4 The evaluation of lived and perceived UX in VR: A methodological framework

Our research aims to partially fill the aforementioned gap in literature by providing a more comprehensive assessment of how users live and perceive VR experiences in real-life contexts of use. As such, we aim to shed light with regards to the following research question: **How do different attributes afforded by a virtual environment, namely with regards to its sensory, social, and interactive dimensions, influence a user’s lived and perceived experience in VR?**

Altogether, with VR aiming to replicate real-life multisensory experiences, we expect that an increase in the vividness of each of those attributes will positively enhance overall user experience. We address this overarching theme through a subset of related questions and hypotheses which we detail in the following chapters: our theoretical and methodological approach becoming clearer along the line of this thesis.

Accordingly, Chapter 2 covers the first research phase of this thesis, consisting of a laboratory-based study conducted to ensure the feasibility of evaluating user experience in VR using measures of lived experience including electrodermal, cardiac and cognitive activity. Building upon the successful outcome and strong methodological foundations insured by the former part of our research, Chapter 3 covers the second research phase of this thesis, which was confidently taken out of a controlled laboratory environment, into the field. That being said, the second study evaluated the user experience of a real-world VR exhibition, with the central aim to extend preliminary results to more ecologically valid contexts. Along the way, this research adopted a mixed methods approach leveraging innovative NeuroIS measures, i.e., electroencephalography and electrodermal activity, in combination to more commonplace UX measures, i.e., self-report surveys and user interviews, towards the achievement of our end-goal: carry out UX VR research directly into the field as to provide ecologically valid contributions for developers of this rising technology. Thus, unlike the majority of UX studies which are generally carried out in controlled laboratory settings, results that have emerged from this research constitute an innovative lens in providing ecologically valid insights to emerging professionals within the field. As we speak, VR is expanding through various industries and holds great potential in numerous domains, adding along its technological revolution a notable pressure on VR developers and VEs designers. Thus, Chapter 4 of this thesis, through a review of important research implications, aims to provide guidance and serve as pillars for this new set of professionals, soon to be the leaders of our technological era.

1.5 The fruit of shared labor: Author’s responsibilities in the completion of her thesis

This research was undertaken in the context of the student’s Master’s thesis project. It was deployed with the precious supervision of the student’s research directors and notable help from the Tech3Lab research team. Table 1 summarizes the input of the student through the various steps leading to the submission of her Master’s thesis, with her contributions and responsibilities detailed along the process.

Table 1.1 Author's Contributions

Research process		Student contribution
Literature review		**100% Literature review:** Read over 50 scientific articles on previous research performed in VR to assess successful methodologies, find guidance in optimal tools installation, select appropriate validated psychometric scales, detect emerging trends and identify the current gap in literature.
Chapter 2: Laboratory study	Research question	**100% Research question formulation:** Formulate a novel yet pragmatic research question in response to the identified gap in literature and in consideration of the topical issues arising from the pandemic, i.e., mental health concerns.
	Experimental design	**90% Ethics approval:** Prepare the required documentation for the REB. Help was provided for a final review of the application. **100% VR stimuli selection:** Create a typology of VR stimuli based on literature and select VR videos aligned with the RQ. **20% ERP auditory stimuli:** Advise on the ERPs' appropriate mean inter-stimulus intervals and standard deviations. Notable help was provided at this stage; the delivery of the stimuli through the LSL procedure was coded in Python by a co-author. **90% EEG electrodes positioning:** Select the optimal electrodes positioning based on the literature and research question, with respect to tools' physical constraints. Help from co-authors was provided to assess and confirm the chosen electrodes positioning. **100% Experimental protocol:** Write the research protocol for data collection. **100% Questionnaires & interview questions:** Develop online Qualtrics questionnaires and formulate interview questions.
	Recruitment	**80% Participants recruitment:** Develop participation criteria, recruitment documentation and consent forms. Oversee recruitment logistics including communication with participants. Help was provided by research assistants for scheduling.
	Data collection	**80% Experimental pretests:** Plan and oversee pretests to confirm the choice of VR stimuli, stimuli sound levels, user ergonomic position, and quality of the collected brain activity. Help was provided by the operations teams and research assistants for troubleshooting, as well as by co-authors for post hoc quality assessment of neurophysiological data. **80% Data collection**: Manage data collection including technical setup, tools installation (e.g., EEG / EDA), and physiological signals calibration / verification. Moderate the experiment and conduct user interviews. Help was provided by a research intern for stimuli launch, timestamp records, note keeping, material cleansing.

	Statistical analysis	**80% EEG data analysis**: Perform ICA analysis to clean ocular artifacts, inspect data visually, calculate grand average ERPs, and perform adequate statistical analyses. Help and guidance was provided by a co-author throughout the process. **80% Psychometric & physiological data analysis**: Extract, clean and format the psychometric data file. Help was provided by a statistician at this stage for performing analyses pertaining to psychometric, EDA, and ECG data. **60% Qualitative data analysis**: Transcribe verbatim from user interviews and detect emerging trends in qualitative data. Help was provided by a research intern.
	Results presentation	**80% Report preparation**: Prepare slide content and presentation script. Help was provided by a graphic designer for the final slide design. **100% Conference presentation**: Presentation of the research and results at the annual SIG HCI Conference, December 2021.
Chapter 3: Field study	Research question	**100% Research question definition**: Formulate a research question aligned both with the inherent format of the VR exhibition and with needed contributions to the field of VR. Input regarding the experimental design was provided by research directors at this stage.
	Experimental design	**90% Ethics approval:** Perform modifications to the ongoing REB file. Help was provided for a final review of the application. **80% Research protocol**: Write-up the research protocol for data collection. Help and review was provided by the operations team. **100% Partner relationship management**: Coordinate with PHI with regards to experimental logistics including tools compatibility, ticket reservation and experimental setup. Ensure a smooth data collection process as this was a field study therefore requiring participants to blend in with real spectators of the experience.
	Recruitment	**100% Participants recruitment**: Develop participation criteria, screener for recruitment, tools documentation and consent forms. Manage recruitment logistics including pairing of participants, communication, and scheduling.
	Data collection	**80% Experimental pretests**: Prepare and oversee pretests to assess tools synchronization and overall experimental flow. Help was provided at this stage by research assistants and members of the operations team. **80% Data Collection**: Manage data collection by welcoming participants on-site, assisting in tools installation, and performing user interviews. Sanitize and wash all material overnight, in between experimental sessions. Help was provided by a research assistant for tools synchronization and troubleshooting.

	Statistical analysis	**100% VR stimuli categorization:** Code and categorize all 45 VR videos in specific categories pertaining to their visual, auditive, and spatial features. Viewing of videos was performed at PHI's offices. **90% Psychometric and psychophysiological data analysis**: Extract, clean and format the dataset. Perform analyses using SPSS. Help and guidance was provided by a statistician throughout the process.
	Results presentation	**80% Creation of partner report:** Package results for optimal communication. Create slide content and slide design. Help was provided by a statistician for specific analyses and for results delivery into optimal visual representations. **100% Partner presentation:** Present results to partners, i.e., members of PHI and Félix & Paul Studios, over a 30-minutes presentation. Research directors were also present during this partner presentation.
Scientific articles		**100% Scientific articles write-up**: Write, edit and publish scientific articles in relation to the first and second phases of this research. Review from co-authors was provided on the first study's succinct article (Appendix A). Guidance, review and feedback was provided by research directors on both scientific articles.
Thesis		**100% Thesis write-up**: Write the thesis detailing all phases and implications of this project. Guidance, review and feedback was provided by research directors throughout the process.

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Chapter 2: Laboratory Study

Inhale Positivity, Exhale Presence: Leveraging Multisensory Virtual Reality for Mindfulness Therapy[1]

Abstract: Virtual Reality (VR) is well known for its ability to immerse users in a parallel universe. Accordingly, VR offers great potential for mindfulness therapy, especially in a post-pandemic world. However, the extent to which our senses should be recruited to yield an optimal feeling of presence in the Virtual Environment (VE) remains unclear. This study investigates the lived and perceived effects of adding auditory and motor components to VR experiences, through narration and head movements respectively. A sample of twelve participants experienced four nature-based VR videos in a within-subjects research design. The study employed a mixed methods approach combining a wide set of neurophysiological, psychophysiological, and psychometric measures. Results support a significant relationship between positive affect and presence. While statistical support was not obtained for the remaining relationships between the introduction of auditory and motor components in the VE and users' arousal, positive affect, presence, and immersion, both expected and unexpected directionalities were observed. This study provides rich methodological contributions including a feasibility assessment of utilizing NeuroIS methods in evaluating immersive user experiences, along with qualitative insights that extend our understanding towards optimized VEs design.

Keywords: User Experience, Virtual Reality, Presence, Immersion, Multisensory Experience, NeuroIS

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[1] An abridged version of this study was published in the Association for Information Systems Special Interest Group on Human Computer Interaction (AIS SIGHCI) 2021 Conference Proceedings. The entitled version *Evaluating User Experience in Multisensory Meditative Virtual Reality: A Pilot Study* can be found in Appendix A of this document, and is available online. The longer and complete version of this study, as presented in Chapter 2, has not been published yet.

2.1 Introduction & Research Motivation

2.1.1 The potential of VR: A plausible solution to the mental health pandemic

In the context of the pandemic, chronic stress has considerably risen. In the United States, nearly 37% of adults reported symptoms of anxiety disorder in November 2021, a proportion that rose as high as 48.7% among the 18-29-year-olds. This is a notable increase compared to the 8.9% of adults reporting these symptoms back in 2019 (CDC, 2022). Not only did the pandemic generate significant psychological pressure with regards to the risks of contagion of oneself and loved ones, but social restrictions and extended isolation may also have acted as intensifying triggers to anxiety (Cao et al., 2020; Pera, 2020). Elevated and persistent stress levels, driven by ever evolving sanitary measures and their unpredictable outcomes, are prone to result in emotional, physical, and mental fatigue (Zhang et al., 2020). Needless to say, a particular focus on mental wellbeing has been emerging over the past year, and the increasing prevalence of anxiety in the general population emphasizes the necessity to turn to novel and efficient strategies to alleviate the negative symptoms experienced by many.

In stressful times, the practice of mindfulness, the act of actively bringing our full attention to the present moment by reconnecting mind and body, has been recommended as it predicts positive emotional states (Brown & Ryan, 2003). Numerous studies exploring the benefits of mindfulness therapies such as Mindfulness Meditative Training (MMT) and Mindfulness Based Cognitive Therapy (MBCT) have shown preliminary support for the reduction of anxiety symptoms in patients suffering from anxiety disorders (e.g., Kim 2009, Van Dam et al., 2014). However, these therapies present notable limitations; that of requiring a rigorous process, such as MBCT being an 8-week skills training program, or simply being difficult to learn (Chiesa & Serretti, 2010; Giorini, 2009). Given the stated limitations and the urgency of the situation, novel technologies can help in providing a more accessible solution. Specifically, previous research has supported that a promising approach to facilitating mindfulness lies in the use of Virtual Reality (VR), a technology that mimics real-world sensory stimuli as it immerses users in a simulated Virtual Environment (VE) (Motraghi et al., 2014; Morina et al., 2015; Tarrant et al., 2018). For example, the presentation of natural landscapes in VR was found to successfully increase alpha brain activity, i.e., a proxy for lower anxiety states, increased calmness, and positive affect, in patients with Generalized Anxiety Disorder (GAD) (Tarrant et al., 2018). Thus, through its ability to be used in the comfort of one's home, cutting-edge VR presents an interesting and appealing opportunity for individuals to practice mindfulness in today's era of the "mental health pandemic".

2.1.2 The immersive nature of VR: A heightened presence and immersion

A distinctive feature of VR, among other technologies, is the sense of presence it generates by means of its immersive nature (Riva et al., 2015). The term *immersion* has been described by Kim & Biocca as "the degree to which the range of sensory channels is engaged by the virtual simulation" (Kim & Biocca, 2018, p. 95). In VR, specific affordances are responsible for creating a more immersive experience; these include, but are not limited to, higher resolution, better image quality, higher sound fidelity, and larger field of view (Parong et al., 2020). In line with this, immersion has been related to the objective measure of how vivid a virtual environment qualifies, while *presence*, on the other hand, has been related to the subjective, psychological experience of "being there" in the virtual environment (Cummings & Bailenson, 2016). Thus, the main distinction seems to lie in whether the measure is of objective or subjective nature, but the extent to which each term ends and the other begins is still not clear (Cummings & Bailenson, 2016). Given there remains little consensus about the specific definition for each concept, literature continues to often place them hand in hand (Marto et al., 2020). Nevertheless, a sense of presence is argued to be determined by two major dimensions of the virtual environment: its interactivity and its vividness (Steuer, 1992).

Interactivity refers to the degree by which users' actions can influence the content of the VE (Steuer, 1992). In fact, an important aim of VR is to provide an environment in which users can interact with virtual objects and virtual humans, as well as with the virtual environment itself (Yang et al., 2019). A way by which such interactions are enabled in VR is through the addition of *motor components* to the experience, such as head and/or body movements to explore the virtual environment or manipulate virtual objects (Bricken, 1991). In such cases, relevant feedback must be provided by the VE in response to user movements to render the experience realistic and complete (Yang et al., 2019).

Vividness refers to the sensory richness of the VE, which can be further divided into the sensory depth and sensory breadth of the virtual experience (Steuer, 1992). Depth relates to the quality of information delivered in each sensory dimension (Suh & Lee, 2005). For example, a deep auditory experience would be one that features different *auditory components* such as music, narration, etc., and therefore delivers multiple auditory stimuli simultaneously to the user. Breadth*,* on the other hand, is related to the number of sensory dimensions that are simultaneously presented in the virtual environment (Suh & Lee, 2005). The latter is closely aligned to the notion of multisensory environments, in which information from different senses (e.g., visual, auditory, tactile information) is integrated by our brain into a temporally and sensorially coherent representation (Marucci et al., 2021).

2.1.3 The gap in multisensory therapeutic VR: A call for research

In line with the breadth of an experience, VR aims to recreate real-world multisensory environments through visual, auditory, haptic, and in some cases, even olfactory and taste sensations (Steuer, 1992). Accordingly, VR can elicit experiences that are more vivid than the ones we tend to create using our imagination and/or memory, the latter being the usual resorts for mindfulness practice (Pallavicini et al., 2009). In line with this, previous research showed that VR experiences have the ability to produce a broad empowerment process, mainly through the high sense of presence it generates (Riva & Gaggioli, 2009). Specifically, research by Villani et al. (2007) reported the sense of presence as a mediating variable when it comes to the efficacy of mindfulness therapy using VR. In other words, mindfulness therapy could leverage VR in delivering multisensory experiences, therefore immersing users in highly vivid VEs, as a means to enhance their sense of presence and ultimately optimize the therapeutic potential of the technology.

To date, however, many studies investigating VR have looked at its multisensory nature through learning or educational contexts (Makransky et al., 2019; Parong et al., 2020; Baceviciute et al., 2020, 2021), rather than from a mindfulness or meditative lens. In fact, many VR studies have built upon the modality principle; a principle by which learning through different senses is more beneficial than through a single modality. For example, studies by Makransky et al. (2019) and Baceviciute et al. (2020) investigated the effect of textual and auditory components via text-narrated content on learning outcomes. However, very few studies have transposed this multisensory approach to therapeutic contexts (Dinh et al., 1999; Ranasinghe et al., 2018). This gap in literature is reinforced by the fact that evaluating movement in VR is challenging, which has been raised as a considerable limitation by previous research. Specifically, the addition of motor components to VR experiences is difficult to evaluate through measures of lived experience, such as electroencephalography (EEG), due to the noise that movements introduce in the analysis of brain activity (Zhang et al., 2017; Baka et al., 2018). As a result, restricting user movements to ensure data quality comes at the cost of evaluating ecologically valid immersive user experiences, leading many studies to point out movement restriction as a significant limitation to their results (Tromp et al., 2018; Baceviciute et al., 2020). For example, in a study comparing brain activity between physical and 3D virtual environments, the authors concluded being "aware that [they] may have had better results if the subjects had the possibility to move their body in the physical space" (Baka et al., 2018, p. 114).

Together, these limitations create an important lack of evidence regarding *which* sensory dimensions of the VE are responsible for optimizing the sense of presence, and by extension, the therapeutic potential of VR. Building upon the existing body of literature, and the growing need to attend to mental wellbeing in our post-pandemic world, our study aims at resolving the existing gap in multisensory therapeutic VR research by, first, varying the sensory vividness of the VE by manipulating the auditory and motor components of the experience and, second, compensating for user movement by adopting a mixed methods approach. Therefore, the main objective of this study is to explore the effects of multisensory VEs on the user's lived and perceived experience, hence:

> **RQ1.** Does the addition of an auditory component to the VR experience, through narration, increase a user's sense of presence and immersion?
>
> **RQ2.** Does the addition of a motor component to the VR experience, through head movements, increase a user's sense of presence and immersion?

Given the aforementioned premise that vividness is related to the sensory richness of an experience, our general hypothesized lens is the following; we expect more multisensory experiences, those created in VR by manipulating the experience's auditory depth through added narration and sensory breadth through added head movements, to be more vivid, and therefore result in better therapeutic outcomes by enabling a greater sense of presence. Guided by this central directionality, a detailed set of hypotheses is presented next.

2.2 Theoretical Background & Hypotheses Development

2.2.1 Perceived experience in VR

Sense of presence

A study by Van Kerrebroeck et al. (2017) on the determining role of vividness in VR, showed that VR experiences afford higher levels of vividness and presence than 2D videos, with vividness positively affecting presence. As described earlier, vividness refers to the sensory richness of a virtual environment, namely through its sensory breadth and sensory depth. A more vivid experience is therefore one that recruits a greater number of sensory dimensions simultaneously. To date, the majority of studies that have investigated the effect of an experience's sensory depth on a user's sense of presence have done so through the visual dimension of the experience, namely by evaluating the difference between 2D desktop and 3D virtual experiences (e.g., Kober et al., 2012; Slobounov et al., 2015; Xu & Sui, 2021). Going back to the early ages of VR, around the time when next-generation commercial headsets were first released, behavioral data from a Slobounov et al.'s (2015) study showed that fully immersive 3D conditions, compared to 2D conditions, elicited a higher subjective sense of presence. A few years later, a study by Kweon et al. (2017) showed similar results through the evaluation of beta waves, a proxy for attention, which were greater for users exposed to 3D than 2D videos. These findings suggest that 3D representations, which offer closer-to-reality graphics, provide an additional layer of visual information when compared to their 2D counterparts. Over the years, studies by Dan & Reiner (2017), Makransky et al. (2019), and Xu & Sui (2021) all came to the agreement that 3D immersive experiences elicit a greater subjective sense of presence than 2D representations: a conclusion reinforced by Van Kerrebroeck et al. (2017) demonstrating that VR leads to higher vividness as compared to their 2D counterparts, with the former generating a greater sense of presence. Applying this logic to our research lens, we expect the addition of sensory layers to the VE (i.e., other than visual) to act similarly by increasing the vividness of the experience, and to therefore elicit a greater sense of presence as follows;

> **H1a:** The addition of an auditory component to the VR experience will generate a greater sense of presence.
>
> **H1b:** The addition of a motor component to the VR experience will generate a greater sense of presence.

Positive affect

The extent to which we describe an experience with pleasurable emotions (i.e., feeling content, good and happy) can be characterized as positive affect (Pressman et al., 2019). A recent study, performed in augmented reality (AR), investigated the impact of adding different sensory layers of visual, auditory, and olfactory stimuli on presence and enjoyment (Marto et al., 2020). Results pertaining to the effect of an experience's auditory depth on positive affect showed that conditions which were designated as multisensory, i.e., with added visual and auditory components, were rated higher on enjoyment than the baseline condition. With AR sharing a similar digital nature to VR, and enjoyment being a main component of positive affect, we expect positive affect to fluctuate similarly for VR experiences in which narration, i.e., an additional auditory component, is introduced. When exploring the relationship between movements and positive affect, a study by Plante et al. (2006) investigating the effects of exercise in VR demonstrated that scores of enjoyments were higher for conditions with an added motor component, i.e., walking during the experience, than those that did not. Based on extant literature, we expect positive affect to be enhanced in experiences that feature an added auditory and/or motor component as follows;

> **H2a:** The addition of an auditory component to the VR experience will generate more positive affect.
>
> **H2b:** The addition of a motor component to the VR experience will generate more positive affect.

2.2.2 Lived experience in VR

Emotional arousal

Electrodermal activity (EDA), measured at a user's palmar location, reflects eccrine sweat glands activity which are regulated by the sympathetic nervous system (Dillon et al., 2000). Thus, EDA is particularly relevant as it highly correlates with different levels of arousal (Riedl and Léger, 2016). In line with this, emotional arousal, a state of heightened physiological activity, has been associated with changes in EDA, and further supported by measures of heart rate variability (HRV) and heart rate (HR) that are provided by the electrocardiogram (ECG) (Sequeira et al., 2009). Specifically, HR increases as a function of the emotional intensity of an experience (Dillon et al., 2000). These measures of lived experience become particularly interesting when wanting to evaluate the activation of the nervous system as a response to the sensory load of an experience.

In fact, each sensory stimulus being picked up by the nervous system contains a certain amount of perceptual information. Accordingly, we would expect that adding sensory components to a VR experience would increase the experience's perceptual load, which, in turn, would increase the activity of the sympathetic nervous system and generate greater arousal. In support of the above, a recent study by Marucci et al. (2021) that compared arousal between high perceptual load conditions, i.e., visual-audio or visual-vibrotactile, and low perceptual visual-only conditions, found arousal to be significantly higher in multisensory conditions. Thus, in the lens of our multisensory approach, we expect the addition of auditory and/or motor components to yield greater emotional arousal as follows;

H3a: The addition of an auditory component to the VR experience will increase emotional arousal.

H3b: The addition of a motor component to the VR experience will increase emotional arousal.

Immersion in VR

In the past, the majority of studies evaluating presence and immersion in VR have focussed on post-evaluation measures, thus failing to capture the intricate processes that occur *during* immersion. However, post-evaluation measures introduce memory, recency and recall biases (Freeman et al., 1999; Marto et al., 2020). Nowadays, some studies are turning to EEG measures of brain activity to counter these potential biases and get a better grasp of a user's cognitive state (Baceviciute, 2021). In line with this, an interesting study by Kober & Neuper (2012) successfully showed a way to replace post-immersive questionnaires by relying on event-related potentials (ERPs) of the electroencephalogram as a proxy for a user's subjective feeling of presence in a virtual environment. By definition, ERPs are very small voltages that are generated by the brain as a response to specific events or stimuli (Sur & Sinha, 2009). As time-locked brain signatures, ERPs can therefore be used to infer a user's allocation of attentional resources, and by extension, a user's immersion in a VE (Kober & Neuper, 2012). In this line, previous research on multisensory VR driving simulations showed performance to be higher in bimodal visual-audio and trimodal visual-vibrotactile simulations than unimodal visual stimulations (Marucci et al., 2021). Additionally, a study by Slater, Usoh & Kooper (1996) found a positive relationship between performance and immersion. Thus, based on these combined findings, we expect multisensory VEs to generate greater user immersion as follows;

H4a: The addition of an auditory component to the VR experience will increase user immersion.

H4b: The addition of a motor component to the VR experience will increase user immersion.

2.2.3 Additional effects on perceived presence

Positive affect & presence

When focussing on a user's sense of presence, previous research showed that positive affect acts as a predictor of flow (Tobert & Moneta, 2013). Flow, as famously described by Csikszentmihalyi, refers to a state of absolute absorption in which people feel completely immersed in their activity (Csikszentmihalyi, 1990). From a phenomenological perspective, flow and presence are both characterized as absorbing states, with defining features ranging from the loss of self-consciousness to an altered perception of time (Riva & Gaggioli, 2009). Accordingly, with previous research qualifying positive affect as a predictor of flow, and with flow being closely related to the sense of presence, we expect virtual experiences that elicit greater positive affect to make users feel more present in the VE as follows;

H5: Greater positive affect will generate a greater sense of presence.

Emotional arousal & presence

Furthermore, previous studies have shown a positive relationship between enhanced physiological reactions, namely HR and EDA, and the act of assigning personal relevance, i.e., presence, to an environment (Weech et al., 2019). Aligned with this, one would logically believe that when experiencing a variety of strong emotions, humans become even more aware of themselves and their bodily reactions, thus likely to momentarily increase their perceived sense of presence in a given environment. Therefore, we expect greater emotional arousal to generate a greater sense of presence as follows, and as summarized in Figure 2.1;

H6: Greater emotional arousal will generate a greater sense of presence.

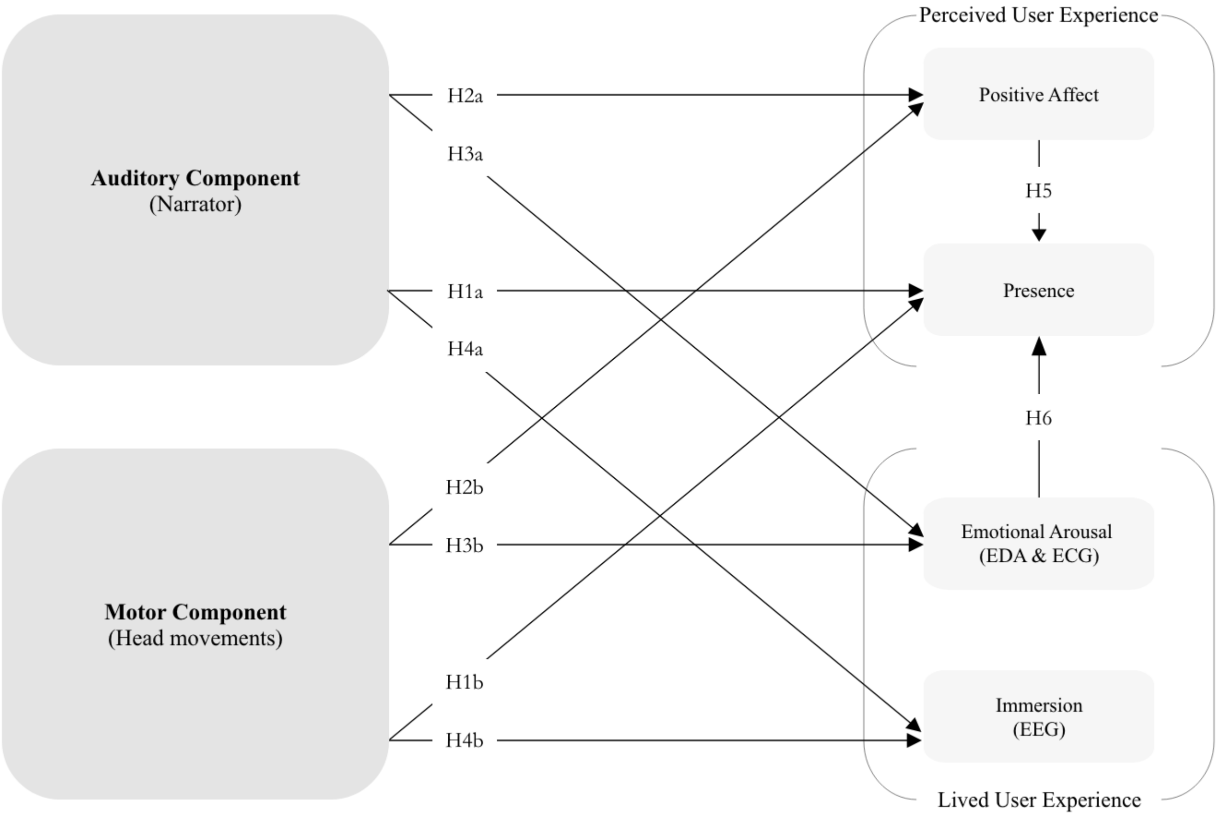

Figure 2.1 Research model

2.3 Method

2.3.1 Sample

Twelve healthy participants (eight females; four males; zero non-binary) aged between 19 and 31 years old (*M* = 22.92 years*, SD* = 3.90) took part in this study. All participants reported a normal or corrected-to-normal vision and no history of a psychiatric or neurological disorder. The study was approved by the Ethics Research Committee of the authors' institution, with participants' prior written consent and their verbal consent reiterated at the time of the study (Certificate number 2022-4458). Although all participants had limited-to-no prior experience with VR, i.e., seven participants had never used VR and five participants had used it between one to five times, none reported cybersickness during the experiment. Participants were compensated with CA$40 for their time.

2.3.2 Experimental design

Given the novel mixed-methods approach of this research, its experimental design was built upon the feasibility assessment performed by the authors and presented as a pilot study in Guertin-Lahoud et al. (2021). As such, the experiment presented four unique VR experiences of natural landscapes in a counterbalanced randomized order. Specifically, the experiment employed a 2 x 2 within-subjects design, in which two factors were manipulated: the auditory component of the VR experience (with/without narration) and the motor component of the VR experience (with/without head movements), with no narration/movement used as baseline and always presented first. Accordingly, participants each underwent four conditions: music-only video without head movement (i.e., Raja Ampat baseline condition), music-only video with head movements (i.e., Borneo Forest), music-and-narrated video without head movements (i.e., Wadi Rum Desert) and music-and-narrated video with head movements (i.e., Angel Falls) as detailed in Figure 2.2. In the moving conditions, participants were allowed to explore the VE through slow and lateral head movements, as the extent of these movements were found to not significantly impede the quality of the EEG signal during pretests. To ensure a proper level of similarity between videos, these were chosen on the basis of specific selection criteria as detailed in Table 2.2 of Section 2.3.3. Additionally, their audio fidelity and users' personal preference for each video were assessed during the experiment as manipulation checks.

Figure 2.2 Experimental design

2.3.3 Materials & measures

This study employed a mixed methods approach combining psychometric, psychophysiological, and neurophysiological measures. The hardware consisted of a VR head-mounted display (HMD), an EEG headset, EDA and ECG sensors. The software consisted of questionnaires and four different VR videos. Additional materials included auditory ERP stimuli emitted into the test room.

All VR videos and questionnaires were delivered in English, while the briefing, instructions and interview were conducted in French. Materials and measures are presented in detail next.

Surveys and psychometric measures

All surveys were administered using the software Qualtrics (Qualtrics, Provo, Utah, USA, 2021) and were deployed on a VR browser web page. The study comprised three different surveys. First, considering Baka et al.'s (2018) study showing a significant and positive relationship between users' prior experience with VR and immersion, participants were asked to answer a pre-experiment survey to assess their prior VR experience (i.e., number of uses, ownership) as well as their basic demographics (i.e., age, gender, education level, occupation, matrimonial status, nationality, ethnicity). Then, after viewing each video, participants were asked to answer a short survey to assess presence, positive affect and audio fidelity. This post-video survey was completed a total of four times. Finally, a post-experience survey was filled out at the end of the experiment to assess video preference. Respective psychometric constructs are detailed next. Based on Cronbach's alpha, the reliability of all chosen scales (i.e., SUS, GEQ, PQ) ranged between good and excellent per values detailed in Table 2.1.

Table 2.1 Cronbach's Alpha

Scale	Construct	Number of items	Cronbach's alpha
SUS	Sense of Presence	6	0.93
GEQ	Positive Affect	5	0.95
PQ	Sensory Audio Fidelity	3	0.83

Reliability coefficients for self-report scales

Sense of presence, a user's subjective sense of "being there" in the virtual environment, was measured using Slater-Usoh-Steed's (2000) Presence Questionnaire (SUS). Scores were recorded on a seven-point Likert scale, where (1) corresponded to not feeling there at all and (7) corresponded to feeling as present as in the real world.

Positive affect elicited by the experience was measured using the positive affect component of IJsselsteijn et al.'s (2013) Game Experience Questionnaire (GEQ). Items were adapted to a seven-point Likert scale from (1) not at all to (7) extremely.

Audio fidelity was measured using the validated audio fidelity sub-scale of Witmer, Jerome & Singer's (2005) Presence Questionnaire (PQ). Items were adapted to a seven-point Likert scale from (1) not at all to (7) somewhat completely, and were used as a manipulation check to ensure all chosen videos featured similar quality in the audio they delivered.

Video preference (VP) was measured with a ranking of all four videos at the end of the experiment. The options ranged from (1) preferred video to (4) least preferred video. VP served as manipulation check to ensure all chosen videos were similarly appreciated by participants.

VR head-mounted display

The Oculus Quest 2 HMD (Facebook, Inc., Menlo Park, CA, USA) with a display resolution of 1832 x 1920 per eye and 72Hz refresh rate, was chosen for this experiment. Its all-in-one design included built-in speakers, preventing from overcrowding the participant's head with external earphones, and thus allowing for a comfortable setup when combined with the EEG headset as shown on Figure 2.3. The interaction with the VE was enabled through two Oculus controllers, but participants were instructed to perform actions with the right one only, due to EDA sensors placed in the palm of their left hand. During the study, participant's VE was streamed to a laptop so that researchers could monitor participants' experience in real-time.

Figure 2.3 Combination of the EEG and VR HMD (left); VR controllers (right).

Credits: Photos taken by David Brieugne, Tech3Lab.

VR stimuli

When selecting the VR stimuli, several parameters had to be considered. These included the interactive nature of the stimuli (i.e., passive or active), their stereoscopic and visual properties (i.e., depth of view, viewing perspective, image quality, speed of transitions), their music genre, their respective durations, and their compatibility and availability on the Oculus Store. Four stimuli were selected from the Oculus Store based on their similarity in visual, musical, stereoscopic, and generic properties as detailed in Table 2.2. That is, they were all classified as bird's-eye view videos of natural landscapes featuring soft background music. Passive stimuli were selected rather than active ones, to minimize participants' body movements and optimize overall EEG quality. From the chosen stimuli, two of the videos featured narrated historical and geographical facts. Although their content differed, both videos were narrated by the same male voice. Additionally, to further ensure that the core attributes of the chosen VR stimuli were equivalent, i.e., that videos were similar in all the other dimensions of the experience except for the manipulated variables, manipulation checks were completed with regards to the audio fidelity and content preference for each video as further detailed in Section 2.4.1.

Table 2.2 VR Stimuli Properties

Landscape	Media	Duration	Music	Narrator
Raja Ampat, Indonesia	Ecosphere Journey	6min 50s	✓	
Borneo Forest, South-East Asia	Ecosphere Journey	6min 27s	✓	
Wadi Rum Desert, Jordan	AirPano	6min 16s	✓	✓
Angel Falls, Venezuela	AirPano	6min 34s	✓	✓

Descriptive properties of the chosen VR stimuli

Neurophysiological measurement stimuli

Event-related potentials are changes in the activity of neuronal populations that are induced by specific events or stimuli, most often sensory stimuli (Pfurtscheller & Da Silva, 1999). The rather unique advantage of ERPs is that they are time-locked cerebral signatures. For instance, N100 is an early and negative component of ERPs (Kok, 1997). It is said to be exogenous, and associated with the allocation of perceptual resources, as it can be elicited by any discernible auditory stimulus (Kok, 1997; Rosburg et al., 2008). On the other hand, later positive components of the ERP, such as P200, reflect the allocation of both perceptual and central resources (Kok, 1997). These late

ERP components therefore allow to measure correlates of mental processes and, by extension, the allocation of a user's mental resources (Kober & Neuper, 2012). In line with this, conditions that recruit higher attentional resources leave less attentional resources for the processing of task-irrelevant stimuli, therefore resulting in decreased amplitudes of the P200 peaks (Kober & Neuper, 2012). Accordingly, greater immersion can be inferred from smaller P200 amplitudes. Per this regard, and building upon Kober & Neuper's (2012) methodology, our study used auditory tones as ERP stimuli, and investigated resulting amplitudes of P200 peaks as proxies for user immersion.

The auditory tones were emitted in the test room at a mean inter-stimulus interval of 7s and standard deviation of +/-3s through two identical speakers (Logitech, Lausanne, Switzerland). Those were placed on a table, in front of the participant, at an interior angle of 25°, 70 cm apart, and 120 cm away from the seated participant. The auditory ERP stimuli were launched simultaneously to the start of each VR stimulus and were ended automatically as the VR stimulus came to its end.

Neurophysiological measurement tools

The EEG data was collected using the wearable Unicorn Hybrid Black (g.tec Neurotechnology GmbH, Graz, Austria) wireless 8-channel system running at a sampling rate of 250 Hz per channel. The eight electrodes were positioned at F3, F4, FC5, FC6, C3, C4, P3, P4 according to the extended 10-20 international placement system, and referenced to linked mastoids. The positioning of electrodes was determined as a trade-off between, first, an adequate coverage of the regions of interest for ERP analysis, namely frontal and central regions, and, second, a non-obstructive placement with regards to the VR HMD's lateral and superior adjustable straps. Hence the reason why midline electrodes (e.g., Fz, Cz) were not used. Given head movements were allowed for a subset (i.e., one-half) of the conditions, Ag/AgCl wet electrodes were used; the added electrolyte gel allowed for better conduction and adhesion, thus making the signal less prone to motion artifacts. Indeed, pretests comparing wet and dry electrodes indicated a significantly improved signal quality when using the former. The EEG data and markers of the ERP stimuli were collected and synchronized through the Lab Streaming Layer (LSL) protocol.

Psychophysiological measures and tools

To both compensate for the potential effect of movement on the EEG signal quality and to enrich data analyses in relation to the proposed research model, additional measures of lived experience, including psychophysiological measures of EDA and ECG (i.e., HR and HRV), were used in this study. These were measured via disposable Ag/AgCl electrodes that were placed on the palm of the left hand and on the chest of the participant respectively. Psychophysiological data was collected using the MP-160 BIOPAC acquisition system and the AcqKnowledge software (BIOPAC Systems Inc., Goleta, CA, USA).

2.3.4 Sound levels pretests

As the chosen videos were created by different developers, they each featured a different built-in sound level. Thus, stimuli volume levels were adjusted based on pretests such that VR stimuli were clear, comfortably audible, and perceptibly constant across all videos. Sound levels of the ERP stimuli were also determined during pretests such that they were comfortably audible when emitted in parallel to the VR audio, but not distracting. Additionally, the videos' audio fidelity, i.e., how well the users could localize and identify sounds and the extent to which the auditory aspects of the environment involved them, was measured during the experiment to ensure all videos were rated similarly on that dimension, as detailed in Section 2.4.1.

2.3.5 Procedure

Room setup

Participants were tested individually in a user experience lab at a North American University. For improved external validity, the test room was an imitation of one's living room with a sofa, painting and side tables decorating the space, as if users were to engage in a meditative VR experience in the comfort of their own home. Participants were seated on a fixed chair at 45 cm above floor level allowing for a comfortable position, having both feet on the ground. The test room was soundproofed, and the lightning was stable as blinds were kept closed. A one-way mirror wall separated the moderator and participant throughout the experiment.

Sanitary protocol

As this study was performed while COVID-19 related regulations were in effect, particular sanitary measures and precautions were put in place to ensure participants' safety. The sanitary protocol required both the moderator and the participant to sanitize their hands upon arrival, wear a disposable surgical face mask throughout the experiment, maintain a two meters distance whenever possible and minimize unnecessary physical contacts. In addition, the test room was cleaned, and all materials were sanitized between each participant.

Experimental procedure

Upon arrival, participants were briefed on the tools and the general format of the experiment, after which their consent was obtained. This was followed by a set of demonstrations regarding functionalities of the VR controllers and the VR headset (e.g., volume button), as well as a demonstration of the permitted head movements. Specifically, participants were instructed to move their heads slowly and on the horizontal axis only, i.e., to avoid fast, vertical and/or circular head movements, such that their head position should be maintained for a few seconds and their torso should remain still despite head movements.

The following step was the tools installation. Participants were first guided through EDA and ECG sensors placement, after which a psychophysiological data quality check was performed using the AcqKnowledge software. Participants were then fitted with the EEG cap followed by the VR HMD. To ensure a comfortable physical setup, the lateral and superior straps of the VR headset were carefully adjusted to the participant's head. At this point, participants were instructed to minimize unnecessary facial movements such as excessive frowns and eye blinks to reduce possible interference with the EEG signal. A subsequent neurophysiological data quality check was performed using the Unicorn Hybrid Black software. Once data quality was assessed as satisfactory through visual inspection of the EEG signal, the VR HMD was turned on and the virtual experience was streamed to the moderator's laptop. From then onwards, participants were left alone in the test room and further instructions were provided by the moderator through a microphone.

Once immersed in the VE, the first step for participants was to complete the pre-experiment survey administered in the VR browser. Upon completion, participants were directed to the main menu to select the VR baseline stimuli. While participants watched the video, auditory ERP stimuli were emitted in the test room in parallel, but unrelated, to the VR experience. At the end of the video, participants were redirected to the VR browser to fill out the post-video survey. This process of watching the video and filling out the short survey was repeated for the three subsequent conditions. Specific instructions regarding each condition were delivered when relevant as to not overload participants with extraneous information. At the end of the experiment, the post-experiment survey was completed, recordings were stopped, and the equipment was removed. A short interview was then conducted to better grasp participants' overall experience. More specifically, participants were queried about reasons for their most and least preferred video, the experience in which they felt the most and least present, along with their post-experience state of mind. To minimize error and improve internal validity, experimental procedures were outlined in a standardized laboratory protocol; procedural steps and verbatim were closely followed by the moderator at the time of the experiment. Test sessions each lasted for an approximate duration of 120 minutes, and were finalized with participants' compensation.

2.3.6 EEG data processing

The EEG data was preprocessed and analyzed using the open-source Brainstorm software (http://neuroimage.usc.edu/brainstorm). Data was processed and analyzed following guidelines from Demazure et al. (2021). For the preprocessing, Independent Component Analysis (ICA) was performed to remove ocular artifacts, i.e., eye blinks, and other recurring noise from the data. EEG data was then bandpass filtered from 1–40 Hz. Subsequently, the EEG data was epoched from -1000ms to 2000ms relative to ERP stimulus onset. On average, a total of 46 epochs were generated per condition. Visual inspection of all epochs was performed, and epochs with marked artifacts were excluded from further analysis. Accordingly, an average of 11.16% epochs across conditions were rejected (i.e., 16.20% for Raja Ampat, 11.33% for Borneo Forest, 6.90% for Wadi Rum Desert, and 8.41% for Angel Falls). Time-series ERP waveforms were averaged across epochs for each condition within each participant. These ERP waveforms were then averaged across all participants to produce a grand-average ERP for each condition. The time point of peak amplitude for the N100 and P200 peaks was visually identified, and the mean time point across all conditions was calculated. Then, the amplitudes of the N100 and P200 peaks were averaged over time within each participant from -25ms to +25ms relative to these peak amplitude time-points. The resulting values were used in subsequent statistical analyses, detailed in the following section.

2.3.7 Statistical analysis

Statistical analyses were performed using the Statistical Analysis Software SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Psychometric data was exported from Qualtrics to be aggregated and reordered in an Excel file. Psychophysiological data was exported from the AcqKnowledge software, and data synchronization was performed following guidelines from Léger et al. (2014; 2019). Potential outlier values in ECG data were visually identified. Accordingly, values inferior to 40bmp and superior to 100ms were considered outliers with regards to HR and HRV respectively, and were excluded from further analyses. The effect of the two independent variables of interest, i.e., narrator and head movement, on the sense of presence, positive affect, EDA, HR and HRV were examined using a linear regression with random intercept model. Additionally, potential effects of emotional arousal and positive affect on the sense of presence were examined using a multiple linear regression with random intercept model. Differences in ERP amplitudes between conditions were analyzed using repeated measures ANOVA for the P200 peaks, with narrator and head movements as factors. The threshold for significance was set at $p<0.05$.

2.4 Results

This section presents psychometric, psychophysiological, neurophysiological, and qualitative results for the sample of 12 participants. Upon testing normality of the dependent variables using a Shapiro-Wilk tests, the values for presence and HR showed to be normally distributed ($p=0.10$ and $p=0.06$, respectively). On the other hand, positive affect, EDA and HRV were not normally distributed, even when a log transformation was applied. Thus, median splits were applied to these variables and a logistic regression was used to investigate the effects of narration and head movements on the dependent variables of interest. However, the conclusions obtained from the logistic regression were not any different than the conclusions obtained using a linear regression with random intercept model. Hence, results from the latter test (i.e., linear regression) are those presented in the results section.

2.4.1 Manipulation checks

Did participants' demographics have an effect on the model?

The pre-experiment survey served as a basis to evaluate whether participants' demographics (i.e., age, gender, group identification and previous VR use) would influence other variables of interest. Potential effects of these control variables were tested, but were not significant. Accordingly, results presented in the following sections did not change even after accounting for all control variables.

Did all videos deliver equal audio fidelity?

To evaluate whether participants could equally localize and identify sounds across all videos, the mean scores of the audio fidelity were compared between conditions. Results outlined in Table 2.3 show that narrated experiences were rated lower (M=4.86, SD=1.41) than music-only experiences (M=5.82, SD=0.91). Indeed, as Table 2.4 indicates, the addition of a narrator had a significant and negative effect on the audio fidelity of the video (t=-3.49, p=0.0013). This can be interpreted as an important limitation of adding an auditory component to VR experiences, as it implies that the added narration might have overshadowed the clarity of the VR's core audio component (i.e., nature sounds).

Table 2.3 Descriptive Statistics of Perceived and Lived Measures by Sensory Component

		No narrator		Narrator		No head movement		Head movement	
		M	SD	M	SD	M	SD	M	SD
Perceived UX	Presence	4.18	1.37	3.99	1.72	3.99	1.48	4.18	1.62
	Positive Affect	5.68	1.01	5.65	1.30	5.53	1.20	5.81	1.11
	Audio Fidelity	5.82	0.91	4.86	1.41	5.19	1.27	5.49	1.29
	Video Preference	2.50	1.22	2.50	1.06	2.46	1.22	2.54	1.06
Lived UX	EDA	5.11	2.82	4.75	2.51	5.00	2.77	4.86	2.57
	HR	70.46	10.46	70.69	10.59	70.67	10.52	70.46	10.53
	HRV	0.24	0.01	0.25	0.03	0.25	0.02	0.24	0.02

Means and standard deviations of psychometric and psychophysiological data per added sensory component.

Table 2.4 Sensory Component Effects on Perceived and Lived Experience

		Narrator effect			Movement effect			Interaction effect		
		df	*t*	Sig (2-tailed)	df	*t*	Sig (2-tailed)	df	*t*	Sig (2-tailed)
Perceived experience	Presence	35	-0.67	0.5094	35	0.67	0.5094	33	1.58	0.1245
	Positive Affect	35	-0.13	0.8987	35	1.11	0.2754	33	1.94	0.0613
	Audio Fidelity	35	-3.49	0.0013	35	0.93	0.3608	33	0.15	0.8818
Lived experience	EDA	32	-1.62	0.1143	32	-0.81	0.4214	30	0.76	0.4554
	HR	31	0.28	0.7834	31	-0.91	0.3709	29	0.11	0.9160
	HRV	31	1.05	0.3009	31	-1.32	0.1975	29	-1.85	0.0748

Linear regression with random intercept model for narrator and movement effects, and their interaction effect.

Were all videos equally preferred?

To ensure all chosen videos were equally appreciated by participants, and to eliminate a potential confounding effect of video preference on other variables, participants were asked to report their video preference on a ranking from 1 to 4, (1) being their preferred video and (4) being their least preferred video, such that lower VP scores indicate higher preference. The mean scores of video preference were then compared between conditions. Results showed that video preference did not significantly differ between conditions (F(3,44)=1.885, p=0.146), which confirms that the chosen videos were not perceived differently in this aspect.

2.4.2 Psychometric results

Narration and head movements effects on presence

Descriptive statistics detailed in Table 2.3 show that mean presence scores were lower in conditions with a narrator (M=3.99, SD=1.72) than without (M=4.18, SD=1.37), but higher in conditions with head movements (M=4.18, SD=1.62) than without (M=3.99, SD=1.48). Although descriptive results suggest a relationship by which the addition of an auditory layer to the VR experience would reduce subjective feeling of presence whereas the addition of a sensorimotor layer would increase it, results from the linear regression outlined in Table 2.4 were not significant. In fact, neither the addition of a narrator (t=- 0.67, p=0.5094) nor the addition of head movements (t=0.67, p=0.5094) had a significant effect on a user's subjective sense of presence, therefore H1a and H1b are not supported respectively.

Narration and head movements effects on positive affect

Although descriptive statistics detailed in Table 2.3 indicate greater mean positive affect scores in moving (M=5.81, SD=1.11) as opposed to still conditions (M=5.53, SD=1.20), results outlined in Table 2.4 do not support a significant difference between the conditions (t=1.11, p=0.2754). As a result, H2b is not supported. Similarly, mean positive affect scores for narrated (M=5.65, SD=1.30) as opposed music-only conditions (M=5.68, SD=1.01) were not significantly different (t=-0.13, p=0.8987) as outlined in Table 2.4. Thus, H2a is not supported either. Nevertheless, a significant and positive relationship emerged between positive affect and presence. That is, the higher the positive affect, the greater the presence (t=5.64, p<0.0001) as shown in Table 2.5. Hence, H5 is supported, i.e., more positive affect leads to a heightened sense of presence in the VE.

Table 2.5 Fixed Effects on Presence

	Fixed variable effects on presence		
	df	*t*	Sig (2-tailed)
Positive Affect	27	5.64	< 0.0001
Audio Fidelity	27	0.46	0.6493
Video Preference	35	-4.83	< 0.0001
EDA	27	-1.06	0.2983
HR	27	-0.88	0.3446
HRV	27	0.84	0.4076

Multiple linear regression with random intercept model for fixed variable effects on the sense of presence.

Video preference effect on presence

An interesting trend emerged upon examining descriptive results between video preference and presence. In fact, Table 2.6 shows that the two videos for which the highest sense of presence was reported (M=4.31) were also the most preferred ones by participants (M=2.08, SD=1.24 and M=2.17, SD=0.94; note that video preference was reverse coded; i.e., a lower score corresponds to greater preference). This relationship was therefore investigated using a multiple linear regression, and the effect of video preference on presence was found to be significant (t=- 4.83, p<0.0001) as presented in Table 2.5.

Table 2.6 Descriptive Statistics of Lived and Perceived Measures by Experimental Condition

		Music-only without movement		Music-only with movement		Music-narrator without movement		Music-narrator with movement	
		M	SD	M	SD	M	SD	M	SD
Perceived UX	Presence	4.31	1.13	4.06	1.61	3.68	1.77	4.31	1.69
	Positive Affect	5.78	0.89	5.58	1.15	5.27	1.44	6.03	1.07
	Audio Fidelity	5.69	0.70	5.94	1.10	4.69	1.53	5.03	1.34
	Video Preference	2.08	1.24	2.92	1.08	2.83	1.11	2.17	0.94
Lived UX	EDA	5.22	3.20	4.99	2.48	4.76	2.35	4.74	2.77
	HR	70.89	10.82	69.98	10.57	70.43	10.70	70.98	11.03
	HRV	0.24	0.01	0.25	0.01	0.25	0.03	0.24	0.02

Mean and standard deviations of psychometric and psychophysiological data across participants per condition.

2.4.3 Psychophysiological results

Descriptive results from Table 2.6 suggest that participants' EDA was at its highest in the baseline condition (M=5.22, SD=3.20) and at its lowest (M=4.74, SD=2.77) in the most multisensory experience, i.e., music-and-narrated experience with head movements. Surprisingly, descriptive results for heart rates are not aligned with this, as the highest HR was recorded in the most multisensory experience (M=70.98, SD=11.03). However, Table 2.4 shows that these differences in arousal between conditions were not significant. Therefore, H3a and H3b are not supported. Additionally, Table 2.5 reports that the effect of a user's arousal on their subjective sense of presence was not significant either (EDA t=-1.06, p=0.2983; HR t=-0.88, p=0.3446), therefore not supporting H6.

2.4.4 Neurophysiological results

Results from the repeated measures ANOVA presented in Table 2.7 show no significant difference in the P200 mean amplitudes according to the main effects of narrator (F=0.472, p=0.506) and head movement (F=3.299, p=0.097), nor was there a significant interaction effect (F=0.024, p=0.881). Hence, although descriptive statistics detailed in Table 2.8 show that the lowest mean amplitude of the P200 peak (M=0.366, SD=1.793) was observable in the condition with an added narrator but without head movements; and that the largest mean amplitude of the P200 peak (M=1.194, SD=0.955) was observable in the condition without a narrator but with added head movements, these differences were not supported by statistical tests. Therefore, H4a and H4b, by which the addition of narration and movements would increase immersion, are not supported.

Table 2.7 Sensory Component Effects on Immersion

	Narrator effect			Movement effect			Interaction effect		
	df	*F*	Sig	df	*F*	Sig	df	*F*	Sig
P200	1	0.472	0.506	1	3.299	0.097	1	0.024	0.881

Repeated measures ANOVA for P200 mean amplitudes with narrator and movements as within-subject factors.

Table 2.8 Descriptive Statistics of Immersion by Experimental Condition

	Music-only without movement		Music-only with movement		Music-narrator without movement		Music-narrator with movement	
	M	SD	M	SD	M	SD	M	SD
P200	0.611	1.118	1.194	0.955	0.366	1.793	0.869	1.268

Mean and standard deviations of P200 mean amplitudes (uV) across participants per condition.

2.4.5 Qualitative results

Downside effect of added narration

During the interview phase, more than half participants, i.e., 7/12, expressed feeling most present in the baseline condition. Additionally, half participants, i.e., 6/12, reported a preference for music-only conditions. When queried about the reasons for their greater presence and preference, participants reported that the clarity of nature sounds, e.g., birds chirping, wind blowing, etc, were put forward in the absence of a narrator, thus enhancing the overall immersive nature of the environment. In line with this, a few participants reported that the added narrator modified the way they perceived their experience as it made them feel like “watching a documentary, a movie, rather than being in a virtual experience [in which you] move and discover [by] yourself” (P01).

Upside effect of added head movements

The majority of participants, i.e., 10/12, qualified the addition of head movements as beneficial to their experience, as it provided them with a broader field of view, thus enabling them to visually explore more of the virtual landscape. Participants expressed that not being able to move their head made them feel physically limited which consequentially reminded them of their surrounding reality, i.e., the laboratory study context of their experience, whereas head movements empowered their sense of presence and enhanced the immersive nature of the experience.

Meditative potential of VR

Finally, when queried about their states of mind, the majority of participants, i.e., 10/12, reported feeling much more relaxed post-experience. For some participants, viewing the natural landscapes in VR allowed them to “feel as if [they were] flying” (P04), or “feel really immersed as [they] could hear nature” (P05). For some participants, the multisensory experience even went beyond the recruited senses as some reported they “could smell the warmth of the desert” (P04) and “feel the water [on their skin]” (P03).

2.5 Discussion

The main aim of this study was to explore the effects of multisensory VEs on the users’ lived and perceived experience in VR. Concurrently, we aimed to engage in a feasibility assessment of utilizing NeuroIS methods, including EEG, ECG, and EDA, along with more commonplace UX methodologies, including questionnaire and interview, in the evaluation of immersive user experiences. We address both aims through the reporting of theoretical, practical, and methodological implications; we extend that discussion by highlighting the limitations of this study, and conclude with recommendations for future research.

2.5.1 Theoretical implications

The theoretical underpinning of this research was that multisensory VEs, through their increased vividness and ability to recruit a user's senses to a greater extent, would enhance overall user experience. This general premise was aligned with previous research exploring the concept of vividness in VR; building on which we expected experiences that recruit a broader range of senses (i.e., greater breath) and deliver better quality of information in each sensory dimension (i.e., greater depth), to optimize a user's sense of presence, positive affect, arousal and immersion. Revisiting first research questions that were initially posed, descriptive results indicate that the addition of narration to the VR experience might have a *negative* effect on a user's sense of presence, positive affect and arousal, while the addition of head movements to the VR experience seems to have a *positive* effect on a user's sense of presence and positive affect. Although these relationships were not statistically supported, the reported corresponding directionalities offer interesting insights with regards to multisensory VR.

With regards to RQ1 investigating the addition of an auditory component to VR experiences, our results seem to indicate an opposite directionality than the one hypothesized. In fact, it seems that the addition of a narrator to the VR experience might have had a negative effect on a user's sense of presence, positive affect and arousal. These results may be partially explained by an interfering narration on the overall audio fidelity; in fact, the extent to which users could localize and identify sounds was significantly lower in conditions that featured a narrator as opposed to their music-only counterparts. These results suggest that the addition of a narrator could have overshadowed the clarity of the VR's core audio component (e.g., birds chirping, wind blowing, etc.), the latter being identified by many participants as highly supportive of their meditative experience.

With regards to RQ2 investigating the addition of a motor component to VR experiences, our results seem to indicate a directionality in accordance with the one hypothesized. As such, an important theoretical implication of this study is rooted in the relationship between a VE's interactivity and a user's sense of presence. In fact, our results confirm evidence from limited prior research showing that interactivity has a greater influence on the sense of presence when it allows users to map out real world interactions, such that users are not reminded of the simulation boundaries (McRoberts, 2018). Aligned with this, the majority of participants in this study reported that the addition of head movements to explore the VE positively contributed to their experience.

They also reported that the physical limitation arising from keeping their head still acted as a reminder of their surrounding reality, thus hindering their sense of presence in the VE. In line with this, many participants reported that a wider variety of head movements, such as vertical and circular ones, would have even further enhanced the immersive nature of their experience, which should be taken into consideration in the design of future studies.

With regards to the addition of both an auditory and a motor component to the VR experience, we would have anticipated the degree of physiological activation and emotional arousal to be positively correlated with the sensory breadth and depth of the experience. Aligned with previous research showing increased arousal in multisensory VEs (Maruci et al., 2021), we expected the baseline condition (i.e., music-only video without head movements) to be the least arousing. However, results demonstrated that arousal was rated highest in the baseline condition. Along with higher arousal, descriptive results for the sense of presence, positive affect, and video preference all favored this condition. This rather unexpected finding, suggesting enhanced UX in the least multisensory experience, may have been an artifact of the research design. As this condition was always presented first, it is unclear whether these results were due to the order of presentation or to the sensory components recruited in that VE specifically. It is plausible that these results could have arisen from the fact that the baseline condition, always presented as the first of four immersive experiences, appeared as more novel than others, therefore triggering higher physiological activation especially for novice users of VR. In other words, participants might have become gradually calmer given the decreasing novelty of the VR experience as the experiment progressed. In line with the above, another important detail to note is that the physical discomfort of the equipment was positively correlated with the order of the presented VR stimuli. In other words, as the experiment evolved, participants reported feeling less comfortable with regards to the EEG-VR combination. In fact, half of the participants noted a slight headache, which, for the majority, began around the end of the third or beginning of the fourth condition. Thus, the fact that the baseline condition was free of physical discomfort could also partially explain why higher presence, positive affect and preference scores were recorded with regards to that condition.

Another empirical implication of this study is the significant relationship that was supported between positive affect and presence. Specifically, users' positive affect was found to positively influence their feeling of presence in the virtual environment. This is aligned with previous research that qualified positive affect as a predictor of flow, a state which is associated with an increased feeling of presence (Tobert & Moneta, 2013). Thus, results from this study are aligned with those supported by previous literature, and could motivate future research to further explore the relationship between positive affect, flow and presence in VR.

2.5.2 Practical implications

Beyond theoretical implications, a number of important practical implications emerged from this study. First, the significant influence of positive affect on users' presence could serve as a motivation for designers of virtual environments to focus on experiences that elicit joy and happiness, rather than promoting violent and/or negatively loaded content. From a therapeutic perspective, this supports that meditative VEs should promote positively loaded content to enhance users' presence, and, by extension, optimize the meditative benefits of VR.

On the use of VR in therapeutic contexts, results from this study suggest that multisensory VEs are not necessarily the ones to elicit a greater sense of presence nor to promote greater meditative advantages. In fact, much more nuanced results have emerged, as partly demonstrated by the significant relationship between video preference and presence. This finding, according to which a user's preference for a video positively influenced their sense of presence, suggests that the latter construct might be driven by subjective internal dispositions, including personal preferences for a specific type of landscape. From a practical lens, towards an optimal use of VR in mindfulness treatments for anxiety, this finding suggests that VEs should closely attend to users' personal preferences, as to create environments that can be easily tailored and modified accordingly. This could be enabled, for instance, by providing users with greater control over the VE's features regarding the choice of musical and narrative styles, namely through the presence or absence of background sounds, male / female narration, etc. As a result, users could align the content of the VE to their personal preferences; such tailored experiences, per the significant relationship between video preference and presence, would appear beneficial for mindfulness practice in VR.

2.5.3 Methodological implications

As previously mentioned, our study was partially built upon Kober & Neuper's methodology (2012), which, although very insightful in providing a novel way to measure presence in VR, showed certain limitations we aimed to build upon. First, this study was conducted with an immersive screen rather than a more sophisticated VR HMD. Second, the study compared ERPs across groups of participants that subjectively ranked their experience as low or high on the immersion dimension, rather than comparing ERPs across different immersive VR stimuli. In this regard, these limitations served as basis for our study, namely by motivating the use of the Oculus Quest HMD, and the measurement of ERP for four sensorially different VR stimuli. In doing so, the present study afforded valuable methodological insights, a number of which were already referenced in the earlier section on theoretical implications. In what follows, we extend the discussion on methodological implications.

Despite the fact that results from the EEG analysis were inconclusive, the methodology employed can provide important lessons and significant methodological implications for future studies using auditory ERP as a proxy for user immersion. In fact, the lack of statistical difference in the amplitudes of the P200 component between conditions could have been due to an unreasonably small amount of stimulation epochs per condition. As such, an average of 46 epochs were generated by conditions, which might have shown to be too low given the noise induced by surrounding equipment, namely the VR headset, as well as motion artifacts introduced in a subset of the conditions (i.e., one-half). On that note, however, head movements did not seem to be the main cause of induced noise, as the proportions of rejected epochs were on average lower in moving (9.87%) than still (11.5%) conditions. Nevertheless, at this signal to noise ratio, results from our study support that at least twice as many stimulations would be desirable. For instance, future research should select VR stimuli of longer duration, i.e., at least twice the 6-7 minutes duration of our chosen stimuli, in order to provide a greater number of epochs, or, alternatively, reduce the number of presented stimuli and have each of them presented for a longer duration instead.

Nonetheless, this study provided foundations on how to synchronize, in real-time, mixed measures of physiological and neurophysiological activity in parallel to a lived VR experience. Furthermore, it demonstrated the feasibility of combining a wearable EEG headset with a wireless all-in-one VR HMD. The successful combination of two wireless devices paves the way for future studies to use this approach to test even more ecologically valid contexts of VR. Moreover, in line with the call for research from Vom Brocke et al. (2020), this study aimed to perform a feasibility assessment of combining more commonplace UX evaluation methods with NeuroIS methods. We successfully demonstrated that measurement through EEG, ECG, and EDA, is feasible in the context of immersive experiences. This feasibility assessment encourages future studies to move beyond the use of predominantly self-reported measurement methodologies in VR studies, which in turn would allow for a more holistic assessment of the user's immersive experience (Coursaris and Kim, 2011; Coursaris and Kim, 2006).

2.5.4 Limitations & future directions

As previously mentioned, one of our main objectives was to adopt a mixed methods approach, i.e., combining various measures of lived and perceived experience in VR, to enrich the evaluation of a user's immersion and presence in a VE as a function of a user's senses being recruited. While our approach was successfully implemented, results, on the other hand, were inconclusive. Hence, while methodological feasibility was confirmed, the theoretical concepts could be only partially supported, and the aforementioned research questions only partially answered with confidence. Thus, changes in the protocol and research design would be needed to reach conclusive results. Based on our analyses and collected data, recommended changes are further discussed with regards to the limitations that were encountered in this study.

Limitations

To ensure that video preference did not have a confounding effect on other variables, participants were asked to rank the four videos with regards to their preferred video content. However, as participants were asked to fill this preference ranking at the end of the experiment, i.e. once they had viewed all four videos, the actual content of the video was inevitably correlated to the conditions in which it had been presented. For instance, Borneo Forest was always used as the baseline as it was narration and movement free. Hence, we cannot rule out the fact that the video preference ranking could have been biased by the experience associated with each video. A way to move past this limitation could be to investigate participants' personal preferences regarding different types of landscapes (i.e., ocean, forest, desert, waterfalls) prior to beginning the experiment as part of the pre-experiment survey. Although this preference ranking would only serve as a proxy for video content preference, it would avoid having the latter measure being correlated with the conditions in which participants experienced each landscape.

As this study aimed for a feasibility assessment of the utilization of NeuroIS methods in assessing lived UX in VR, the study sample size was relatively small. Although the within-subjects research design and the measurement approaches allowed for the collection of a fairly large data set, the latter was generated by twelve participants. As such, any inherent measurement issues (e.g., outliers; errors) become inevitably more pronounced. Thus, future studies evaluating the impact of multisensory experiences in meditative VR should aim for larger samples. Additionally, the selected sample mainly comprised novice or rare users of VR. Per this regard, research by Witmer et al. (2005) showed that immersion is very closely related to a user's ability to adapt to the virtual environment – even more so than related than a user's involvement in the VE (Witmer, Jerome & Singer, 2005). This is indeed highly aligned with our qualitative results. In fact, many participants reported higher presence in environments which were familiar to them. For instance, one participant stated the fact that the "jungle is [a] mysterious [environment]" as the reason explaining why they "felt less comfortable and immersed" (P07) in that condition. A similar comment was raised by another participant such that the condition in which they felt least present was also the one that was "a little more different... [therefore] didn't seem realistic [to them]" (P09). It could be plausible that the difficulty to adapt to VEs for novice users of VR might have contributed to the lack of significant difference detected across the multisensory conditions. In line with this, results might appear different for a more VR-savvy sample, or alternatively, for a sample that is more familiar with meditative practices, given they might adapt more easily to these kinds of natural and meditative VR landscapes. Accordingly, future research could explore whether a user's prior use of VR or their level of meditative experience enhances the benefits of multisensory VR.

Future directions

Qualitative results that emerged from this study have indicated an interesting relationship between visual aesthetics and presence. Indeed, many participants reported that the visual aspect of the virtual landscapes constituted an important determinant of their sense of presence. For instance, one participant reported that the condition in which they felt most present was also the one "they found the prettiest [as] the sunset, especially, was very pleasing" (P11). Another participant reported the fact that the "the beach and the view were beautiful" (P10) as the reason explaining why they felt most present in that particular VE. Our study investigated the effect of adding auditory and motor components to a VR experience, but did not investigate the effect of manipulating specific visual components of the experience. Therefore, a focus on the VE's visual aesthetics as a factor responsible for greater presence and mindfulness in VR would be an interesting path for future research.

An additional insight that came out of this study is the fact that, for some participants, the VR experience even went beyond a user's recruited senses. As discussed through qualitative results presented in Section 2.4.5, some participants reported that the experience triggered olfactory and haptic sensations – although these were not *really* recruited by the VE. Accordingly, imagination seems to have been an important factor in the way users perceived and lived their experience in VR. In line with theory, imagination has been stated as one of the three defining characteristics of VR by Burdea & Coiffet (2003), alongside immersion and interaction. This could suggest that a user's creative and imaginative abilities might act as a predisposition that affects the sense of presence in VR; another path worth exploring.

2.6 Conclusion

In closing, we hope our study can motivate greater adoption of a mixed methods approach for measuring user experience in immersive environments. Although our results did not offer statistical support for a number of hypothesized relationships, descriptive results, along with qualitative data, seemed to indicate overall preferences and immersive benefits to the addition of a motor component to VR experiences. Thus, we hope this can inspire future empirical studies to move past movement restrictions and aim for novel ways to account for movements on, namely, the EEG signal quality. Finally, we believe that, as the majority of participants reported a more relaxed post-experience state of mind, this study paves the way towards a motivation for VR to be used, and further tested, in meditative and therapeutic contexts.

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Chapter 3: Field Study

Take My Virtual Hand: An Evaluation of User Experience in Shared Interactive Virtual Reality[2]

Abstract: For a few years now, Virtual Reality (VR) has served the entertainment industry all the way from a user's living room to world-leading museums in delivering engaging experiences through multisensory Virtual Environments (VEs). Today, the rise of the Metaverse fuels a growing interest in leveraging this technology, bringing along an emerging need to better understand the way different dimensions of VEs, namely social and interactive, impact overall User Experience (UX) in applied contexts of use. This between-subject exploratory field study investigates differences in the perceived and lived experience of 28 participants engaging, either individually or in dyad, in an immersive VR experience comprising different levels of interactivity, i.e., passive or active. A mixed methods approach combining conventional UX measures, i.e., psychometric surveys and user interviews, as well as psychophysiological measures, i.e., wearable bio- and motion sensors, allowed for a comprehensive assessment of users' immersive and affective experiences. Results pertaining to the social dimension of the experience reveal that shared VR elicits significantly more positive affect; while presence, immersion, flow and state anxiety are unaffected by the co-presence of a real-world partner. Results pertaining to the interactive dimension of the experience suggest that VEs affording greater interactivity significantly increase users' sensory immersion and state anxiety, regardless of the social context. Additionally, shared active VR experiences are those eliciting the greatest level of exploration behavior. Together, these findings suggest that well-designed VR can be shared with a real-world partner not only without hindering users' immersive experience, but also by promoting positive affect and exploration behavior, especially in interactive VEs. Hence, in addition to offering methodological directions for future VR field research, this study provides practical insights for VR developers towards the design of optimal Multi-User Virtual Environments (MUVEs).

Keywords: Virtual Reality, Multi-User Virtual Environment, Co-Presence, Interactivity, Presence, Immersion, Emotional Arousal, Exploration Behavior, Entertainment, Metaverse

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[2] A succinct version of this study has been submitted to the journal of Cyberpsychology, Behavior, and Social Networking for consideration in their special issue on "Virtual Emotions: Understanding Affective Experiences in the Metaverse." The manuscript, available in Appendix B, has been submitted on July 31st 2022 and is currently under review by the journal.

3.1 Introduction & Research Motivation

3.1.1 The Metaverse: Leveraging the potential of VR in the entertainment industry

Fuelled by important technological advancements, our society has embarked on a journey best known as the “experience age”: an era in which we are constantly seeking novelty. Virtual Reality (VR), a next-generation technology that enables immersive experiences through its ability to create vivid 3-dimensional Virtual Environments (VEs), successfully aligns with this social eagerness (Xiong et al., 2021). Hence, VR is increasingly used in numerous spheres of society, namely in the arts and entertainment sector by unlocking a world of immersive opportunities to a point that would have been deemed almost impossible a few years back. In museum contexts specifically, previous research supported the potential of VR in enhancing the User Experience (UX) of museum visitors by reinventing content delivery and boosting crowd engagement (Shehade, 2020). In media contexts, previous studies suggested that VR can be a powerful tool in increasing users’ sense of presence and enjoyment while consuming news content (Van Damme et al., 2019). Overall, for entertainment-based purposes, VR is considered an appealing technology and a valuable storytelling tool as its content can be conveyed mostly via sensorial feedback, such as visual and auditory cues, making the information easily understandable and rendering it accessible even to non-specialized users (Carrozzino & Bergamasco, 2010). By its very nature, VR enables users to gain a unique access to a diversity of reconstituted scenes, such as Space or other remote locations, therefore unraveling a set of situations that would be otherwise abstractly or physically impossible to experience in the real world (Shin & Biocca, 2018; Scavarelli et al., 2021). Not to mention that, today, the realism afforded by these virtual experiences reaches a level close to that of real-life experiences, making its storytelling purpose even more so engaging. Needless to say, this unique potential places VR under the spotlight in the entertainment industry, a spotlight that has been shining brighter than ever with the rise of the Metaverse.

As its name implies, the Metaverse, enabled through Augmented and Virtual Reality (AR / VR), is an alternate universe that merges physical and digital worlds (Mystakidis, 2022). Best known for creating multisensory interactions within a Multi-User Virtual Environment (MUVE), the Metaverse is a transformative technology that not only allows for seamless interactions with virtual objects within a virtual environment, but also promotes social networked and embodied interactions (Riva & Wiederhold, 2022; Mystakidis, 2022). In this line, Meta’s Facebook Reality

Labs, a division that focuses on developing these digital worlds in which people exist in immersive, virtual and shared spaces, recently received $10 billion in funding for the 2022 research year (Bobrowsky, 2021). Altogether, the fact that leaders of the tech industry are currently heavily investing in AR/VR research towards the development of interactive and shared VR supports the emerging need to better understand the way users interact within these VEs, as to offer guidance for the development of an alternate world that will be successfully accepted and adopted amongst the general public.

Accordingly, the comprehensive assessment of user experience during these immersive experiences is highly contingent upon the context of evaluation. In fact, although users of VR are immersed in a virtual world upon putting on their VR head-mounted display (HMD), the surrounding context in which the experience takes place still plays a defining role in their overall experience. In line with this last point, there is a need to carry out VR research directly into the field, out of controlled laboratory-based environments, to genuinely evaluate applied contexts of use of this technology. Of course, performing research in uncontrolled real-world settings introduces challenges, but it also significantly improves the ecological validity of the collected data. Thanks to recent innovations, these methodological challenges can be compensated by combining advanced psychophysiological and conventional UX measures, hence resulting in a thorough mixed methodology. To our knowledge, however, field research that has evaluated UX in VR is rather scarce and typically focuses on educational, rather than artistic or entertainment, purposes (Markowitz et al., 2018). Therefore, the present study conveys important contributions by taking place outside a controlled laboratory environment, i.e., in a multimedia entertainment center, and by evaluating the social and interactive dimensions of VR, both dimensions being detailed next.

3.1.2 The social dimension of VR: A duality between social yet immersive experiences

Humans, social beings by nature, tend to seek social experiences. In fact, between 32 and 75% of our waking time includes some sort of social interaction (Mehl & Pennebaker, 2003). Thus, experiences that can be socially shared are usually among the most coveted ones. Well aligned with this innate human drive, the Metaverse heavily relies on leveraging social experiences in the virtual world, making shared VR one of the hottest areas at the moment (Gaggioli, 2018). Paradoxically, VR's portrayal as a single-user, rather isolating, technology still makes up the core of its reputation as it requires users to disconnect from their physical reality and block all external distractions to plunge into a virtual world (Sung, 2021; Carrozzino & Bergamasco, 2010). In fact, by definition, VR is a technology that aims to recreate immersive VEs which are independent from a user's real physical surroundings (Zhan et al., 2020). Accordingly, the sole process behind the use of VR renders this technology particularly vulnerable to events, e.g., social interactions, occurring in the real world, as those typically break immersion by acting as reminders of a user's surrounding reality (Liszio & Masuch, 2016). Thus, there seems to be an emerging duality between creating a social yet optimally immersive experience in VR.

Indeed, in the field of social psychology, an essential tenet of social interactions is that one's behavior is undeniably influenced by the social context (Mehl & Pennebaker, 2003). As VR developers are putting time and effort towards building VEs that afford optimal UX, there is a growing need to ensure that the envisioned social dimension of shared VR does not backfire into the immersive nature of the experience. To date, although previous studies have evaluated the impacts of virtual avatars in VEs, relatively little research has empirically evaluated the effect of the co-presence of *real-world* partners during immersive experiences (Liszio & Masuch, 2016; Moustafa & Steed, 2018). Studies related to the topic of virtual avatars in VR have explored, for instance, the impact of mutual gaze and avatar gender on interpersonal physical distance (Bailenson et al., 2003), as well as the impact of a virtual audience on task performance (Hoyt et al., 2003), and even that of virtual avatars on participant's arousal (Slater et al., 2006). Accordingly, the current body of literature provides varied insights on the use of avatars in VEs. Current research, however, does not allow to extend or transpose these findings to the co-presence of real-world partners (Gajadhar et al., 2009). Hence, while more research needs to be done on the topic of shared VR, we shall confirm whether allowing social interactions with a real-world partner influences the overall immersion afforded by the VR experience, which is what the present study evaluates through its first research question.

> **RQ1**. How does the co-presence of a real-world partner in a shared virtual environment influence the overall user experience in VR?

3.1.3 The interactive dimension of VR: Setting an optimal level of interactivity

As previously mentioned, optimal VR experiences are not only those enabling social networked and embodied interactions, but also those affording seamless interactions with virtual objects and the virtual environment itself (Mystakidis, 2022). Therefore, the notion of a VE's interactivity is a central dimension in the design of virtual environments. However, current research does not offer a clear line of conduct with regards to the optimal level of interactivity that VEs should afford for. In fact, some researchers have argued that the range of moderate interactivity levels should be avoided, as those tend to hinder overall UX, while high or low interactivity levels should be prioritized, as those typically yield more favorable UX (Rogers et al., 2019). Their reasoning is partly explained through a familiarity moderating effect, such that higher interactivity is efficient in depicting the real world, and lower interactivity is easily associated with experiences delivered through other communication media such as TV/computers (Rogers et al., 2019). On the other hand, other researchers have argued that the interactivity of a given VE needs to be properly aligned with the purpose of the VR experience (Zhang et al., 2019). Specifically, experiences that aim to encourage user exploration and sustain user engagement would benefit from more interactive VEs, while experiences that serve relaxing and meditating purposes could tend towards less interactive VEs. Additionally, the few studies that have explored the impact of a VE's interactivity on UX have done so from a learning-specific scope, namely by evaluating the impact a VE's interactivity with regards to spatial knowledge transfer and learning gains using VR (Wallet et al., 2008; Cao et al., 2019; Zhang et al., 2019). Nevertheless, given the absence of consensus among researchers pertaining to a VE's optimal level of interactivity, the current body of literature lacks insights on the way interactivity can influence a user's affective and immersive experience in VR.

As a field study, the present research evaluated an existing VR experience that intrinsically featured different levels of interactivity, each afforded by different phases of the experience. Thus, through the intrinsic format of the VR experience, the present study aims to fill the aforementioned gap with regards to a VE's interactivity and its related effects on user experience, as formulated through its second research question.

> **RQ2**. How does the interactivity of the virtual environment influence the overall user experience in VR?

3.2 Theoretical Background & Hypotheses Development

3.2.1 Individual versus shared VR

Immersive UX: Presence, immersion, flow

Shared virtual environments (SVEs), also known as MUVEs, are virtual environments supporting multiple users that are geographically distributed (Pan & Steed, 2017). Through the years, research has successfully made the point in defining the core characteristics of SVEs as environments that include, first, the presence of anthropomorphic avatars and, second, the co-presence of other users' avatars (Hong et al., 2016). Anthropomorphic avatars, also called virtual humans, refer to 3-dimensional computer-generated digital representations of real humans, with corresponding visual and behavioral attributes (Bombari et al., 2015). Virtual humans can either take the form of human-avatars, i.e., human-looking virtual avatars controlled by humans, or agent-avatars, i.e., human-looking virtual avatars controlled by computers (Blascovich, 2002). That being said, despite major technological progress in the field of VR, a virtual human still inevitably differs from a real-world partner; while the former is solely present in the virtual world, the latter is present in a user's physical and virtual environments simultaneously. Regardless of the avatar's nature, however, the sole introduction of another human in a VE undeniably plays on a user's sense of presence.

Presence is commonly defined as the subjective sense of "being there" in an environment, even when one is physically situated in another (Witmer & Singer, 1998). It is a subjective feeling influenced by the attentional and perceptual resources allocated to sensory inputs from a given environment (Steuer, 1992). In VR specifically, the elicited sense of presence is contingent upon one's ability to block irrelevant real-world stimuli in order to focus on actions occurring in the VE (Witmer & Singer, 1998). Thus, when virtual environments are shared with others, as it is the case in SVEs, the concept of presence needs to be extended to encompass another dimension; that of co-presence. *Co-presence* can be defined as "being there *together*" such that one believes they are not alone and secluded (Schroeder, 2006). As a matter of fact, it involves some sort of mutual awareness by which individuals not only actively perceive one another, but also feel that others are actively perceiving them in return (Biocca et al., 2001; Yassin et al., 2021). Although critical, the broad construct of presence is not alone in making up the immersive nature of VR; in fact, when it comes to qualifying user experience in immersive environments, presence is rarely mentioned without immersion and flow.

Immersion is based on the technology's affordances, including, but not limited to, image resolution, field of view, stereoscopic vision, sound quality (Cummings & Bailenson, 2016). Accordingly, the key difference between presence and immersion is the technological, more objective, aspect that immersion accounts for (Michailidis et al., 2018). However, although presence and immersion are distinct constructs, they are still very closely related. In fact, previous research supports that a higher level of system immersion not only leads to, but also predicts, a higher sense of presence (Van Damme et al., 2019). In other words, presence is contingent upon the degree by which users feel immersed in a given VE (Witmer & Singer, 1998). With immersion being related to the technological attributes of VR, the construct can take multiple subdimensions including those of adaptive and sensory immersion. Specifically, previous research by Witmer et al. (2005) revealed an important relationship between a user's ability to adapt to the virtual environment and their resulting degree of immersion, therefore making up the adaptive dimension of immersion. Further research by Bombari et al. (2015) suggested that the degree of user immersion in a given VE is also influenced by the amount of sensorial information provided to them, calling attention to the sensory dimension of immersion. When all subsidiary dimensions come together, one could say that immersion in VR becomes optimal. In such cases, it is believed that well-designed VEs, e.g., those delivering numerous sensory stimuli allowing for easy adaptation, can act as an appropriate medium for flow.

Flow is defined as a mental state of absolute absorption in which people feel completely immersed in their activity (Csikszentmihalyi, 1990). This mental focus is characterized through an energizing feeling, complete involvement, and success towards the activity on hand (Weibel & Wissmath, 2011). While both flow and presence are characterized as absorbing states, with defining features ranging from the loss of self-consciousness to an altered perception of time, there is a notable distinction in the degree of interaction and physical effort that both constructs encompass: flow is associated with a user's sense that they can influence the activity taking place in the virtual world, while presence solely refers to the sense of being in the virtual world (Riva & Gaggioli, 2009; Weibel & Wissmath, 2011).

Per the review of presence, immersion and flow offered in this section, there seems to be an emerging trade-off between sharing a VR experience with a real-world partner and feeling optimally immersed in the VE. In MUVEs, the overall immersive user experience becomes contingent upon the co-presence of others; as such, the co-presence of a real-world partner is likely to introduce external disruptions and make a user's physical world salient again. Simply put, people are a link to the real world and can therefore interrupt a user's immersion in the virtual environment (Sweetser & Wyeth, 2005). Altogether, given immersive UX being contingent on world-based external stimuli and aligned with previous research supporting that active distractions decrease social presence (Oh et al., 2019), we posit the following hypothesis with regards to social interactions in VR.

H1. The co-presence of a real-world partner will hinder the immersive user experience (i.e., presence, immersion and flow), such that:

H1a. Co-presence of a real-world partner will hinder the user's presence.

H1b. Co-presence of a real-world partner will hinder the user's adaptive immersion.

H1c. Co-presence of a real-world partner will hinder the user's sensory immersion.

H1d. Co-presence of a real-world partner will hinder the user's flow.

Affective UX: Positive affect & state anxiety

In addition to its expected outcomes on immersive UX, the introduction of a real-world partner in SVEs is also likely to influence a user's emotional experience. In fact, extensive research in the field of social psychology supports that the social context of an experience influences emotional reactions, the latter ranging between the positive and negative ends of the emotional spectrum (Golland et al., 2015). In line with this, whether an experience unfolds positively or negatively refers to a user's affective experience, one that can be assessed by looking into perceived measures of positive affect and state anxiety among other constructs.

Positive affect refers to the combination of pleasurable emotions (i.e., feeling content, good and happy) that are elicited by an experience (Pressman et al., 2019). On the opposite end of the emotional spectrum lies negative affect, which encompasses a variety of moods including fear, sadness, anger and guilt, into a broad factor of emotional distress, closely related to that of state anxiety (Joiner et al., 1996).

State anxiety refers to a transitory anxious emotional state elicited by the activity at hand (Zsido et al., 2020). In other words, state anxiety is a response to an imminent threat, which gets translated into feelings of worry and tension through an activation of the sympathetic nervous system.

One mechanism through which social contexts are believed to influence emotions is that of social facilitation, a well-established theory supporting that social contact leads to emotional happiness (Zajonc, 1965). Previous research building upon this theory supported that the feelings of reward, pleasantness and enjoyment increase when performing activities with others (Brandtzæg et al., 2018). In the context of immersive technology precisely, a recent study by Bowman et al. (2022) performed in the gaming industry found that video game experiences elicited greater enjoyment when shared with others. When exploring the link between co-presence and state anxiety, literature also builds upon social facilitation theory by suggesting that social support, e.g., sharing an experience with a close other, is a successful mechanism in coping with a variety of life stressors (Roohafza et al., 2014). Extending these findings to VR, it seems that SVEs indeed represent an interesting medium in which the co-presence of a real-world partner could not only lead to more positive affect, but also alleviate negative feelings associated with state anxiety that could arise from experiencing a novel VE. Our theoretical frame builds upon extant theory and previous research, leading us to posit the following hypothesis with regards to users' affective experience.

H2. The co-presence of a real-world partner will enhance the affective user experience (i.e., positive affect and state anxiety), such that:

H2a. Co-presence of a real-world partner will lead to greater positive affect.

H2b.Co-presence of a real-world partner will lead to lower state anxiety.

Lived user experience: Emotional arousal & exploration behavior

Although a user's affective experience can be inferred from psychometric measures as discussed in the above section, emotions are still elicited through transitory bodily reactions. Thus, it can be quite difficult, sometimes merely impossible, for users to accurately recall the way they felt at a particular moment over the course of their experience – even more so for engaging experiences like those taking place in VR. Additionally, users' immersion should be prioritized at all costs in VR, which is another reason raising the need for measuring UX retrospectively rather than during the experience. In line with this, typical techniques like talk-aloud feedback used in the evaluation of user experience would appear counterintuitive in the present study. Thankfully, research has exponentially grown in the last few years and now offers an important body of literature supporting the use of psychophysiological data, i.e., autonomic nervous system signals, as a solution for the recall biases introduced by post-experience psychometric measures (Rield et Léger, 2016). Among those, a measure that is particularly relevant in providing a comprehensive assessment of users' affective experience is emotional arousal.

Emotional arousal refers to the strength or intensity of an emotional experience (Watson, 1988). It is often measured through electrodermal activity (EDA), a physiological signal regulated by the sympathetic nervous system that can be detected at users' palmar location through the activity of eccrine sweat glands (Riedl & Léger, 2016; Dillon et al., 2000). Given that EDA varies as a function of emotional intensity, high EDA is related to curious or anxious emotional states, while low EDA is related to emotional states approaching those of relaxation or boredom (Lackmann et al., 2021). In addition to EDA, emotional arousal can be inferred from the electrical activity of the heart measured via an electrocardiogram (ECG), which also varies as a function of heightened physiological activity (Sequeira et al., 2009). Specifically, a higher heart rate (HR) measured in beats per minute (BPM) is linked to greater emotional arousal (Cacioppo et al., 2007).

Previous research that has used these measures of lived experience found emotional arousal to fluctuate as a function of the social nature of an experience. For instance, a study investigating HR patterns in members of a romantic relationship showed an enhanced synchronization of autonomic signals in members of the dyad, along with specific patterns of activation based on the task on-hand (Helm & Sbarra, 2012). In line with this, a study by Lougheed & Koval (2016) investigated the question of emotional load sharing, measured through EDA, in members of a mother-daughter relationship. Results showed reduced arousal for adolescent daughters that shared physical closeness with their mothers during the task (Lougheed & Koval, 2016). In the context of our research, and as discussed earlier, the novelty of the virtual environment could be perceived as a transient stressor; accordingly, the presence of a real-world partner could act as a buffer to arising feelings of state anxiety. Therefore, we would expect the arousal of members in dyads to be approaching a calmer end of the emotional spectrum than those undergoing the experience alone. In light of previous literature, we posit that the social context of VR will influence arousal per the following directionality.

H3. The co-presence of a real-world partner will be associated with lower emotional arousal (i.e., electrodermal activity and heart rate), such that:

H3a. Co-presence of a real-world partner will lead to a decrease in EDA.

H3b. Co-presence of a real-world partner will lead to a decrease in heart rate.

Exploration behavior, measured through users' motion in their physical environment, constitutes another measure of lived user experience. In this line, we extend our previous reasoning, i.e., that the co-presence of a real-world partner will alleviate state anxiety elicited by the novelty of the experience, to predict a user's degree of exploration of the VE. Put simply, we expect that members of a dyad, feeling calmer in the presence of a real-world partner, will feel more confident in exploring the VE. Supporting this directionality, previous research evaluating social contexts' impact on navigation behavior reported that participants undergoing a spatial VR task alone navigate less, i.e., explore less, than those performing it in a collaborative co-located condition (Liang et al., 2018). Hence, aligned with empirical evidence, we posit the following with regards to users' exploration behavior in VR.

H4. Co-presence of a real-world partner will increase a user's exploration behavior.

3.2.2 Passive versus active VR

Virtual social experiences require a convincing depiction of other humans to render the virtual world convincing; those are being portrayed through virtual humans. Previous research demonstrated that when these virtual humans can be touched and/or provide haptic feedback, the subjective perception by which other entities in the VE seem tangible and physically co-present increases (Nam et al., 2008; Hartmann, 2021). Accordingly, the concept of co-presence in VR is tightly linked to the level of interactivity afforded by the virtual environment.

Interactivity can be defined as the degree through which the content of a VE can be influenced by a user's actions (Steuer, 1992). A user's actions can be directed towards the exploration of the virtual environment or the manipulation of virtual objects, all of which fuel back into the interactivity of the experience (Bricken, 1991). A simpler way to make sense of interactivity in VR is through the amount of control over the VE that is granted to users. As such, a defining feature of VR, among other media, is the extent to which it engages a user's sensorimotor system through head and body movements (Zhang et al., 2019). In fact, today's VR shows high interactive potential through tracking, i.e., measuring movement and behavior through sensing equipment, and rendering, i.e., depicting users digitally as a representation of the real world (Bailenson et al., 2008). Additionally, in sophisticated SVEs specifically, anthropomorphic avatars typically consist of full-body depictions, rather than partial hands and/or arms representations. As a result, movements and embodied interactions can be transposed virtually and portrayed accurately, therefore allowing for more precise interactions (Bermejo-Berros & Martinez, 2021; Freeman & Maloney, 2021).

The range of these so-called interactions afforded by the VE translates into the passive-active spectrum of the VR experience. While passive experiences do not afford users to interact with the virtual environment, active experiences do (Ferraz-Torres et al., 2022). This passive-active spectrum is closely related to user embodiment, such that it is reinforced through different ergonomic body positions. For instance, active VR experiences that allow users to stand up and walk incite more movements and interactions than passive seated VR experiences in which movements are limited to the head and upper body. Altogether, the ability to be in a standing ergonomic position unlocks more interactive possibilities with the VE, and replicates more accurately real-life experiences, therefore rendering the overall virtual experience more immersive in nature. To date, the small body of research that has explored the relationship between the interactivity afforded by either active or passive VR and the overall immersive nature of the experience provide a few guiding premises. Specifically, a higher sense of presence has been reported during active VR than during its passive equivalent (Gutierrez-Maldonado et al., 2011; Ferguson et al., 2020), a directionality that is likely supported through greater exploration behavior taking place during the former (Bermejo-Berros & Gil Martinez, 2021). Per the previous review of immersive UX, demonstrating the extent to which presence is intertwined with immersion and flow, findings associated with a user's presence are likely to be extended to these constructs as well. Thus, we posit the following relationship between a VE's interactivity and a user's immersive experience.

H5. Active VR will increase the immersive user experience (i.e. presence, immersion, flow) compared to passive VR, such that:

H5a. Active VR will generate greater presence than passive VR.

H5b. Active VR will generate greater adaptive immersion than passive VR.

H5c. Active VR will generate greater sensory immersion than passive VR.

H5d. Active VR will generate greater flow than passive VR.

With regards to a user's affective experience, previous research performed in VR has highlighted the VE's interactivity as an important player in users' psychological experience (Neumann et al., 2018). On the positive end of the emotional spectrum, previous studies suggested a directionality by which VR experiences that incorporate motor components, such as head movements, tend to elicit higher positive affect than their static equivalents (Guertin-Lahoud et al., 2021). In the same line, greater enjoyment, i.e., an important component of positive affect, was associated with VR experiences allowing users to walk (Plante et al., 2006). With regards to the negative end of the emotional spectrum, we expect active VR to introduce feelings of state anxiety, e.g. feeling nervous and/or confused, to a greater extent than passive VR. Thus, we expect that greater interactivity will increase the overall intensity of users' affective experience, and posit the following directionality.

H6. Active VR will intensify the affective user experience (i.e., positive affect and state anxiety) compared to passive VR, such that:

H6a. Active VR will lead to more positive affect than passive VR.

H6b. Active VR will lead to more state anxiety than passive VR.

Previous studies have further investigated the link between affective UX and a VE's interactivity using psychophysiological measures of lived experience. In fact, a study by Gall et al. (2021) supported that users embodiment in VR intensifies emotional reactions, namely arousal and valence, elicited by the VE. Following this directionality, we posit that active VR, affording more embodied interactions in the VE, will influence emotional arousal as follows.

H7. Active VR will be associated with greater emotional arousal than passive VR.

H7a. Active VR will be associated with higher EDA than passive VR.

H7b. Active VR will be associated with higher heart rates than passive VR.

In the same vein, and supported by the ergonomic position (i.e., sanding or seated) in which the experience takes place, one would logically believe that more interactive VEs are associated with greater exploration behavior. Previous research supported this directionality by arguing that greater involvement and immersion in the VE tend to be elicited by more interactive experiences, e.g., active VR (Witmer & Singer, 1998). Additionally, we expect user involvement to be translated into greater motion through the VE. Hence, based on both constructs' intrinsic nature, we posit the following relationship with regards to a VE's interactivity and its related degree of exploration behavior, and as summarized in Figure 3.1.

H8. Active VR will be associated with greater exploration behavior than passive VR.

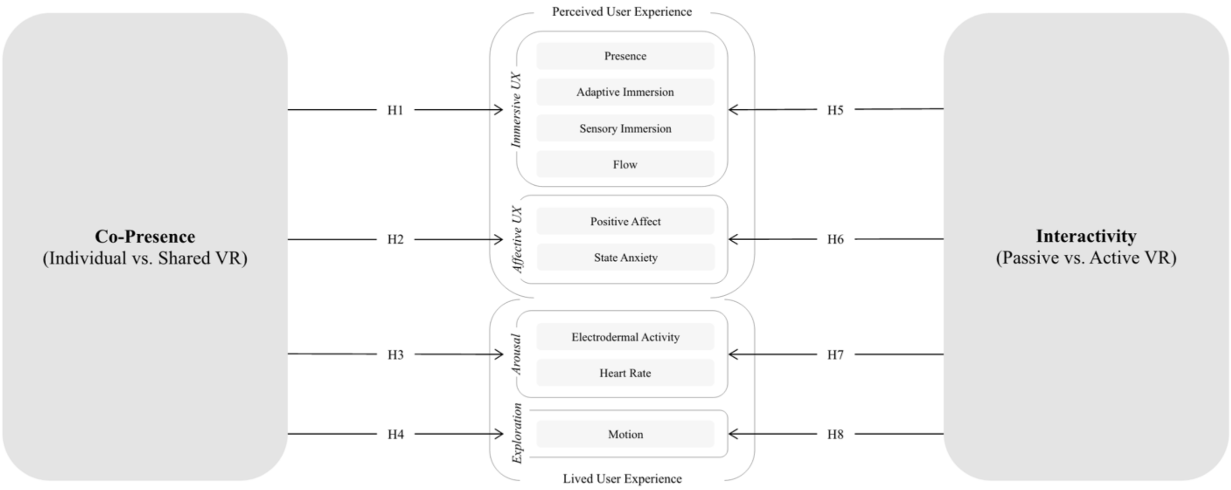

Figure 3.1 Research model

3.3 Method

3.3.1 Sample

A total of 28 participants, 12 females and 16 males, aged between 20 and 34 years old (M = 24.71 and SD = 3.17 years old) took part in this study. All participants were bilingual, with a normal or corrected-to-normal vision. None reported history of a psychiatric or neurological disorder. Participants were recruited through a word-of-mouth snowball sampling process and screened for motion sickness propensity. The study was approved by the Research Ethics Board of the authors' institution, with participants' written consent obtained at the time of the study (Certificate number 2022-4458). The majority of the sample, i.e., 19 participants, were familiar with VR as they had used it at least once in the past; the remainder, i.e., 9 participants, were novice users of this technology. In exchange for their time, participants were provided free entry to the VR experience, a CA$45 value compensation.

3.3.2 Experimental design

This field study was undertaken at l'Arsenal, a multimedia arts & entertainment center located in Montreal, Canada, host to the immersive VR exhibition *The Infinite Experience*. It employed a between-subject design in which the social context of the experience was manipulated. Participants were assigned to one of the two experimental conditions: the solo or the duo group. The solo group was composed of 12 participants, 4 females and 8 males; the duo group was composed of 16 participants, 8 females and 8 males, summing to a total of 8 dyads. In the solo condition, each participant underwent the experience on their own, i.e., without a real-world partner, while strangers took part in the experience at the same time they did. In the duo condition, participants underwent the experience in pairs, i.e., with a real-word partner, among other strangers. To ensure a meaningful relationship between members of a dyad, participants in the duo condition signed up together at the time of enrollment and were paired accordingly. The selected dyads were either made up of close friends or romantic partners.

3.3.3 Virtual environment

VR head-mounted display (HMD), virtual avatars and tracking system

The VR experience was powered through the Oculus Quest 2 HMD (Facebook, Inc., Menlo Park, CA, USA) with a display resolution of 1832 x 1920 per eye and a 72Hz refresh rate. For better sound surround, the audio was delivered through external headphones connected to the HMD. The experience was free of controllers; accordingly, participants were brought to interact with the VE directly with their hands, those being tracked in real-time and depicted virtually. Each user perceived themselves in the VE through their virtual avatar, i.e., a full-body first-person representation. With an average of 30 spectators simultaneously present in the physical and virtual space, all users' movements were tracked and portrayed through their virtual avatar in real time. This state-of-the-art tracking system allowed users to monitor others' displacements and ensured a smooth exploration of the VE by reducing colliding probabilities. Additionally, a color-coded tracking system allowed members of the same group to recognize each other and differentiate themselves from surrounding strangers. Specifically, members of a dyad could recognize their partner as their avatar displayed a yellow heart, while others' were blue. This subtlety was not present for solo participants, as all strangers' avatars were blue-hearted. Throughout the course of the experience, participants' HMDs were monitored on a moderator's tablet to prevent and fix, if needed, any arising technical issues (e.g., low battery, overheating hardware, erroneous tracking, etc.).

Figure 3.2 Active standing phase (left); Passive seated phase (right) of the VR experience.

Credits: Photos taken by David Brieugne, Tech3Lab.

VR stimulus

The VR experience, taking users in Space aboard the International Space Station (ISS), comprised two phases: a 30-minute active standing phase followed by an 8-minute passive seated phase (Figure 3.2). In the first phase, participants were taken to Space, a vast virtual environment dotted with stars, and brought to walk towards a life-sized, 3-D modelized representation of the International Space Station located a few meters away from them in the VE. This virtual representation was a simplified version of the corresponding real-world ISS as to meet the expectations of game scene design (Figure 3.3). That is, it was minimalistic, yet aesthetically pleasing, with translucent walls and corridors. Upon entry, and throughout their exploration of the ISS, participants were invited to interact with virtual objects, such as virtual phones and computers, and most importantly, virtual luminous spheres (Figure 3.3). Upon touching, each sphere opened a new virtual environment, such that the virtual representation of the ISS disappeared and was replaced with a high-resolution 360-degree video. These videos showcased astronauts undergoing a variety of daily activities such as performing scientific experiments, sharing a meal with their confederates, preparing for EVA missions, etc. During these videos, participants could explore the virtual environment through desired head movements and on-site body rotations. These videos, however, did not allow participants to walk; in the event that they did, the video was interrupted, and participants were brought back to the ISS. On the other hand, between these 360-degree videos, participants were free to walk and explore the environment as desired. Due to the self-paced nature of the experience, not all participants watched the same content, i.e., the same 360-degree videos, nor did they watch the same number of videos. On average, participants had time to go through 12 videos over the course of their active experience, but this number varied depending on each participants' speed and their level of exploration of the ISS. In the second phase of the experience, participants were virtually guided to a physical chair located in a quieter subsection of the room. Upon sitting, an 8-minute 360-degree video was automatically launched. This unnarrated video consisted of a rotation around planet Earth as seen from the ISS cupola. Altogether, the VR experience lasted nearly 40 minutes.

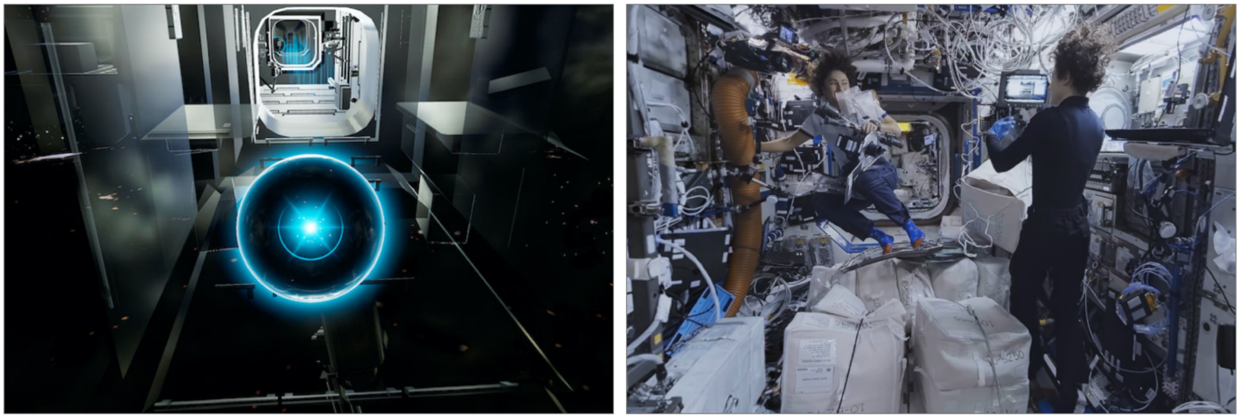

Figure 3.3 Virtual representation of the ISS featuring a luminous sphere (left); Preview of a 360-degree video showcasing astronauts' daily activities (right).

Source: Retrieved from https://phi.ca/fr/evenements/infini-montreal/, with PHI's permission.

3.3.4 Procedure

While this study was performed in a public venue at the time of the COVID-19 outbreak, a strict sanitary protocol was put in place to ensure participants safety. That included validating participants' proof of vaccination upon entry on-site. Additionally, moderators and participants were required to sanitize their hands upon arrival and wear a disposable surgical face mask throughout the experiment. All wearable materials were carefully washed, and tools were disinfected between participants. The HMDs were sanitized using UVC lamps.

Participants were first welcomed on site of the experience, and directed to a preparation room (Figure 3.4, step 1). There, participants were briefed on the tools to be used and informed on the general format of the experiment. Precisely, participants were instructed to behave as naturally as possible while undergoing the VR experience; pairs of participants were further informed that interactions with their partner, verbal and physical, were allowed over the course of the VR experience. Participants' informed consent was then obtained, followed by a short pre-experiment questionnaire.

The next step consisted of the tools' installation. Participants were first guided to a nearby restroom and asked to change into the Hexoskin Smart Garment (Carré Technologies Inc., Montreal, Canada). Instructions regarding the proper wear of the smart shirt were provided beforehand. Upon return, participants were fitted with a chest mount harness onto which a GoPro was fixed (Hero 4, Woodman Labs Inc., San Mateo, CA, USA). The camera was oriented outwards such that its field of view captured the surrounding environment including participants' hand movements and body displacements in the physical space. Additionally, a small external microphone was connected to the camera to record the VR experience's audio. Participants were then guided through self-placement of the EDA sensors in the palm of their non-dominant hand (Cobalt System, Tech3Lab, Montreal, Canada).

Following tools setup, participants were ready to begin the VR experience and were guided towards the exhibition entrance (Figure 3.4, step 2). While queuing for entry, participants were asked to go over written instructions, providing an overview of general guidelines. There, additional verbal instructions regarding virtual space navigation were also provided by an employee of the VR exhibition. After entering the exhibition area, the GoPro was turned on, and tools were synchronized simultaneously in front of the camera, serving as a visual cue for later data processing. Participants were assisted for the installation of their respective VR HMD, and the microphone was fixed to one of the external HMD's headphones (Figure 3.4, step 3).

Participants were then ready for the onboarding phase of the VR experience (Figure 3.4, step 4); they were instructed to walk towards a large white square, i.e., the virtual entrance to their immersive experience. Once immersed in the VE, participants were let alone to explore the ISS (Figure 3.4, step 5). At this point, the moderator withdrew, but stayed in the room to overview any potential technical issue. After 30 minutes, i.e., the fixed duration of the active phase of the experience, participants were virtually instructed, through a message appearing in their HMD, to start walking towards their assigned chair (Figure 3.4, step 6). Upon sitting, the virtual rotation around planet Earth was automatically launched. At the end of the video, a final message appeared in participants' HMD, an indication they could remove the VR headset as the experience came to its end. Participants were then guided out of the exhibition area, back to the preparation room. The experiment was concluded with a post-experience questionnaire and an individual 10-minute semi-structured interview (Figure 3.4, step 7).

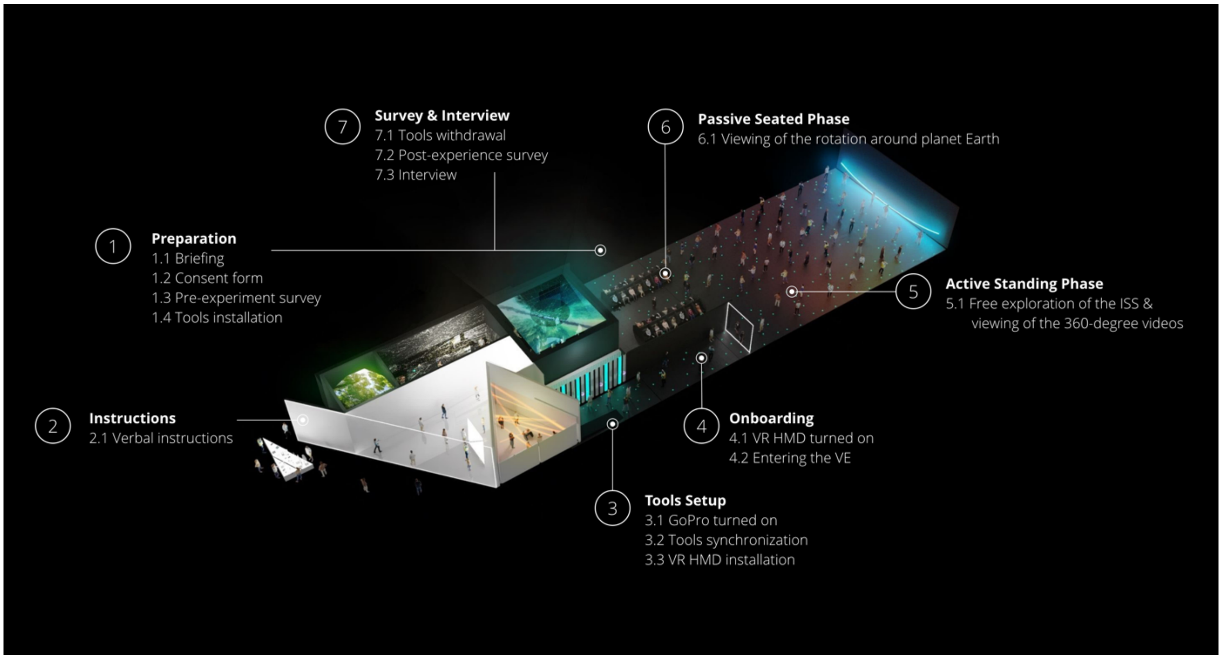

Figure 3.4 Experimental procedure detailed along the exhibition room plan.

Source: Retrieved from https://phi.ca/fr/evenements/infini-montreal/, modified with PHI's permission.

3.3.5 Measures & tools

Perceived experience: Psychometric self-report questionnaire

To assess perceived experience, a self-report post-experience questionnaire comprised the measures detailed next. Based on Cronbach's alpha, the internal consistency of all chosen scales ranged from acceptable to excellent with values between 0.706 and 0.937 (Table 3.1).

Table 3.1 Cronbach's Alpha

Construct	Number of items	Cronbach's alpha
Co-Presence	7	0.754
Cybersickness	9	0.875
Presence	6	0.831
Adaptive Immersion	8	0.747
Sensory Immersion	6	0.895
Flow	5	0.886
Positive Affect	5	0.937
State Anxiety	5	0.706

Reliability coefficients for self-report scales.

Cybersickness induced by the VR experience was measured using Kim et al. 's (2018) Virtual Reality Sickness Questionnaire (VRSQ) composed of 9 items measuring sensations of general discomfort, fatigue, eyestrain, headache, difficulty focussing, fullness of head, blurred vision, dizziness, and vertigo. Additionally, the scale includes a 2 items pre-exposure baseline assessing a user's physical state through their level of feeling "sick" and "in another state than their usual state of fitness". Items were adapted to a 7-point Likert scale ranging from (1) not at all to (7) very.

Co-presence was measured using Poeschl & Doering's (2015) Co-Presence Subscale. Specifically, 7 items were used and adapted to a 7-point Likert scale ranging from (1) not at all to (7) completely. The last item was reverse coded to increase overall scale reliability.

Presence was measured using the Slater-Usoh-Steed Presence Questionnaire (Usoh et al., 2000). Responses to the 6 items were recorded on a 7-point Likert scale ranging from (1) not feeling there at all and (7) feeling as present as in the real world.

Adaptative Immersion was measured using the Adaptation / Immersion Subscale of the Presence Questionnaire (Witmer et al., 2005). Responses to the 8 items were recorded on a 7-point Likert scale ranging from (1) not at all to (7) completely.

Sensory Immersion was measured through the Sensory and Imaginative Immersion Component of the Game Experience Questionnaire (IJsselsteijn et al., 2013). Responses to the 6 items were adapted to a 7-point Likert scale ranging from (1) not at all to (7) extremely.

Flow elicited by the VR experience was measured by the Flow Component of the Game Experience Questionnaire (IJsselsteijn et al., 2013). Responses to the 5 items were adapted to a 7-point Likert scale ranging from (1) not at all to (7) extremely.

Positive affect elicited by the experience was measured using the Positive Affect Component of the Game Experience Questionnaire (IJsselsteijn et al., 2013). The 5 items were adapted to a 7-point Likert scale ranging from (1) not at all to (7) extremely.

State anxiety was measured using the STAIS-5 (Zsido et al., 2020), a shorter form of the widely used Spielberg State-Trait Anxiety Inventory (STAI). Specifically, the 5 items assessed the extent to which users had been feeling upset, frightened, nervous, jittery and confused during their experience. All items were adapted to a 7-point Likert scale ranging from (1) not at all to (7) very much so.

Lived experience: Psychophysiological and motion sensors

To assess lived user experience, a combination of non-invasive tools and wearable technology was worn by participants over the course of the VR experience to provide a continuous assessment of their activity.

Exploration behavior was measured through a non-invasive 64Hz 3-axis accelerometer motion sensor located on the participant's torso and embedded in the Hexoskin Smart Garment. As such, motion was based on a user's acceleration according to the formula: motion = sqrt(acc_x^2 + acc_y^2 + acc_z^2), where acc_x corresponded to the x-axis acceleration. To complement users' exploration behavior, an audio of the experience, along with a visual record of participants' displacements, were provided by the GoPro to keep track of any technical issues or unexpected events that might have taken place during the VR experience.

Emotional arousal was inferred from heart rate measured by a 1-lead 256 Hz ECG embedded in the Hexoskin Smart Garment. To further enrich the assessment of arousal, electrodermal activity was measured in the palm of the participant's non-dominant hand via disposable Ag/AgCl sensors of the portable Cobalt system. Together with the psychometric measures presented in the previous section, EDA and HR allowed for a more comprehensive assessment of a user's affective experience during the VR experience.

3.3.6 Data preprocessing

For psychophysiological and exploration data, behavioral coding and data synchronization was performed using The Observer XT software (Noldus, Wageningen, the Netherlands). Specifically, video recordings of all participants were visually inspected such that start and end times for each phase of the experience, i.e., active and passive phases, were coded. The same process was performed with regards to start and end times for each 360-degree video viewed by the participant. During this process, any atypical event, e.g., technical problems or physical / verbal interruptions from any other spectator than a participants' respective partner, were removed from the data.

3.3.7 Statistical analyses

With regards to the lived experience, i.e., user arousal measured through heart rate (HR), electrodermal activity (EDA) and exploration behavior (motion), normality of the data was first assessed using Shapiro-Wilk tests. However, even upon removal of outliers falling outside the sample's standard deviations, results confirmed that these measures of lived experience were not normally distributed. Therefore, given the moderate sample size and the lack of normality observed in the data, non-parametric tests were used for further statistical analyses. Specifically, differences across social conditions with regards to dependent variables were examined using independent samples Mann-Whitney U tests. On the other hand, considering the use of repeated measures for the evaluation of the different interactive phases of the experience, differences with regards to dependent variables were examined using related samples Wilcoxon signed rank tests. Additionally, the interaction between the social context and exploration behavior on either of the perceived or lived measures was tested, but no significant results were obtained. Statistical analyses were performed using SPSS Statistics (Version 28.0, IBM Corp., Armonk, NY, USA), with a significance threshold set at $p < 0.05$.

3.4 Results

3.4.1 Manipulation checks

Co-presence: Social condition manipulation

Did duos experience higher levels of co-presence than solos?

To ensure that the social context of the VR experience was manipulated as desired, mean scores of co-presence were compared between social conditions. Results confirmed that participants in dyads ($M = 5.509$, $SD = 0.71$) experienced significantly higher levels of co-presence than those completing the experience alone ($M = 4.536$, $SD = 0.95$), ($z = 2.722$, $p = 0.005$). These results support that the manipulation of the experience's social context, i.e., performing the experience alone or with a real-world partner, was successful in delivering different levels of perceived co-presence. Going back to the construct's theoretical definition, this implies that participants in dyads were, as desired, mutually aware of one another (Yassin et al., 2021).

Cybersickness: Participants' overall state

Did participants' overall physical wellbeing differ pre / post experience?

To assess whether the VR experience had an effect on participants' overall wellbeing, their physical state was measured pre and post experience using the 2-items VRSQ baseline. Results showed that the mean scores reported by participants were significantly greater post-experience (M = 1.786, SD = 1.066) than pre-experience (M = 1.268, SD = 0.50) (z = 2.388, p = 0.017), suggesting that the VR experience hindered their physical wellbeing. A deeper look into the highest scoring items of the VRSQ indicated that the symptoms seemingly responsible for this increased feeling of sickness were those of "blurred vision" (M = 2.9643) and "fullness of head" (M = 2.3929). These results help in nuancing the qualitative results presented towards the end of this section.

3.4.2 Social dimension effects on user experience

To investigate differences in user experience between social conditions, independent samples Mann-Whitney U tests were performed for each phase of the experience, across social conditions. Results are detailed next, starting with perceived UX followed by lived UX.

Perceived user experience: Psychometric results

With regards to the *active* phase of the VR experience, results outlined in Table 3.2 demonstrate that no significant difference in users' immersive experience, i.e., sense of presence, adaptative immersion, sensory immersion, and flow, emerged between social conditions. However, one significant difference was supported with regards to users' affective experience; positive affect scores were significantly higher for participants in the duo (M = 6.38, SD = 0.80) than those in the solo group (M = 5.60, SD = 1.06) (U = 145.50, p = 0.020). Scores of state anxiety, on the other hand, did not significantly differ between social conditions (U = 101.00, p = 0.837). With regards to the *passive* phase of the VR experience, results outlined in Table 3.2 show that no significant difference emerged between social conditions with regards to users' immersive nor affective experience. In other words, being alone or sharing the experience with a real-world partner did not seem to influence perceived user experience during the passive phase of the VR experience. Therefore H1, i.e., H1a, H1b, H1c, H1d, are not supported. On the other hand, H2a is partially supported (i.e., supported in the active phase), while H2b is not, as Table 3.6 shows.

Table 3.2 Co-Presence Effects on Perceived User Experience

		Presence					Adaptation / Immersion					Sensory Immersion				
		M	SD	*Mean Rank*	*U*	*p*	M	SD	*Mean Rank*	*U*	*p*	M	SD	*Mean Rank*	*U*	*p*
Active Phase	Solo	4.50	1.04	15.71	81.50	0.507	5.49	0.77	13.96	102.50	0.767	6.00	0.74	13.04	113.50	0.423
	Duo	4.07	1.42	13.59			5.55	0.77	14.91			6.14	0.99	15.59		
Passive Phase	Solo	4.63	1.25	15.75	81.00	0.507	5.77	0.71	16.88	67.50	0.189	4.67	1.36	12.75	117.00	0.347
	Duo	4.19	1.53	13.56			5.30	0.88	12.72			5.15	1.46	15.81		

		Flow					Positive Affect					State Anxiety				
		M	SD	*Mean Rank*	*U*	*p*	M	SD	*Mean Rank*	*U*	*p*	M	SD	*Mean Rank*	*U*	*p*
Active Phase	Solo	5.47	1.32	12.46	120.50	0.260	5.60	1.06	13.38	145.50	0.020	2.08	0.87	14.08	101.00	0.837
	Duo	5.86	1.29	16.03			6.38	0.80	17.59			2.20	1.04	14.81		
Passive Phase	Solo	5.12	1.52	15.04	89.50	0.767	5.53	1.12	14.50	96.00	1.000	1.13	0.18	13.38	109.50	0.537
	Duo	5.04	1.31	14.09			5.31	1.62	14.50			1.34	0.55	15.34		

Results from independent samples Mann-Whitney U tests investigating differences across social groups with regards to perceived experience (i.e., presence, adaptative immersion, sensory immersion, flow, state anxiety and positive affect).

Lived user experience: Psychophysiological results

During the *active* phase of the experience, looking into measures of emotional arousal, Table 3.3 demonstrates that users' EDA was ranked significantly lower for participants in the duo group (M = 1.5333, SD = 0.194) than those in the solo group (1.600, SD = 0.696) (U = 9833, $p < 0.001$). This is aligned with the hypothesized directionality of H3a, by which the presence of a real-world partner reduces arousal. On the other hand, HRs were ranked significantly higher for participants in the duo group (M = 83.910, SD = 12.554) than those in the solo group (M = 79.275, SD = 7.343) (U = 10566, p = 0.003). While these results do not support the hypothesized directionality of H3b, higher HRs in shared active VR might be explained by an increased exploration behavior, i.e., more extensive walking. In fact, Table 3.3 shows that average motion of participants in the duo group (M = 0.017, SD = 0.011) was ranked significantly higher than that of the solo group (M = 0.015, SD = 0.013) (U = 12950, p = 0.016) during the active phase of the experience. In simpler terms, participants undergoing the experience with a real-world partner appeared to be moving more, i.e., exploring more, than participants who completed the experience alone. With regards to the *passive* phase of the experience, none of the above patterns were observed. In fact, Table 3.3 shows no significant difference between social conditions with regards to emotional arousal, i.e., HR and EDA, nor exploration behavior, i.e., motion (p = 0.413; p = 0.157; p = 0.085 respectively). Hence, while H3a and H4 are partially supported (i.e., supported during the active phase), H3b is not supported.

Table 3.3 Co-Presence Effects on Lived User Experience

		HR						EDA						Motion					
		M	SD	N	*Mean Rank*	*U*	*p*	M	SD	N	*Mean Rank*	*U*	*p*	M	SD	N	*Mean Rank*	*U*	*p*
Active Phase	Solo	79.275	7.343	128	117.95	10566.00	0.003	1.600	0.696	114	105.25	9833.00	<0.001	0.015	0.013	143	137.44	12950.00	0.016
	Duo	83.910	12.554	136	146.19			1.533	0.194	134	140.88			0.017	0.011	156	161.51		
Passive Phase	Solo	67.696	7.779	11	10.73	80.00	0.413	1.335	0.179	8	8.13	67.00	0.157	0.002	0.003	12	10.67	118.00	0.085
	Duo	71.796	11.212	12	13.17			1.453	0.222	12	12.08			0.005	0.009	14	15.93		

Results from independent samples Mann-Whitney U tests investigating differences across social groups with regards to lived experience (i.e., electrodermal activity, heart rate, motion).

3.4.3 Interactive dimension effects on user experience

To investigate whether the interactivity afforded by different phases of the experience yielded within-subject differences in user experience, related samples Wilcoxon signed-rank tests were performed for each social condition, across interactive phases of the experience. Results are detailed next, starting with perceived UX followed by lived UX.

Perceived user experience: Psychometric results

For participants in the *solo* group, Table 3.4 shows that significant differences in the sensory immersion and state anxiety emerged between the active and passive phases of the VR experience. Specifically, sensory immersion was ranked significantly higher during the active (M = 6.00, SD = 0.74) than passive phase (M = 4.67, SD = 1.36) (z = -2.625, p = 0.009). State anxiety followed the same directionality by scoring higher during the active (M = 2.08, SD = 0.87) than passive phase (M = 1.13, SD = 0.18) (z = -3.084, p = 0.002). All other psychometric constructs did not significantly differ between the two phases of the experience for participants in the solo group. For participants in the *duo* group, Table 3.4 demonstrates that significant differences emerged between the interactive phases of the experience with regards to the sensory immersion, positive affect, and state anxiety. Similarity to participants in the solo group, those who performed the experience in dyads also reported higher sensory immersion and state anxiety during the active (M = 6.14, SD = 0.99; M = 2.20, SD = 1.04) than passive phase (M = 5.15, SD = 1.46; M = 1.34, SD = 0.55) (z = -2.502, p = 0.012; z = -3.191, p = 0.001). An additional interesting finding was that positive affect scores were ranked significantly higher by members of dyads for the active (M = 5.53, SD = 1.12) than passive phase (M = 5.31, SD = 1.62) (z = -2.38, p = 0.017). Accordingly, H5c and H6b are fully supported, regardless of the social context in which the experience unfolds, while H6a is partially supported, i.e., supported in shared contexts of VR only.

Table 3.4 VE's Interactivity Effects on Perceived User Experience

		Presence					Adaptation / Immersion					Sensory Immersion				
		M	SD	*Median*	*z*	*p*	M	SD	*Median*	*z*	*p*	M	SD	*Median*	*z*	*p*
Solo	Active	4.50	1.04	4.50	-0.446	0.656	5.49	0.77	5.63	-1.379	0.168	6.00	0.74	6.25	-2.625	0.009
	Passive	4.63	1.25	4.58			5.77	0.71	5.88			4.67	1.36	4.59		
Duo	Active	4.07	1.42	4.50	-0.362	0.717	5.55	0.77	5.88	-0.740	0.459	6.14	0.99	6.33	-2.502	0.012
	Passive	4.19	1.53	4.33			5.30	0.88	5.50			5.15	1.46	5.50		

		Flow					Positive Affect					State Anxiety				
		M	SD	*Median*	*z*	*p*	M	SD	*Median*	*z*	*p*	M	SD	*Median*	*z*	*p*
Solo	Ative	5.47	1.32	5.70	-1.226	0.220	5.60	1.06	5.80	-0.354	0.723	2.08	0.87	2.00	-3.084	0.002
	Passive	5.12	1.52	5.00			5.53	1.12	8.70			1.13	0.18	1.00		
Duo	Active	5.86	1.29	6.20	-1.709	0.088	5.53	1.12	6.70	-2.38	0.017	2.20	1.04	1.70	-3.191	0.001
	Passive	5.04	1.31	5.00			5.31	1.62	5.60			1.34	0.55	1.00		

Results from related samples Wilcoxon signed-rank tests for investigating differences across the different interactive phases of the VR experience with regards to perceived experience (i.e., presence, adaptative immersion, sensory immersion, flow, state anxiety and positive affect).

Lived user experience: psychophysiological results

For participants in the *solo* group, looking into measures of emotional arousal, Table 3.5 shows significantly higher HR and EDA during the active (M = 75.109, SD = 13.974; M = 1.579, SD = 0.667 respectively) than passive phase (62.094, SD = 20.776; M = 1.281, SD = 0.195) for participants that performed the experience alone (z = -2.275, p = 0.0105; z = -2.803, p = 0.0010 respectively). For participants in the *duo* group, no significant difference emerged with regards to HR nor EDA (z = -2.101, p = 0.0647; z = -2.908, p = 0.1543 respectively). Therefore, H7 is partially supported (i.e., supported in the solo group only). Not surprisingly, with regards to exploration behavior, results detailed in Table 3.5 are aligned with the hypothesized directionality, such that greater motion was recorded during active than passive VR by participants from both social conditions (z = -3.169, p = 0.0003; z = -2.984, p = 0.0157 respectively). Therefore, H8 is supported regardless of the social context in which the VR experience takes place, as summarized in Table 3.6.

Table 3.5 VE's Interactivity Effects on Lived User Experience

		HR					EDA					Motion				
		M	SD	Median	*z*	*p*	M	SD	Median	*z*	*p*	M	SD	Median	*z*	*p*
Solo	Active	75.109	13.974	80.25	-2.275	0.0105	1.579	0.667	1.46	-2.803	0.0010	0.015	0.008	0.012	-3.169	0.0003
	Passive	62.094	20.776	66.77			1.281	0.195	1.27			0.002	0.003	0.001		
Duo	Active	73.676	27.538	81.04	-2.101	0.0647	1.500	0.214	1.47	-2.098	0.1543	0.017	0.006	0.02	-2.984	0.0157
	Passive	64.355	22.433	68.07			1.418	0.247	1.38			0.005	0.009	0.00		

Results from related samples Wilcoxon signed-rank tests investigating differences across the different interactive phases of the VR experience with regards to lived experience (i.e., electrodermal activity, heart rate, motion).

Table 3.6 Table of Hypotheses Testing for RQ1 and RQ2

Hypothesis	From	Directionality	To	Phase / Group	U / z	p-value	Status
1a	Co-presence	↓	Presence	Active Phase	81.50	0.507	Not supported
				Passive Phase	81.00	0.507	
1b	Co-presence	↓	Adaptive Immersion	Active Phase	102.50	0.767	Not supported
				Passive Phase	67.50	0.189	
1c	Co-presence	↓	Sensory Immersion	Active Phase	113.50	0.423	Not supported
				Passive Phase	117.00	0.347	
1d	Co-presence	↓	Flow	Active Phase	120.50	0.260	Not supported
				Passive Phase	89.50	0.767	
2a	Co-presence	↑	Positive Affect	Active Phase	145.50	0.020	Partial support (Supported in the active phase)
				Passive Phase	96.00	1.000	
2b	Co-presence	↓	State Anxiety	Active Phase	101.00	0.837	Not supported
				Passive Phase	109.50	0.537	
3a	Co-presence	↓	Electrodermal Activity	Active Phase	9833.00	<0.001	Partial support (Supported in the active phase)
				Passive Phase	67.00	0.157	
3b	Co-presence	↓	Heart Rate	Active Phase	10566.00	0.003	Not supported
				Passive Phase	80.00	0.413	
4	Co-presence	↑	Exploration	Active Phase	12950.00	0.016	Partial support (Supported in the active phase)
				Passive Phase	118.00	0.085	
5a	Interactivity	↑	Presence	Solo group	-0.446	0.656	Not supported
				Duo group	-0.362	0.717	
5b	Interactivity	↑	Adaptive Immersion	Solo group	-1.379	0.168	Not supported
				Duo group	-0.740	0.459	
5c	Interactivity	↑	Sensory Immersion	Solo group	-2.625	0.009	Supported
				Duo group	-2.502	0.012	
5d	Interactivity	↑	Flow	Solo group	-1.226	0.220	Not supported
				Duo group	-1.709	0.088	
6a	Interactivity	↑	Positive Affect	Solo group	-0.354	0.723	Partial support (Supported in the duo group)
				Duo group	-2.380	0.017	
6b	Interactivity	↑	State Anxiety	Solo group	-3.084	0.002	Supported
				Duo group	-3.191	0.001	
7a	Interacrtivity	↑	ElectrodermalActivity	Solo group	-2.803	0.001	Partial support (Supported in the solo group)
				Duo group	-2.098	0.154	
7b	Interactivity	↑	Heart Rate	Solo group	-2.275	0.011	Partial support (Supported in the solo group)
				Duo group	-2.101	0.065	
8	Interacrtivity	↑	Exploration	Solo group	-3.169	0.0003	Supported
				Duo group	-2.984	0.016	

↑ *enhancing effect;* ↓ *dampening effect*

3.4.4 Qualitative results

Shared experience elicits more positive affect though partner tracking and gamification

Qualitative results that emerged from user interviews are aligned with quantitative results with regards to positive affect; specifically, sharing the VR experience with a real-world partner seems to enhance the overall pleasantness of the experience. When asked to revisit the social context in which they had performed the experience, the majority of the sample, i.e., 20/28 participants from combined conditions, reported they preferred or would have preferred - if they had been assigned to the solo group - performing the experience in dyads (Table 3.7). The main justification being the physical proximity afforded by a real-world partner, especially given that “because [participants] would try to avoid other strangers, simply touching or following [their] companion made [the overall experience] more pleasant” (P19). Additionally, participants reported that “what [they had] preferred was not only to be able to do the experience with several people, but also to see the avatars walking around while being connected with a friend. It definitely add[ed] something more” (P05). These qualitative results indicate that the enjoyment of the experience seemed reinforced through the state-of-the-art tracking system, becoming more salient in the shared condition, therefore fueling a greater feeling of gamification: “being accompanied, felt a bit more like a game” (P27).

Active VR elicits greater presence through interactivity, but also increases state anxiety

When asked during which stage of the experience they felt most present, the majority of the sample, i.e., 16/28 participants from combined conditions, reported having felt more present during the active phase (Table 3.7). This enhanced sense of presence was repeatedly attributed to the greater interactivity afforded by the VE, particularly due to the active phase allowing more interactions with the virtual environment and virtual objects. Oppositely, participants reported that “as soon as [they] sat down, no interaction allowed [them] to stay focused on what [they were] experiencing in VR, so [their] attention was automatically turned to their own thoughts” (P12). These insights suggest a relationship by which the ability to interact with the VE helps in remaining connected with the on-hand experience, therefore optimizing a user’s sense of presence. This underlying relationship between a VE’s interactivity and the related sense of presence was further evoked by one participant sharing that “during the seated phase [they] felt more like a spectator, while during the active standing phase [they] felt more like an actor” (P28). Building upon the quantitative results presented in Section 3.4.3, user interviews were also particularly helpful in identifying the reasons explaining why the active phase was associated with greater state anxiety; in fact, many participants pointed out to the large number of people going through the experience simultaneously and the reduced physical personal space as the underlying causes of their anxious feelings. Accordingly, participants felt “a little less comfortable in the first part since [they] had to be careful” (P04), “very careful not to run into people” (P09).

The overall experience elicits positive states of mind, but appears physically strenuous

Quantitative results from the VRSQ checklist detailed in Section 3.3.5. reported a significantly more negative physical state post-experience than pre-experience. Surprisingly, this was not transposed by the qualitative results obtained from user interviews. In fact, when queried about their overall state post-experience, 12/28 participants reported feeling more excited and awake than they did prior to beginning the experience (Table 3.7). On the other hand, 8/28 participants reported feeling much calmer and relaxed; the remaining 8/28 participants reported no difference in their pre/post states of mind. Despite this seemingly general positive trend, some important nuances were raised by participants and help in making sense of the negative post-experience physical states that were detected through quantitative results. In fact, a few participants reported that they “fe[lt] a little more excited and awake (post-experience), [but they] also found that the experience required some energy” (P03). They “fe[lt] a little physically drained” (P03) as “the standing phase asked for more energy, (…) [specifically] having to always pay attention to collisions” (P04). Aligned with previous results, the overwhelming nature of the experience, namely through the crowded physical space, might have contributed to increasing the feeling of “fullness of head” experienced as one of the highest scoring items of the VRSQ.

Table 3.7 Qualitative Insights Summary

Qualitative Insight	Solo Frequency	Duo Frequency	Total Frequency
Overall preference for sharing the experience	6/12 particiapnts	14/16 participants	20/28 participants
Feeling more present during the active VR phase	6/12 particiapnts	9/16 participants	16/28 participants
Feeling more excited / awake post-experience	4/12 participants	8/16 participants	12/28 participants

Frequency of each qualitative insight per social grouping condition.

3.5 Discussion

The main purpose of this research was to investigate the impact of the social and interactive dimensions of VR on user experience. Accordingly, a field study leveraging an existing VR experience comprising different interactivity levels, and manipulating the social context of the experience, was completed. Our general conclusion, surprisingly aligned with the up-and-coming eagerness to develop MUVEs in light of the Metaverse, suggests that the addition of a real-world partner in VR is altogether beneficial, as it elicits greater positive affect and motivates the exploration of interactive VEs, without hindering the overall immersive nature of the experience. Building upon the inherent design of the VR exhibition, this study also investigated the effects arising from a VE's level of interactivity. Results revealed that sensory immersion and state anxiety tend to be significantly higher during active VR, regardless of the social context in which the experience unfolds. In parallel, the mixed methods approach employed by this research allowed for a comprehensive assessment of users' immersive and affective journeys. Accordingly, several implications have emerged from this field study, and are addressed next through theoretical, practical, and methodological lenses.

3.5.1 Theoretical & practical implications arising from the experience's social dimension

The earlier sections of this paper reviewed social support theories, namely Zajonc's social facilitation theory (1965), supporting that shared social experiences are beneficial in eliciting emotional happiness. While this theoretical lens served as a guiding premise for the development of our research design, the addition of a real-world partner to shared virtual environments raised an interesting dichotomy given the inherent nature of VR. That is, building upon existing theory, we posited that shared VR would enhance the overall *affective* user experience, through an increase in positive affect and a decrease in state anxiety, but would hinder the overall *immersive* user experience. The obtained results suggest confirming and opposing directionalities, which we attempt to make sense of next.

Revisiting the part of RQ1 pertaining to the *affective* user experience, results showed that shared, rather than individual, active VR elicits greater positive affect (H2a). This finding is aligned with previous research performed in other immersive media, namely in the gaming industry, according to which shared gaming experiences elicit greater enjoyment and fun, a central component of positive affect (Gajadhar et al., 2008, Bowman et al., 2022). On the other hand, we were surprised to notice that our results did not reveal significant differences in the perceived state anxiety between social conditions. In fact, social support theories, by which the act of sharing stressful situations with a close other typically acts as a coping mechanism, had led us to posit that the presence of a real-world partner, especially in a relatively dark and novel Space-like VE, would decrease induced feelings of anxiety. In fact, as one participant reported during the interview, we expected that "it (would be) more reassuring to be with someone else" (P09). However, our results did not support this directionality. One plausible reason behind this lack of significant difference in state anxiety between social conditions could be that, given that numerous spectators were undergoing the VR experience simultaneously, even participants in the solo group could have ultimately benefited from the presence of real-world others. Although as strangers, therefore not allowing for the same extent of social interactions than those experienced by members of a dyad, the mere presence of other humans could have worked towards alleviating potential feelings of state anxiety, even for participants in the solo condition. This reasoning can be supported by Steed et al.'s (2003) study according to which the effect of partner history, i.e., pairs of friends or strangers, does not seem to have an effect on positive affect. Extending these results to state anxiety could thereby explain why the mere presence of strangers in the physical, and virtual, space might have prevented significant differences in state anxiety from arising between social conditions.

Still with regards to RQ1, results pertaining to the *immersive* user experience offered an opposite directionality than the one hypothesized, such that no significant difference was found in the elicited presence, immersion, and flow between social conditions. This undeniably constitutes one of the most interesting and insightful findings that have emerged from this study. In fact, the earlier sections of this paper reviewed VR as a technology engaging users by means of its immersive nature thus rendering it particularly vulnerable to external disruptions. Accordingly, it was hypothesized that the introduction of a real-world partner would have acted as a disruptor to the immersive nature of the experience. Many authors have agreed to this directionality, suggesting that there exists a contradiction between social interactions in VR and immersion, which is the premise that guided our hypothesis (Sweetser & Wyeth, 2005). However, a minority of other authors have argued in favor of the opposing directionality, suggesting that cognitive immersion in digital gaming is actually increased in the presence of others - when these so-called "others" are either online or co-located rather than controlled by a computer (Cairns, 2012). In line with this perspective, a way to ensure optimal immersion consists of integrating players in the digital environment to such an extent that their actions and interactions become part of the digital world, therefore no longer acting as breaking points to a user's immersion (Liszio & Masuch, 2016). Our results support this latter directionality, rather than the former one we had hypothesized. Thus, it would imply that the VR experience provided a sophisticated enough integration of real-world partners, such that their actions and interactions became a seamless part of the VE. Upon reflection on qualitative results that have emerged from user interviews, we can advance that this integration was mainly enabled through the state-of-the-art tracking system detailed in Section 3.3.3. In fact, the VR experience not only provided a reliable virtual representation of people's physical location in the surrounding space through real time tracking, it also featured an embedded color-coding system that allowed users to differentiate their partners from surrounding strangers. Thus, not only was the tracking more salient, but also was it more relevant for participants in the duo condition as they relied on this color cue to locate their partner. The fact that this subtlety was not experienced by participants in the solo group, as all surrounding users were depicted as blue-hearted avatars, seemed to have been responsible for eliciting a difference in the overall enjoyment as supported by qualitative results presented in Section 3.4.4. These findings are aligned with Freeman & Maloney's research (2021) suggesting that full body tracking and movement correspondence are key factors in delivering a social VR experience that appears intimate and appealing. In line with previous theory, our quantitative and qualitative results seem to suggest that the co-presence of a real-world partner was a key component in embracing the full potential of the avatar tracking system, ultimately preventing from breaking the immersive nature of the experience, and increasing the overall enjoyment of the experience. The implication of these findings goes well beyond theory; it gives rise to insightful practical contributions for VR developers. In fact, it suggests that VR, contingent upon well-designed real-time tracking, can be successfully shared, such that the introduction of a real-world partner is not a threat to the elicited immersive user experience. Thereby, this study unlocks a variety of social opportunities for VR developers and guides their creative process towards an optimal design of SVEs, which is particularly relevant in the context of the Metaverse. Additionally, it stresses the importance to create a reliable transposition of real-world entities into virtual ones, namely through sophisticated avatar tracking systems.

With regards to the lived experience, this study also investigated the effect of the social context on users' exploration of the VE. Results revealed that participants in dyads significantly explored more than those alone, specifically during the active phase of the VR experience. This serves another important practical contribution as it suggests an underlying directionality by which shared VR should take place in virtual environments that are more interactive if the VR experience's main purpose is to drive user exploration. Again, this guides VR developers by helping them to focus time and effort in their design process of optimal SVEs.

Furthermore, qualitative results revealed that more than a third of the participants felt calmer and much more relaxed post-experience. This trend is aligned with findings from Guertin-Lahoud et al. (2021) supporting the meditative potential of VR. For practical use, as the present study evaluated entertaining interactive VR rather than a fully meditative VR experience, this seems to indicate that VR can offer a general soothing effect, even when the content of an experience is not fundamentally meditative. Perhaps this can be explained by the core immersive nature of VR, allowing users to escape their reality momentarily by helping them to "put problems in perspective, and look at things from the outside" (P11).

3.5.2 Theoretical & practical implications arising from the VE's interactive dimension

With regards to RQ2, the different levels of interactivity afforded by the different phases of the experience resulted in significant differences in user experience, therefore offering support towards a few of the hypothesized relationships. Specifically, directionalities posited with regards to sensory immersion and state anxiety were fully supported, while that of positive affect was partially supported in shared social contexts.

First, participants from both social conditions reported a significantly higher sensory immersion during active VR compared to passive VR. In parallel, results from user interviews revealed that the active phase of the VR experience taking place in the ISS, was also responsible for eliciting a greater sense presence. The emerging association between quantitative *immersion* and qualitative *presence* is aligned with previous research supporting that a higher level of system immersion acts as a predictor to a higher perceived sense of presence (Van Damme et al., 2019). Therefore, our results offer additional evidence in strengthening the underlying relationship between immersion and presence.

Another measure of perceived UX that appeared significantly higher in active VR across social conditions was that of state anxiety. This finding, aligned with our hypothesis, can be explained in light of the inherent features of the active phase of the experience. Specifically, the virtual environment brought users to Space, the latter being depicted in VR as a dark and vast environment; an environment that is rather unfamiliar to all humans other than astronauts. Thus, the nature of the VE is likely to have fueled different feelings of state anxiety, namely through making users feel confused and / or upset upon entry into such unfamiliar settings, nervous and / or jittery due to the concern of colliding into other individuals, or frightened upon looking out into the vastness of space. These feelings were reiterated by a few participants during interviews as they revealed a sense of confusion and unfamiliarity while “feeling completely elsewhere, (...)” and a transitory fear “thinking [they were] falling when [they] first entered space” (P17). Additional qualitative results supported that “it [was] a little disturbing, when first arriving in space at the beginning” (P21). However, despite a significant difference in state anxiety elicited between the active and passive phases of the experience, the overall scores of state anxiety remained low, ranging between 2.20 and 1.13 out of 7 points respectively, which suggests that these emotions were experienced extremely infrequently/lightly, if at all, during the entire journey within the immersive experience. Per that regard, state anxiety did not seem to hinder the overall positive affect of the experience as a whole, which is something we address next.

With regards to the effect of a VE’s interactivity on positive affect, our hypothesis was only partially supported: positive affect scores were significantly higher during active VR, compared to passive VR, for participants in the duo group only. In other words, participants undergoing the experience in dyads reported more positive affect during the active phase of the experience, but this finding was not supported in the solo group. Qualitative results detailed in Section 3.4.4 are aligned with these results, and identify the possibility to interact with a real-world partner as the underlying reason behind greater positive affect during shared active VR, a feeling that was further reinforced through color-cued tracking in the shared social condition.

3.5.3 Methodical implications arising from this field study

From a methodological point of view, our study has shown the combination of a wide variety of psychophysiological measures to be useful, and successful. Our mixed methods approach was enabled through advanced wearable technology using embedded bio- and motion sensors, compensating for the underlying challenges of a field study. Thus, our proposed methodology appears as a notable contribution towards the ecological evaluation of VR experiences for a variety of real-life entertainment applications, especially considering that current literature offers very few instances in which VR research has been carried out into the field, out of controlled laboratory-based environments. This is particularly important in today's era given the growing interest to leverage VR for a variety of art and entertainment purposes; two domains in which the user's surrounding environment needs to be accounted for in the delivery of the experience. Thus, limiting VR studies to laboratory-based controlled environments deprives research from covering dimensions that are likely to play an important role in real-world applications of this rising technology. This research offers innovative methodological solutions, and inspires a novel outlook in performing research in ecologically valid contexts as a way to offer theory-driven guidance to VR developers of tomorrow's Metaverse. Although providing results and conclusions that are high in ecological validity, undergoing this research in a field study context definitely came with its share or challenges, thereby introducing some limitations that we touch upon next.

3.5.4 Limitations & future research

It was discussed in the earlier sections of this paper that emotional burden tends to be shared among members of a dyad; a concept known as load sharing. Revisiting a study by Lougheed & Koval (2016), results showed that load sharing, measured through emotional arousal, is mediated by physical contact. Specifically, the authors found that emotional arousal is independent of the dyad's relationship in the presence of physical contact, e.g., when holding hands, but dependent on the strength of their relationship in the absence of physical contact. In light of our study, this implies that the extent to which members of a dyad physically interacted with each other during their experience could have impacted their emotional arousal, and by extension, their affective experience. In the present study, however, although dyads were made of close friends or romantic partners, the strength of their relationship, along with the extent to which they talked, touched or remained physically close during their experience, was not controlled for. Inevitably, the strength of a dyad's relationship could have had an influence on the degree to which they physically interacted with one another during the experience, which could have fueled back into their emotional arousal. Thus, while this is a limitation to our results, it also sets path to future research to further investigate the effects of dyadic relationships on lived and perceived UX.

Additionally, while we were able to manipulate co-presence through different social grouping conditions, we lacked control over participants' surrounding physical and social environment as this was a field study. In fact, as participants underwent the experience at different hours and/or different days, the surrounding crowd varied as a function of time. For instance, specific time slots were more crowded with scholars, others with retirees, therefore introducing environmental variations depicted through e.g., noisier or less tech savvy crowds, both susceptible to impact overall UX. However, this study remained successful in evaluating real-life contexts of VR, therefore offering pertinent conclusions beyond these inherent limitations.

3.6 Conclusion

Overall, this field study sheds light onto the social and interactive dimensions of VR, by evaluating users' affective and immersive experience. In doing so, it leveraged a mixed methods approach to assess lived and perceived user experience, which, hopefully, can serve as motivation for future studies to carry out UX VR research into the field. By evaluating a real-world VR exhibition, this research provides theory-driven insights and highly ecological practical implications for VR developers towards the design of optimal MUVEs as follows. In fact, results emerging with regards to a VE's interactivity support that the power of immersive experiences in evoking favorable UX is amplified through a user's active interaction with the VE, as those significantly increase sensory immersion and exploration behavior regardless of the social context in which the experience unfolds. Furthermore, results emerging with regards to a VE's social dimension suggest that the introduction of a real-world partner, contingent upon a sophisticated real-time tracking system, is not a threat to the elicited immersive user experience in VR. In other words, users' awareness of their real-world partner, as supported through significantly higher co-presence in dyads, manifests into greater positive affect; while the absence of significant difference in all other measures of perceived UX between social conditions implies that the avatar representation of a real-world partner seamlessly integrated in the immersive experience, neither detracting nor enhancing it. Hence, by supporting that VR experiences can be shared while maintaining their unique immersive properties, our results suggest that social interactions and virtual reality can indeed make up a dynamic duo, therefore pointing in a direction that agrees with Palmer Luckey, founder of the Oculus, claiming that "VR is a way to escape the real world into something more fantastic. It has the potential to be the most social technology of all time" (Barbazenni, 2022, para.1).

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Chapter 4: Conclusion

Considering the growing scope of virtual reality in several fields of application, and in view of the upcoming technological revolution occasioned by the Metaverse, this thesis explored the underpinnings of user experience in VR. It did so by adopting an innovative and novel research outlook, namely by carrying out VR research directly into the field, as to provide ecologically valid and theory-driven guidance to VR developers. The relevance of this thesis with regards to its contributions to the field of UX VR research was partly demonstrated through the recognition of Best Paper Award at the SIG HCI 2021 Conference for the study presented in Chapter 2. Additionally, we are grateful that the methodological approach developed over the course of this thesis, which was put to the service of arts and entertainment purposes during the field study presented in Chapter 3, was able to raise interest and gain a greater reach through coverage by leading newspapers including Le Devoir and La Presse. Hopefully, this thesis can serve as an inspiration and motivation for readers and researchers to further evaluate user experience in VR as to bring forward and optimize the ever-evolving potential of this promising technology.

Specifically, this research was guided by the central objective to help new emerging professionals including VR developers and VE designers in the development of optimal virtual experiences for varied contexts of use, ranging from mental health to entertainment purposes. As such, this research explored the extent to which different attributes of VEs are responsible for influencing user experience. Specifically, the sensory, social, and interactive dimensions of VR were manipulated, and their respective effects were assessed through measures of lived and perceived UX. This final chapter revisits the methodology deployed to achieve this central aim, and arising challenges are discussed. The underlying research questions, and their related hypotheses, are then reiterated and refined to a final answer. Finally, significant results are contextualized, and formulated into actionable insights. Accordingly, this concluding chapter offers a logical summary of methodological, theoretical, and practical contributions to the field of VR.

4.1 Methodological contributions: Revisiting the methods employed by this thesis and their related challenges

Considering the end goal to take VR research out of a laboratory-based environment, and given the mixed methods approach adopted throughout this research project, a rigorous pretesting process was undertaken before diving into the core of the research. Important methodological steps, related challenges and limitations, as well as their main takeaways are covered next.

Selecting the appropriate VR HMD for UX research: A comparative market assessment

First, the use of cognitive activity, i.e., electroencephalography, as a proxy for user immersion implied that brain activity had to be measured through electrodes positioned on a user's scalp. For the choice of the EEG cap, the Unicorn Hybrid Black was selected (g.tec Neurotechnology GmbH, Graz, Austria). As a wireless device, this EEG cap provided users with the freedom to move, therefore allowing for the VE to be explored during the experiment. That being said, the EEG cap not only had to be physically compatible with the VR HMD, i.e., affording a physically comfortable combination for users wearing both devices on their head, but the quality of the collected brain signals also needed to be insured. Therefore, for the choice of the VR HMD, the physical setup and the quality of the collected brain activity were the two central selection criteria. With this in mind, four different VR HDM and their, either successful or unsuccessful, combination with the Unicorn Hybrid Black EEG were assessed through extensive pretesting: these VR HMDs were the VIVE Pro (HTC, Taoyuan City, Taiwan), the HoloLens 2 (Microsoft, Redmond, Washington, USA), the PlayStation VR (Sony, Minato, Tokyo, Japan) and the Oculus Quest 2 (Facebook, Inc., Menlo Park, CA, USA). Based on the aforementioned selection criteria, and for the reasons outlined next, the Oculus Quest 2 was selected.

Configuring an adequate electrodes placement: Physical and theoretical constraints

Out of the four pretested EEG-VR combinations, the Oculus Quest 2, being a wireless all-in-one VR HMD, offered the most comfortable option while minimizing pressure points with the EEG electrodes. However, its minimal two-strap design still occasioned physical constraints with regards to the electrodes positioning of the EEG. In fact, to minimize potential pain arising from a one-hour VR experience, electrodes could not be placed under the HMD's securing straps. Thus, the electrodes configuration needed to account for physical constraints, i.e., excluding the superior midsagittal and lateral regions of the brain, while also being aligned with existing literature such that it would successfully capture spatially located brain activity associated with user immersion. Accordingly, several pretests were performed on different users to control for varying head dimensions, before settling on a final electrodes placement in positions F3, F4, FC5, FC6, C3, C4, P3, P4. Overall, the electrodes configuration was determined as a trade-off between a non-obstructive placement with regards to the VR HMD's lateral and superior adjustable straps, the reason why midline electrodes (e.g., Fz, Cz) were not used, and an adequate coverage of the regions of interest, i.e., the frontal and central cortices including the somatosensory area of the brain (Tremmel et al., 2019; Mancini et al., 2021). Overall, although the EEG-VR combination deemed most comfortable was the one selected moving forward, participants still reported slight physical pressure of the combined headsets towards the end of their one-hour experience. Thus, as previously mentioned, this is a notable limitation to our first laboratory research given that physical discomfort might have been a factor hindering users' meditative experience, especially as the experience came to its end. Nevertheless, not only is the iterative process employed towards the successful combination of a wireless EEG headset and a wireless all-in-one VR HMD an important methodological contribution of this research, but also is the methodology employed towards the use of auditory ERP as a proxy for user immersion, something we discuss next.

Pretesting neurophysiological signals quality: Accounting for user movements

Prior to beginning data collection, the quality of brain signals resulting from the EEG-VR combination following the aforementioned electrodes placement was investigated with the sequence of pretests detailed next. First, brain activity was recorded while alternating between intervals of eyes-open and eyes-closed to generate ocular movements and ensure that these could be detected and successfully removed from the data through later preprocessing. Next, brain activity was recorded while the VR HMD was turned on and off repeatedly to ensure that Bluetooth connections would not interfere with neurophysiological signals. Finally, brain activity was recorded during a variety of head movements; the extent to which these movements were deemed acceptable was set based on the resulting quality of neurophysiological signals. To serve as a buffer against head, facial and ocular movements, along with simply enhancing the quality of the collected data, wet electrodes were chosen to reduce impedance between the recording electrodes and the skin of a user's scalp.

As a result of these numerous pretests, the neurophysiological data that was collected during our first laboratory study made it possible to yield clean patterns of brain activity in which ERP waveforms were detectable as shown on Figure 4.1. However, despite these obtained ERP patterns, and as detailed in Chapter 2, neurophysiological data showed a lack of statistical difference between different multisensory conditions. This might have been due to an unreasonably small amount of stimulation epochs, i.e., an average of 46 per condition. Thus, this signal to noise ratio in the neurophysiological data emerges as another constructive methodological limitation to our research, as it raises the importance for future studies to select VR stimuli of longer duration in order to yield a greater number of epochs.

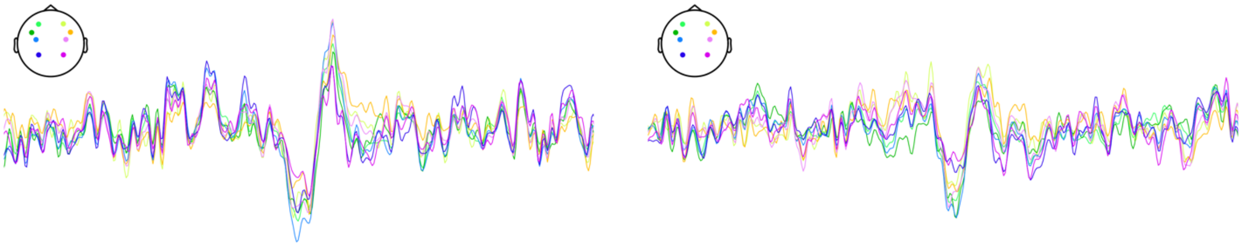

Figure 4.1 Examples of grand average ERPs used as a proxy for user immersion.

Beyond these limitations, this research demonstrated the possibility to synchronize, in real-time, mixed measures of physiological and neurophysiological activity in parallel to a lived VR experience, which is a notable contribution for future studies that wish to evaluate user immersion in VR through cognitive measures. This paves the way for future UX VR research to use this approach to test even more ecologically valid contexts of use.

Adapting to an uncontrolled testing environment: The need for sophisticated tools

The aim of this thesis to extend UX research to applied VR contexts came with its lot of challenges. In real-life uncontrolled environments, not only do a user's actions become more unpredictable than in controlled settings, but those of surrounding spectators, who are unaware of the study taking place around them, are even more unpredictable. These challenges are susceptible to interfere with measures of a user's lived experience, which strengthens the need for robust equipment to be used. Thus, the second phase of our research required a sophisticated tools combination. Specifically, it benefited from the use of the Hexoskin Smart Garment (Carré Technologies Inc., Montreal, Canada) along with the wireless Cobalt System, a device developed in-house at the Tech3Lab for collecting physiological activity remotely (Cobalt, Tech3Lab, Montreal, Quebec). Together, these wireless tools allowed users to move freely in their environment, while enabling measures of lived experience, including electrodermal activity, heart rate, and motion, to be collected in real-time throughout the course of their VR experience.

Responding to a global pandemic: A global research challenge

The entire research presented in this paper was performed during the context of the pandemic, which undeniably introduced notable, sometimes unpredictable, challenges. First, UX research in VR requires researchers/moderators to be in close contact with users, especially when measures of lived experience are used. Accordingly, the usual process behind tools setup had to be entirely rethought, hence partly fueling the need for the introduction of self-applicable or wearable technology. The novel use of these tools also came with a need for more extensive pretesting regarding the quality and reliability of the collected signals as discussed in the preceding sections. In addition to the feasibility challenges generated by the context of the pandemic, more discrete adaptations were needed throughout the entire research process; these were present from the recruitment phase, i.e., overcoming the difficulty to attract people for in-person non-essential purposes, all the way to the execution phase, i.e., conforming to ever-evolving sanitary measures in place. Beyond it all, however, the context of the pandemic also came with its silver lining: the difficult times experienced together as a society served as a major motivation to explore the potential use of VR for mental health purposes in alleviating the symptoms of anxiety experienced by many, and therefore greatly contributed to defining the research angle of our first study.

4.2 Theoretical contributions: Aligning hypothesized directionalities and thesis results to extant theory

Different dimensions of the VR experience were manipulated to assess the factors responsible for eliciting heightened immersive and affective experiences during VR. Specifically, the first study manipulated the sensory, i.e., auditory and motor, dimensions of the experience; the second study investigated the social and interactive dimensions of the experience. Overall, this research was guided by the following central question: *How do different attributes afforded by a virtual environment, namely with regards to its sensory, social, and interactive dimensions influence a user's lived and perceived experience in VR?* This central objective was refined into subsidiary questions guiding each study separately. The emerging results showed varied directionality, sometimes agreeing, sometimes disagreeing, with those hypothesized. The following section offers a final review of the findings associated with these directionalities along with their respective theoretical implications.

The first study presented in Chapter 2 of this thesis aimed to answer the following research questions: *Does the addition of an auditory component to the VR experience, through narration, increase a user's sense of presence and immersion? Does the addition of a motor component to the VR experience, through head movements, increase a user's sense of presence and immersion?* While the majority of posited relationships were not supported, their outcomes still contribute to UX VR research by shedding light onto each of those sensory dimensions and the extent to which they should be considered in the design of optimally meditative VR experiences.

H1. Virtual environments that engage auditory senses (H1a) and / or motor senses (H1b) to a higher degree will generate a greater sense of presence.

> No significant difference in the sense of presence emerged between different multisensory conditions. Hence, H1 is not supported. This lack of statistical support suggests that neither the addition of narration, nor the addition of head movements, seem to significantly influence users' sense of presence in the VE.

H2. The addition of an auditory component (H2a) and / or a motor component (H2b) to the VR experience will generate more positive affect.

> No significant difference in positive affect emerged between different multisensory conditions. Hence, H2 is not supported. This lack of statistical support suggests that neither the addition of narration, nor the addition of head movements, seem to significantly influence the positive affect elicited by the experience.

H3. VR conditions that recruit auditory senses (H3a) and / or motor senses (H3b) to a higher degree will increase emotional arousal.

> No significant differences in emotional arousal, i.e., HR and EDA, emerged between different multisensory conditions. Hence, H3 is not supported. This lack of statistical support suggests that neither the addition of narration, nor the addition of head movements, seem to significantly influence users' emotional arousal.

H4. VR conditions that recruit auditory senses (H4a) and / or motor senses (H4b) to a higher degree will increase user immersion.

> No significant difference in immersion, i.e., P200 amplitudes, emerged between different multisensory conditions. Hence, H4 is not supported. This lack of statistical support implies that neither the addition of narration, nor the addition of head movements, seem to significantly influence user immersion.

H5. Greater positive affect will generate a greater sense of presence.

> A significant and positive relationship emerged between a user's positive affect and their sense of presence. Hence, H5 is supported. This statistical support implies that more positive affect predicts a greater sense of presence in the VE. In other words, the more an experience elicits positive affect, the more a user feels present in the VE.

H6. Greater emotional arousal will generate a greater sense of presence.

> No significant relationship emerged between a user's emotional arousal and their sense of presence. Hence, H6 is not supported. This lack of statistical support seems to suggest that, at least in the given sample, perceived sense of presence does not seem to be significantly influenced by a user's emotional arousal.

The second study presented in Chapter 3 of this thesis aimed to answer the following research questions: *How does the co-presence of a real-world partner in a shared virtual environment influence the overall user experience in VR? How does the interactivity of the virtual environment influence the overall user experience in VR?* Results were in accordance with multiple hypothesized relationships, all of which are detailed next.

H1. The co-presence of a real-world partner will hinder the immersive user experience, i.e., will decrease a user's presence (H1a), adaptive immersion (H1b), sensory immersion (H1c), and flow (H1d).

> No significant difference in users' immersive experience emerged between social conditions. Hence H1 is not supported. This lack of statistical support implies that the introduction of a co-present real-world partner does not seem to detract from the immersive user experience.

H2. The co-presence of a real-world partner will enhance the affective user experience, i.e., will lead to greater positive affect (H2a) and lower state anxiety (H2b).

A significant difference in users' affective experience emerged between social conditions, such that positive affect was significantly higher for participants in the duo than solo group during the active phase of the experience. State anxiety did not vary significantly between social conditions. Hence, H2a is partially supported (i.e., supported in the active phase), while H2b is not supported. This statistical support implies that sharing an active VR experience with a real-world partner seems to render the experience significantly more enjoyable.

H3. The co-presence of a real-world partner will be associated with lower emotional arousal, i.e., will lead to a decrease in electrodermal activity (H3a) and heart rate (H3b).

A significant difference in users' emotional arousal emerged between social conditions, such that EDA was significantly lower for participants in the duo than solo group during the active phase of the experience. Hence, H3a is partially supported (i.e., supported in the active phase), while H3b is not supported. By supporting a decrease in users' emotional arousal, this significant trend suggests that sharing an active VR experience with a real-world partner, rather than performing it alone, seems to elicit calmer, i.e., less stressful / arousing, emotional states.

H4. The co-presence of a real-world partner will increase the user's exploration behavior.

A significant difference in users' exploration behavior emerged between social conditions, such that motion was significantly higher for participants in the duo than solo group during the active phase of the experience. This trend was not supported in the passive phase of the experience. Hence, H4 is partially supported (i.e., supported in the active phase). This statistical support suggests that sharing a VR experience with a real-world partner seems to increase exploration behavior, only when interaction with the VE is made possible as it is the case in active VR.

H5. Active VR will increase the immersive user experience, i.e. will generate greater presence (H5a), adaptive immersion (H5b), sensory immersion (H5c), and flow (H5d) compared to passive VR.

> A significant difference in users' immersive user experience emerged between interactive phases of the experience, such that sensory immersion was significantly higher in active than passive VR for both social conditions. No such significant differences were found with regards to presence, adaptive immersion and flow. Hence, H5c is fully supported while H5a, H5b and H5d are not. This statistical support implies that active VR experiences, i.e., those allowing users to interact with the VE, seem to generate greater sensory immersion regardless of the social context in which the experience takes place.

H6. Active VR will intensify the affective user experience, i.e., will lead to more positive affect (H6a) and state anxiety (H6b) compared to passive VR.

> Significant differences in user's affective experience emerged between interactive phases of the experience, such that state anxiety was significantly higher during active than passive VR for both social conditions, and positive affect was significantly higher during active than passive VR in the duo group only. Hence, H6a is partially supported (i.e., supported by the duo group) while H6b is fully supported. These statistical findings suggest that active VR, compared to passive VR, seems to generate more positive affect only when the experience is shared with a real-world partner, while it seems to lead to greater state anxiety regardless of the social context.

H7. Active VR will be associated with greater emotional arousal than passive VR, i.e., will be associated with higher electrodermal activity (H7a) and heart rate (H7b) compared to passive VR.

> A significant difference in users' emotional arousal emerged between interactive phases of the experience, such that HR and EDA were significantly higher during active than passive VR for the solo group only. This trend was not supported by the duo group. Hence, H7a and H7b are partially supported (i.e., supported in the solo group). This significant trend implies that active VR seems to generate greater emotional arousal, i.e., it appears significantly more arousing / stressful, than passive VR only when participants perform the experience alone.

H8. Active VR will be associated with greater exploration behavior than passive VR.

A significant difference in users' exploration behavior emerged between interactive phases of the experience in both social conditions. Hence, H8 is fully supported. This significant trend implies that more interactive VEs, as enabled through active VR, seem to be explored to a greater extent regardless of the social context in which the experience takes place.

Results that have emerged from combined studies provide important theoretical implications with regards to the effects of varying different dimensions of a VR experience. As the central premise guiding this research, we had postulated that an increase in the vividness of each of those attributes, i.e., sensory, social and interactive dimensions of VR, would positively enhance the overall user experience. Through an aim to provide a more concise answer to our central research question, we revisit the main theoretical implications that have emerged from this research in parallel to this central premise.

First, results obtained by **increasing the sensory dimension of a VR experience, through auditory and motor dimensions, do not point out to a clear positive directionality on neither lived nor perceived user experience**. In fact, our results were not aligned with those of previous research supporting that increasing the sensory vividness of a VR experience enhances a user's sense of presence and emotional arousal (Dan & Reiner, 2017; Makransky et al., 2019; Xu & Sui, 2021; Marucci et al., 2021). On the other hand, this lack of clear directionality could simply imply that, when it comes to defining the appropriate level of a VE's multisensory nature with regards to its auditory and motor components, the different sensory dimensions of VR experiences should be properly aligned with the intended emotional load of the experience rather than simply adhering to a predetermined rule of thumb. Theoretically, this indicates a need for a holistic HCI or UX framework that considers the psychophysiological effects of sensory components in context, not only by means of their increasing sensory nature, but also based on the intended purpose of a given experience as to act in congruence with it.

Second, results showed that **increasing the social dimension of an active VR experience increases positive affect and exploration behavior, reduces emotional arousal, and does not affect immersive user experience**. This former finding, showing that shared experiences lead to greater positive affect, is in accordance with previous literature on social facilitation (Zajonc, 1965). Thus, it extends theoretical support to previous studies performed in other forms of immersive media, namely the gaming industry, that have come to a similar conclusion according to which shared experiences elicit greater enjoyment and fun (Gajadhar et al., 2008, Bowman et al., 2022). The novelty brought by our research, however, lies in the fact that shared VR not only enhances a user's affective experience, but does so without hindering the immersive nature of the experience. Based on extant research, this latter finding is surprisingly not aligned with the main directionality offered by the current literature on shared immersive experiences, the latter pointing to a clear tradeoff between social yet optimally immersive experiences. In fact, the main accepted directionality is that VR, an immersive technology by nature, is vulnerable to external distractions, including social interactions, as those are likely to act as potential obstacles to the immersive nature of the experience (Sweetser & Wyeth, 2005). In fact, our results point in the opposite directionality by agreeing with, and further supporting, those of Cairns (2012) and Liszio & Masuch (2016): authors who have suggested that immersion in digital worlds is actually increased in the presence of others, when these so-called "others" are co-located and well-integrated in the VE, making their actions and interactions become part of the digital world and no longer acting as breaking points to a user's immersion. Thus, by standing alongside a minority of studies that have argued in favor of socially shared immersive experiences, our research contributes to current theory by better positioning literature, and, most importantly, bringing important nuances on the beneficial directionality of sharing a VR experience with a co-present real-world partner.

Third, our results demonstrate that **increasing the interactive dimension of VR increases sensory immersion, state anxiety, and exploration behavior regardless of the social context**, while it also leads to an increase in emotional arousal in individual VR, and an increase in positive affect in shared VR. The former finding emerging from a VE's interactivity and its beneficial impact on sensory immersion is aligned with previous research that has demonstrated greater attention and presence in active contexts of VR (Conniff et al., 2010). Additionally, our results also indicate a logical relationship between perceived state anxiety and emotional arousal for participants undergoing active VR experiences on their own, i.e., without a real-world partner. As mentioned earlier, previous theory of social support such that sharing an experience with a close other typically acts as a successful mechanism in coping with a variety of life stressors (Roohafza et al., 2014). Aligned with this trend, our results reveal that solo participants, unfortunately, showed greater state anxiety and higher emotional arousal during active VR, therefore offering further support to extant theory. Altogether, these findings not only provide additional theoretical support towards an overall beneficial trend in increasing the interactivity of a VR experience; it also brings theoretical relevance by demonstrating the importance of considering these trends in a nuanced fashion, as those are sometimes contingent upon social contexts in which a given VR experience unfolds.

4.3 Practical contributions: Highlighting the main takeaways of this thesis for VR developers

Through the sum of its findings, and building upon the theoretical directionalities that emerged from either significant or not significant results detailed above, this research offers interesting practical insights for VR developers. First, the underlying significant and positive relationship that emerged between positive affect and presence in our meditative laboratory study can serve as a motivation for VR developers to create experiences incorporating elements that elicit happiness, rather than promoting violent and/or negatively loaded content, as to enhance users' presence in VR. In therapeutic contexts, this specifically implies that VR developers should turn to positively loaded content to enhance a user's presence and therefore optimize the meditative benefits of VR.

Second, results from the social dimension of our field study demonstrate that the addition of a real-world co-present partner does not break a user's immersive experience. This suggests that VR, contingent upon well-designed real-time tracking, can be successfully shared, such that the introduction of a real-world partner is not a threat to the elicited immersive user experience. Thereby, this finding unlocks a variety of social opportunities for VR developers and guides their creative process towards an optimal design of SVEs. Most importantly, it stresses the importance that VR developers should focus on creating reliable transposition of real-world entities into virtual ones, namely through sophisticated avatar tracking systems, if they wish to make an experience optimally social and immersive simultaneously. This is a very promising finding for the future of the Metaverse, an alternate world that aims for shared, yet optimally immersive, experiences.

Third, findings pertaining to the interactive dimension of VR also appear quite interesting for VR developers, namely by confirming that active VR is likely to increase users' sensory immersion and exploration behavior regardless of the social context. Thus, VR developers should focus on introducing interactive features to VEs as to engage a user's senses to a greater extent, and therefore render VR experiences even more immersive. Additionally, it points out to the importance of interactive features if the main purpose of an experience is for the VE to be explored.

Finally, the overarching meditative potential of VR has definitely emerged from this multiphasic research. In fact, in both studies, many participants reported feeling calmer and much more relaxed post-experience. For practical use, this indicates that VR can offer a general soothing effect, even when the content of an experience is not fundamentally meditative; as this was the case for *The Infinite Experience*, the latter serving entertainment rather than mindfulness purposes. Perhaps this can be explained by the core immersive nature of VR, allowing users to escape their reality momentarily. Nevertheless, VR developers should keep this added value in mind as they design VEs of different nature serving different end purposes. Building upon this point, and tying together findings from combined studies, it seems that sharing the experience with a real-world partner, rather than performing it alone, renders active VR experiences less stressful. Therefore, developers could also design experiences meant to be shared to further enhance the soothing potential of VR.

4.4 Closing statement

Considering the forecasted technological wave prompted by the Metaverse, this thesis aspires to serve as a first step towards offering theory-driven guidance to VR developers. Through a set of ecologically valid results, we hope this research can help this innovative set of professionals in creating experiences that are optimal for users and properly aligned with the intended emotional load, whether it seeks meditative or entertainment purposes. Additionally, with the great lot of efforts that have gone into the development of a methodological framework for the evaluation of lived UX in VR, we are optimistic that our approach can motivate readers and researchers to leverage current advances in psychophysiological measurement to evaluate the ever-evolving potential of VR in applied contexts of use. May this be a first inspiring step in taking VR research out into the field, as to leverage its adoption in a variety of applied contexts, and, ultimately, extend its promising potential to infinity and beyond.

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Appendix A: Published Article[1] from Study 1

Evaluating User Experience in Multisensory Meditative Virtual Reality: A Pilot Study

ABSTRACT
Virtual Reality (VR) is known for its ability to immerse users in a parallel universe. Accordingly, VR offers great potential for mindfulness therapy, especially in a post-pandemic world. However, the extent to which our senses should be recruited to yield an optimal feeling of presence in the Virtual Environment (VE) remains unclear. This study investigates lived and perceived effects of adding auditory and motor components to VR experiences, through narration and head movements respectively. Twelve participants experienced four nature-based VR videos in a within-subjects research design. The study employed a mixed method approach of psychometric and neurophysiological measures. Results support a significant relationship between positive affect and presence. While statistical support was not obtained for the remaining relationships, this study provides a feasibility assessment of utilizing NeuroIS methods in evaluating immersive user experiences, along with qualitative insights that extend our understanding towards optimized VE designs.

Keywords: User Experience, Virtual Reality, Presence, Immersion, Multisensory Experience, NeuroIS

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[1] Guertin-Lahoud, S., Coursaris, C., Boasen, J., Demazure, T., Chen, S. L., Dababneh, N., & Leger, P. M. (2021). Evaluating User Experience in Multisensory Meditative Virtual Reality: A Pilot Study. SIGHCI 2021 Proceedings. 11. https://aisel.aisnet.org/sighci2021/11

1. INTRODUCTION & RESEARCH MOTIVATION

In the context of the pandemic, chronic stress has considerably risen. In the United States, nearly 27% of adults reported symptoms of anxiety disorder in the last months, a notable increase compared to 8.9% back in 2019 (CDC, 2021). In stressful times, the practice of mindfulness, i.e., bringing our full attention to the present moment by reconnecting mind and body, has been recommended as it predicts positive emotional states (Brown & Ryan, 2003). In line with this, previous research showed that Virtual Reality (VR), a technology that mimics real-world sensory stimuli by immersing users in a simulated virtual environment (VE), has great potential for therapeutic use in today's "mental health pandemic". For instance, patients with General Anxiety Disorder showed increased alpha brain activity, i.e., a proxy for lower anxiety, increased calmness, and positive affect, while viewing natural landscapes in VR (Tarrant et al., 2018).

A distinctive feature of VR is the sense of presence it generates by means of its immersive nature. Immersion has been related to the *objective* measure of how vivid a VE qualifies, while presence has been related to the *subjective*, psychological experience of being there in the VE (Cummings & Bailenson, 2016). Accordingly, presence in VR is said to be determined by two dimensions: vividness and interactivity. *Vividness* refers to the number of sensory dimensions that are simultaneously presented in the VE, i.e., its multisensory breadth, and the quality of information delivered in each dimension, i.e., its sensory depth. For example, a deep auditory experience would feature different auditory components such as music, narration, etc. *Interactivity*, enabled through motor components such as head and/or body movements, refers to how a user's actions can influence the content of the VE (Steuer, 1992).

While immersion is a core attribute of VR, there remains an important lack of evidence regarding *which* sensory dimensions of the VE are responsible for optimizing its immersive nature. To date, multisensory VR has been mainly investigated in learning or educational contexts, rather than from a mindfulness or therapeutic lens (Baceviciute et al., 2021). Another reason fueling this gap in literature is that the addition of motor components to VR experiences is difficult to evaluate through measures of lived experience, such as electroencephalography (EEG), due to the noise that movements introduce in the analysis of brain activity (Baka et al., 2018). As a result, restricting movements comes at the cost of evaluating ecologically valid immersive user experiences. Building upon the existing literature, our study aims at resolving the aforementioned limitations by, first, varying the sensory vividness of the VE by manipulating its auditory and motor components and, second, compensating for movement by adopting a mixed methods approach. The main objective of this study is to explore the effects of multisensory VEs on the user's lived and perceived experience in VR; hence:

> **RQ1**. Does the addition of an *auditory component* to the VR experience, through narration, increase a user's sense of presence and immersion?
>
> **RQ2**. Does the addition of a *motor component* to the VR experience, through head movements, increase a user's sense of presence and immersion?

2. THEORETICAL BACKGROUND & HYPOTHESES

To date, numerous studies came to the agreement that 3D immersive experiences elicit a greater subjective sense of presence than their 2D counterparts (Xu & Sui, 2021). These findings suggest that 3D representations, which offer closer-to-reality graphics, provide an additional layer of visual information. Applying this logic to our context, we expect the addition of sensory layers to the VE (i.e., other than visual) to act similarly by eliciting greater presence.

> **H1a**: VEs that engage auditory senses to a higher degree will generate a greater sense of presence.
>
> **H1b**: VEs that engage motor senses to a higher degree will generate a greater sense of presence.

Pleasurable emotions (i.e., feeling content, good and happy) are characterized as positive affect (Pressman et al., 2019). A recent study, performed in augmented reality (AR), investigated the impact of adding sensory layers of visual, auditory, and olfactory stimuli on presence and enjoyment (Marto et al., 2020). Results showed that multisensory conditions were rated higher on enjoyment than the baseline condition. With AR sharing a similar digital nature to VR, and enjoyment being a main component of positive affect, we expect positive affect to fluctuate similarly in multisensory VR experiences.

H2a: The addition of an auditory component to the VR experience will generate more positive affect.

H2b: The addition of a motor component to the VR experience will generate more positive affect.

Previous research also showed that flow, a state of absolute absorption and complete immersion, is predicted by positive affect (Tobert & Moneta, 2013). Accordingly, we expect positive affect to increase a user's sense of presence.

H4: Greater positive affect will generate a greater sense of presence.

Post-immersive measures of presence are vulnerable to memory, recency and recall biases, thus failing to capture the intricate processes that occur during immersion (Marto et al. 2020). As a solution, a study by Kober & Neuper (2012) showed that Event-Related Potentials (ERPs), i.e., very small voltages generated by the brain in response to specific events or stimuli, can be used as a proxy for a user's sense of presence in a VE. A study by Marucci et al. (2021) on multisensory VR driving simulations showed performance to be higher in bimodal (i.e., visual-audio) and trimodal (i.e., visual-vibrotactile) than unimodal visual simulations. In line with the positive relationship between performance and immersion supported by Slater et al. (1996), we expect greater immersion in multisensory VEs that feature added auditory or motor components.

H3a: VR conditions that recruit auditory senses to a higher degree will increase user immersion.

H3b: VR conditions that recruit motor senses to a higher degree will increase user immersion.

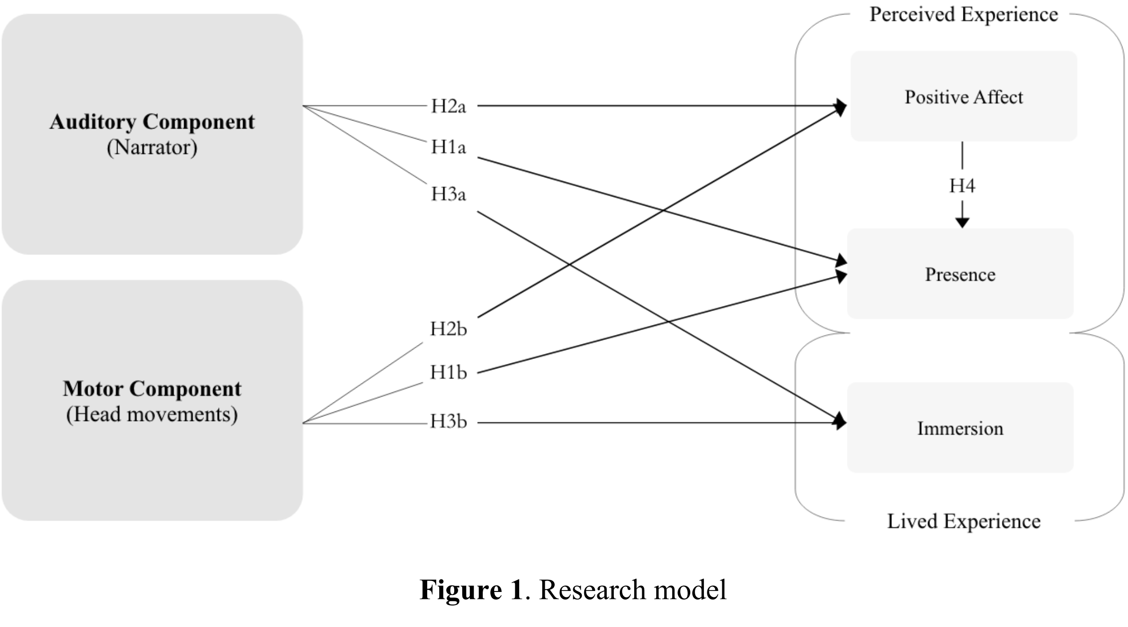

Figure 1. Research model

3. METHODS

3.1 Sample

This study was completed by 12 healthy participants (F=8, M=4) aged between 19 and 31 years old (M = 22.92 years, SD = 3.90). All reported a normal or corrected-to-normal vision and no history of a psychiatric or neurological disorder. The study was approved by the Ethics Research Committee of the authors' institution, with participants' prior written consent and their verbal consent reiterated at the time of the study (Certificate number 2022-4458). Although all participants were inexperienced with VR, none reported cybersickness during the experiment. Participants were compensated with CA$40 for their time.

3.2 Experimental Design

The experiment presented four unique VR experiences of natural landscapes in randomized order (2 x 2 design: with/without music; with/without head movement), with no music/movement used as baseline and always presented first (Figure 2). In movement conditions, participants explored the VE through slow and lateral head movements. Videos were chosen based off similarity criteria, and video preference was assessed during the experiment.

Figure 2. Experimental design

3.3 Materials & Measures

Surveys & Psychometric Measures

Surveys were administered in English on Qualtrics via the VR browser. Pre-test survey items measured participant demographics and VR experience. After viewing each video, sense of presence (Usoh et al., 2000) was assessed with 7-point Likert items from (1) not feeling there at all to (7) feeling as present as in the real world; positive affect (IJsselsteijn et al., 2013) was assessed with 7-point Likert items from (1) not at all to (7) extremely. At the end of the experiment, video preference was assessed with a ranking from (1) preferred video to (4) least preferred video.

VR Head-Mounted Display (HMD)

For the immersive experience, the Oculus Quest 2 HMD was used and interactions with the VE were enabled through two controllers (Figure 3). Researchers monitored the VE in real-time on a laptop.

Figure 3. HMD combination of the EEG and VR headsets.
Credits: Photos taken by David Brieugne, Tech3Lab.

VR Stimuli

All four VR stimuli were bird's-eye view videos of natural landscapes with soft music. Passive stimuli were selected to minimize participants' movements and optimize overall EEG quality. Two were music-only videos [7]; two featured narrated historical and geographical facts [20, 21]. Both videos were narrated by the same male voice.

Neurophysiological Measurement Stimuli

Building upon Kober & Neuper's (2012) methodology, our study used auditory tones as ERP stimuli, and investigated the resulting amplitude values of P200 peaks as a proxy for user immersion. The auditory tones were emitted in the test room at a mean inter-stimulus interval of 7s and standard deviation of +/-3s through two identical Logitech speakers placed on a table in front of the participant at an interior angle of 25°, 70 cm apart, and 120 cm away from the seated participant. The auditory ERP stimuli were launched simultaneously to the start of each VR stimulus and were ended automatically as the VR stimulus came to its end.

Neurophysiological Measurement Tools

The EEG data was collected with gelled electrodes using the Unicorn Hybrid Black wireless 8-channel system at a sampling rate of 250 Hz per channel. Electrodes were positioned at F3, F4, FC5, FC6, C3, C4, P3, P4 according to the extended 10-20 international placement system, and referenced to linked mastoids. The EEG data and markers of the ERP stimuli were collected and synchronized through the Lab Streaming Layer (LSL) protocol.

3.4 Procedure

The experiment was conducted in a soundproofed room with stable lighting and window blinds shut. Participants were seated on a fixed chair at 45 cm above floor level with both feet on the ground. They were briefed on the tools and the general format of the experiment, after which their consent was obtained. With regards to moving conditions, participants were instructed to keep their torso still and move their heads slowly on the horizontal axis only (i.e., to avoid fast, vertical, circular motion), and to maintain their head position for a few seconds following each movement. Participants were then fitted with the EEG cap, followed by the VR HMD. EEG impedance was checked, and the VR HMD was turned on while the virtual experience was streamed to the researchers' laptop. Participants were left alone in the test room and further instructions were delivered via a mic/speakers setup. Researchers monitored the participants continuously throughout the experiment. Concluding the 2-hour test session, a short interview was conducted to better grasp participants' overall experience. The institution's COVID-19 sanitary protocol was applied.

3.5 EEG Data Processing

The EEG data was preprocessed and analyzed using Brainstorm (http://neuroimage.usc.edu/brainstorm). Noise artifacts were removed using Independent Component Analysis. EEG data was then bandpass filtered from 1–40 Hz, and then epoched from -1000ms to 2000ms relative to ERP stimulus onset and visually inspected. On average, 11% of 46 total epochs were rejected. Time-series ERP waveforms were averaged across epochs for each VE within each participant. These ERP waveforms were then averaged across all participants to produce a grand-average ERP for each condition. The time point of peak amplitude for P200 peaks were identified, and the mean time point across all conditions was calculated. Amplitudes of the P200 peaks were averaged over time within each participant from -25ms to +25ms relative to these peak amplitude time-points. The resulting values were used in subsequent statistical analyses.

3.6 Statistical Analysis

Statistical analyses were performed using SAS version 9.4. The effect of the two independent variables of interest (i.e., narrator and head movement) on the sense of presence and positive affect were examined using a linear regression with random intercept model. Additionally, the effect of positive affect on the sense of presence was examined using a multiple linear regression with random intercept model. Differences in ERP P200 amplitudes between conditions were analyzed using repeated measures ANOVA, with movement and narrator as factors.

4. RESULTS

4.1 Psychometric Results

Narrator and Head Movements Effects on Presence

Descriptive statistics show that presence was rated lower in conditions with a narrator (M = 3.99, SD = 1.72) than without (M = 4.18, SD = 1.37), but higher in conditions with head movements (M = 4.18, SD = 1.62) than without (M = 3.99, SD = 1.48). These trends, however, were not significantly supported by the linear regression. In fact, neither the addition of a narrator (t = - 0.67, p = 0.5094) nor the addition of head movements (t = 0.67, p = 0.5094) had a significant effect on a user's subjective sense of presence, therefore H1a and H1b respectively are not supported.

Narrator and Head Movements Effects on Positive Affect

Descriptive statistics show that positive affect scores between conditions with (M = 5.65, SD = 1.30) and without a narrator (M = 5.68, SD = 1.01) did not vary significantly (t = -0.13, p = 0.8987). Thus, H2a is not statistically supported. Similarly, the positive affect scores between conditions with (M = 5.81, SD = 1.11) and without (M = 5.53, SD = 1.20) added head movements did not significantly vary (t = 1.11, p = 0.2754). As a result, H2b is not supported either. Nevertheless, a significant and positive relationship emerged between positive affect and presence. That is, the higher the positive affect elicited by an experience, the greater the subjective sense of presence in the VE (t = 5.64, p < 0.0001). Hence, H4 is supported.

Video Preference Effect on Presence

An interesting trend emerged between video preference and presence. The two videos in which the highest presence was reported (M = 4.31) were also the ones that had been most preferred by participants (M = 2.08, SD = 1.24 and M = 2.17, SD= 0.94; note that video preference was reverse coded; i.e., lower scores correspond to greater preference). This relationship was investigated using a multiple linear regression, and the effect of video preference on presence was found to be significant (t = - 4.83, p < 0.0001).

4.2 Neurophysiological Results

Results from the repeated measures ANOVA show no significant difference in the P200 mean amplitudes according to the main effects of narrator (F = 0.472, p = 0.506) and head movement (F = 3.299, p = 0.097), nor was there a significant interaction effect (F = 0.024, p = 0.881). Hence, although descriptive statistics show that the lowest mean amplitude of the P200 peak (M = 0.366, SD = 1.793) was observable in the condition with an added narrator but without head movements; and that the largest mean amplitude of the P200 peak (M = 1.194, SD = 0.955) was observable in the condition without a narrator but with added head movements, these differences were not supported by statistical tests. Therefore, H4a and H4b, by which the addition of narration and head movements would increase immersion respectively, are not supported.

4.3 Qualitative Results

Downside Effect of Added Narration

During the interview phase, more than half participants (i.e., 7/12) expressed feeling most present in the baseline condition, and half participants (i.e., 6/12) reported a preference for music-only conditions. Reasons included that the clarity of nature sounds (e.g., birds chirping, wind blowing, etc.) were put forward in the absence of a narrator, thus enhancing the immersive nature of the environment. A few participants reported that added narration modified the inherent nature of their experience as it made them feel like "watching a documentary, a movie, rather than discovering a virtual experience [by themselves]" (P01).

Upside Effect of Added Head Movements

The majority of participants (i.e., 10/12) benefited form the addition of head movements as the broader field of view allowed them to visually explore more of the landscape, thus empowering their sense of presence and enhancing the immersive nature of the experience.

Meditative Potential of VR

When queried about their states of mind, the majority of participants (i.e., 10/12) reported feeling much more relaxed. For some participants, viewing the natural landscapes in VR allowed them to "feel as if [they were] flying" (P04). For others, the multisensory experience even went beyond the recruited senses as they "could smell the warmth of the desert" (P04) and "feel the water [on their skin]" (P03).

5. DISCUSSION & CONCLUSION

The theoretical grounding underpinning this research was that multisensory virtual environments, through their vividness and ability to recruit a user's senses to a greater extent, would enhance user experience by optimizing presence, positive affect and immersion. With regards to RQ1, descriptive results indicate an opposite directionality than the one we had hypothesized. Indeed, it seems that the addition of an auditory component (i.e., narrator) to the VR experience might have had a *negative* effect on a user's presence and positive affect. This might be partially explained by the narrator overshadowing the clarity of other core audio components (i.e., nature sounds), the latter being identified by many participants as highly supportive of their meditative experience. With regards to RQ2, the addition of a motor component (i.e., head movements) to the VR experience seems to have had a *positive* effect on a user's presence and positive affect. Many participants reported that head movements enhanced their experience, while the physical limitation arising from keeping their head still acted as a reminder of their surrounding reality, thus hindering their presence in the VE. As such, qualitative results indicate that a wider variety of head movements would have further improved the experience, which should be considered in the design of future studies.

On a practical standpoint, the significant relationship that was supported between positive affect and the sense of presence could serve as a motivation for VR developers to focus on experiences that elicit joy and happiness, rather than promoting violent and/or negatively loaded content. From a therapeutic lens, this supports that VEs should promote positively loaded content to enhance a user's presence and thus optimize the meditative benefits of VR.

Beyond the theoretical and practical implications, a number of valuable methodological insights emerged from this study. First, the lack of statistical difference obtained in the amplitudes of the P200 component between conditions can help orient future VR studies that choose to use auditory ERP as a proxy for user immersion. In fact, the small amount of stimulation epochs per condition (i.e., an average of 46), might have proven to be too low given the noise induced by surrounding equipment, namely the VR headset, as well as motion artefacts introduced in a subset of the conditions. On that note, however, head movements did not seem to be the main cause of induced noise, as the proportions of rejected epochs were on average lower in movement (9.87%) than in still (11.5%) conditions. Nevertheless, results suggest that at least twice as many stimulations would be desirable or, alternatively, VR stimuli of longer duration should be selected. Second, this study successfully combined two wireless devices, i.e., a wearable EEG headset with a wireless all-in-one VR HMD. This reveals opportunities for future studies to use this approach to test even more ecologically valid contexts of virtual reality applications. Moreover, in line with the call for research from vom Brocke et al. (2020), this study aimed to perform a feasibility assessment of combining more commonplace UX evaluation methods with NeuroIS methods. Our feasibility assessment paves the way for enriched future studies to move beyond the use of predominantly self-reported measurement methodologies (Coursaris & Kim, 2011) in VR studies, which in turn would allow for a more holistic assessment of the user's immersive experience.

In closing, we hope our study can motivate greater adoption of a mixed methods approach for measuring immersive user experience. Although our results did not offer statistical support for a number of hypothesized relationships, descriptive statistics, along with qualitative data, seem to indicate an overall preference and immersive benefits to the addition of a motor component to VR experiences. Thus, we hope to inspire future empirical studies to move past movement restrictions and aim for novel ways of accounting for movements on, namely, the EEG signal quality. Finally, we believe that, as the majority of participants reported a more relaxed post-experience state of mind, this pilot study paves the way towards a motivation for VR to be used, and further tested, in meditative and therapeutic contexts.

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Appendix B: Submitted Article[2] From Study 2

Take My Virtual Hand: An Evaluation of User Experience in Shared Interactive Virtual Reality

ABSTRACT
Virtual reality (VR) has served the entertainment industry all the way to world-leading museums in delivering engaging experiences through multisensory virtual environments (VEs). Today, the rise of the Metaverse fuels a growing interest in leveraging this technology, bringing along an emerging need to better understand the way different dimensions of VEs, namely social and interactive, impact overall user experience (UX). This between-subject exploratory field study investigates differences in the perceived and lived experience of 28 participants engaging, either individually or in dyad, in a VR experience comprising different levels of interactivity, i.e., passive or active. A mixed methods approach combining conventional UX measures, i.e., psychometric surveys and user interviews, as well as psychophysiological measures, i.e., wearable bio- and motion sensors, allowed for a comprehensive assessment of users' immersive and affective experiences. Results pertaining to the social dimension of the experience reveal that shared VR elicits significantly more positive affect; while presence, immersion, flow and state anxiety are unaffected by the co-presence of a real-world partner. Results pertaining to the interactive dimension of the experience suggest that the interactivity afforded by the VE moderates the effect of co-presence on users' adaptive immersion and arousal (electrodermal activity). These results support that VR can be shared with a real-world partner not only without hindering the immersive experience, but also by enhancing positive affect. Hence, in addition to offering methodological directions for future VR field research, this study provides interesting practical insights in guiding VR developers towards optimal multi-user virtual environments (MUVEs).

Keywords: Virtual Reality, Multi-User Virtual Environments, Immersive User Experience, Co-presence, Interactivity, Emotional Arousal

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[2] This article has been submitted to the journal of Cyberpsychology, Behavior, and Social Networking for consideration in their special issue on "Virtual Emotions: Understanding Affective Experiences in the Metaverse." The manuscript, submitted on July 31st 2022, is currently under review by the journal.

1. INTRODUCTION

Fuelled by technological advancements, society has entered the "experience age", constantly seeking novelty. Virtual Reality (VR), a next-generation technology enabling immersive experiences through vivid 3-dimensional virtual environments (VEs), successfully aligns with this social eagerness.[1] Hence, VR is increasingly used in the arts & entertainment sector, namely in museum contexts, where it can enhance user experience (UX) by reinventing content delivery and boosting crowd engagement.[2] VR's unique potential places this technology under the spotlight, which has been shining brighter since the rise of the Metaverse. Best known for merging physical and digital realities within a multi-user virtual environment (MUVE), the Metaverse is a transformative technology that not only allows for seamless interactions with virtual objects, but also promotes social networked and embodied interactions.[3,4] With the aim to be adopted by the general public, the Metaverse brings about a growing need to better understand UX in VR, specifically in real-life contexts of use. To our knowledge, VR research carried out in the field is scarce and typically focuses on educational, rather than entertainment, purposes.[5] The present study conveys important contributions by taking place outside a controlled laboratory environment, i.e., in a multimedia entertainment center, and focusing on social and interactive dimensions of VR.

In VR, there seems to be an emerging duality between creating a social yet optimally immersive experience. By definition, VR is a technology that requires users to block all external distractions to plunge into a virtual world, making it particularly vulnerable to events, e.g., social interactions, occurring in the real world.[6,7] Relatedly, an essential tenet of social psychology is that one's behavior is influenced by the social context.[8] However, while VR developers are investing efforts in creating shared VEs, relatively little research has empirically evaluated the effect of world-based social interactions during immersive experiences.[9,10] In addition to enabling social interactions, optimal VR experiences are also those affording seamless interactions with virtual objects and the VE itself.[4] Previous research, however, does not offer a clear consensus pertaining to a VE's optimal level of interactivity. In fact, some researchers support that moderate interactivity should be avoided, while high or low levels should be prioritized;[11] others argue that the interactivity of a given VE needs to be properly aligned with the experience' purpose.[12] Together, these current gaps fuel the following research questions;

RQ1. How does the co-presence of a real-world partner in a shared virtual environment influence the user experience in VR?

RQ2. How does the interactivity of the virtual environment influence the user experience in VR?

2. THEORETICAL BACKGROUND

2.1 Individual versus Shared VR

2.1.1 Immersive UX: Presence, Immersion, Flow

Presence is defined as the subjective sense of "being there" in an environment, even when one is physically situated in another.[13] In VR, presence is contingent upon the ability to block irrelevant real-world stimuli and focus on actions occurring in the VE.[13] In MUVEs, presence is extended to *co-presence*, i.e., "being there *together*".[14] Relatedly, *immersion* is based on the technology's affordances including image resolution or sound quality.[15] When presence and immersion are optimal, *flow*, i.e., a mental state of absolute absorption and involvement, is more likely to emerge.[16] Altogether, considering immersive UX being contingent on external stimuli, and aligned with previous research supporting that active distractions decrease social presence,[17] we posit that;

H1. The co-presence of a real-world partner will hinder the immersive user experience, i.e., will decrease a user's presence (H1a), adaptive immersion (H1b), sensory immersion (H1c), and flow (H1d).

2.1.2 Affective UX: Positive Affect, State Anxiety

Positive affect refers to the combination of pleasurable emotions (i.e., feeling content and happy).[18] The other end of the emotional spectrum comprises negative moods including *state anxiety*, i.e., a transitory anxious emotional state elicited by the activity at hand,[19] which could arise from experiencing a novel VE. However, past studies building upon social facilitation, a well-established theory supporting that social contact leads to emotional happiness,[20] showed that sharing an experience increases feelings of reward, pleasantness and enjoyment,[21,22] therefore serving as a successful mechanism in coping with various life stressors, even that of physical pain.[23,24] Hence, we posit that;

H2. The co-presence of a real-world partner will enhance the affective user experience, i.e., will lead to greater positive affect (H2a) and lower state anxiety (H2b).

2.1.3 Lived UX: Emotional Arousal & Exploration Behavior

Emotional arousal, measured through electrodermal activity (EDA), refers to the intensity of an emotional experience.[25] High EDA is related to curiosity / anxiety, while low EDA is related to relaxation / boredom.[26] Greater emotional arousal is also inferred from higher heart rates (HRs) measured via an electrocardiogram (ECG).[27] Another measure of lived experience consists of *exploration behavior*, measured through users' motion in their physical environment. Previous research found that both emotional arousal and exploration behavior fluctuate per the social context of an experience. For instance, solo participants walk, i.e., explore, less during spatial VR tasks than those in a collaborative co-located condition.[28] Combining extant theories and findings, we posit that;

H3. The co-presence of a real-world partner will be associated with lower emotional arousal, i.e. decreased electrodermal activity (H3a) and heart rate (H3b).

H4. The co-presence of a real-world partner will increase a user's exploration behavior.

2.2 Passive versus Active VR

Interactivity, the degree through which the content of a VE can be influenced by users' actions, translates into the passive-active spectrum of a VR experience.[29] While passive experiences do not afford users to interact with the VE, active experiences do.[30] Given that active VR replicates more accurately real-life experiences than passive VR, previous research reported higher presence, more positive affect and intensified emotional reactions during the former.[31,32,33,34] Thus, considering that interactivity is contingent upon the VE's affordances with surrounding entities, e.g., objects or humans, we posit that an interaction effect will emerge between co-presence and a VE's interactivity as follows, and as summarized in *Figure 1*:

H5. The interaction effect of co-presence and the VE's interactivity is negatively associated with immersive UX (H5a) and users' emotional arousal (H5c), but positively associated with affective UX (H5b) and exploration behavior (H5d).

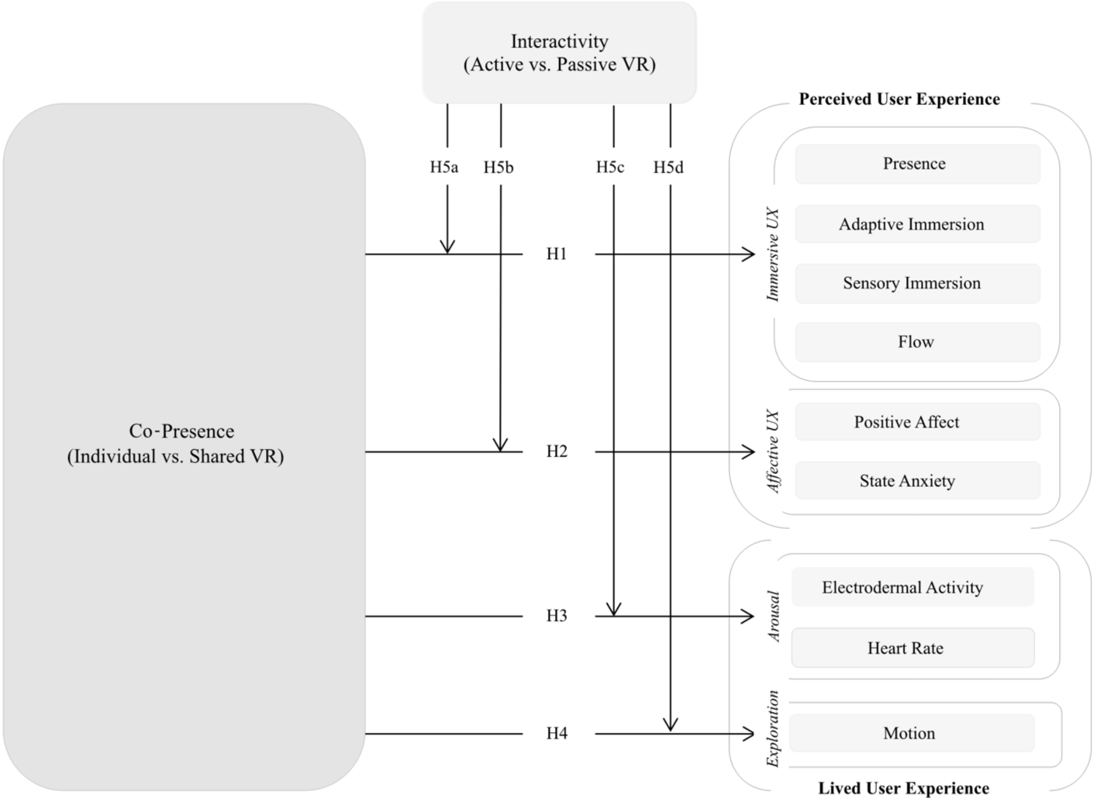

Figure 1. Research model

3. MATERIALS AND METHOD

3.1 Sample

This study was completed by 28 bilingual participants (F = 12, M = 16), aged 20-34 years old (M = 24.71, SD = 3.17). All reported a normal or corrected-to-normal vision and no history of psychiatric or neurological disorders. Participants were screened for motion sickness propensity, but all were retained. The study was approved by the Research Ethics Board of the authors' institution, with participants' written consent obtained at the time of the study (Certificate number 2022-4458). The minority, i.e., 9 participants, were novice VR users while the remainder, i.e., 19 participants, had used it at least once. Participants were provided free entry to the VR experience, valued at CA$45, as compensation.

3.2 Experimental Design

This field study was undertaken at a multimedia entertainment center located in Montreal, Canada, which hosted the VR experience that served as the stimulus in this study. It employed a between-subject design manipulating the social context of the experience. Participants were either assigned to the solo group, composed of 12 participants (F = 4, M = 8) who underwent the experience on their own (among strangers) or the duo group, composed of 16 participants (i.e., 8 duos) (F = 8, M = 8), who underwent the experience with a real-world partner.

3.3 Virtual Environment

The VR experience was powered through the Oculus Quest 2 head-mounted display (HMD) (Facebook, Inc., Menlo Park, CA, USA). A state-of-the-art color-coded tracking system allowed users to portray their body virtually, recognize their partners among strangers, monitor others' displacements, and interact with the VE directly with their hands, free of controllers. The VR experience, taking users in Space aboard the International Space Station (ISS), comprised two phases: a 30-minute active standing phase followed by an 8-minute passive seated phase (*Figure 2*). In the first phase, participants were brought to walk freely through a 3-D modelized ISS representation and interact with luminous spheres. Upon touching, each sphere launched a 360-degree video showcasing astronauts undergoing daily activities; participants could explore this VE through desired head movements and on-site body rotations. In the second phase, participants were virtually guided to a physical chair to watch an unnarrated rotation around planet Earth from the ISS cupola. Participants' HMDs were monitored in real-time on a moderator's tablet.

Figure 2. Active standing phase of the experience (left); followed by the passive seated phase of the experience (middle). Virtual representation of the ISS featuring a virtual luminous sphere (right).
Credits: Photos taken by David Brieugne, Tech3Lab.

3.4 Procedure

Participants were first welcomed on site and directed to a preparation room (*Figure 3*). After being briefed on the tools and general format of the experiment, their consent was obtained. Participants were instructed to behave as naturally as possible during the VR experience; verbal and physical interactions were allowed among dyads. Participants were asked to change into the Hexoskin Smart Garment (Carré Technologies Inc., Montreal, Canada), to which a GoPro was fixed (Hero 4, Woodman Labs Inc., San Mateo, CA, USA), and fitted with EDA sensors in the palm of their non-dominant hand (Cobalt System, Tech3Lab, Montreal, Canada). Participants were then guided towards the exhibition entrance where instructions on virtual space navigation were provided. The GoPro was turned on, tools synchronized, the VR HMD installed, and participants began the experience. The moderator withdrew, but stayed in the room to overview potential technical issues. At the end, participants were brought back to the preparation room, to conclude with a post-experience questionnaire and an individual semi-structured interview.

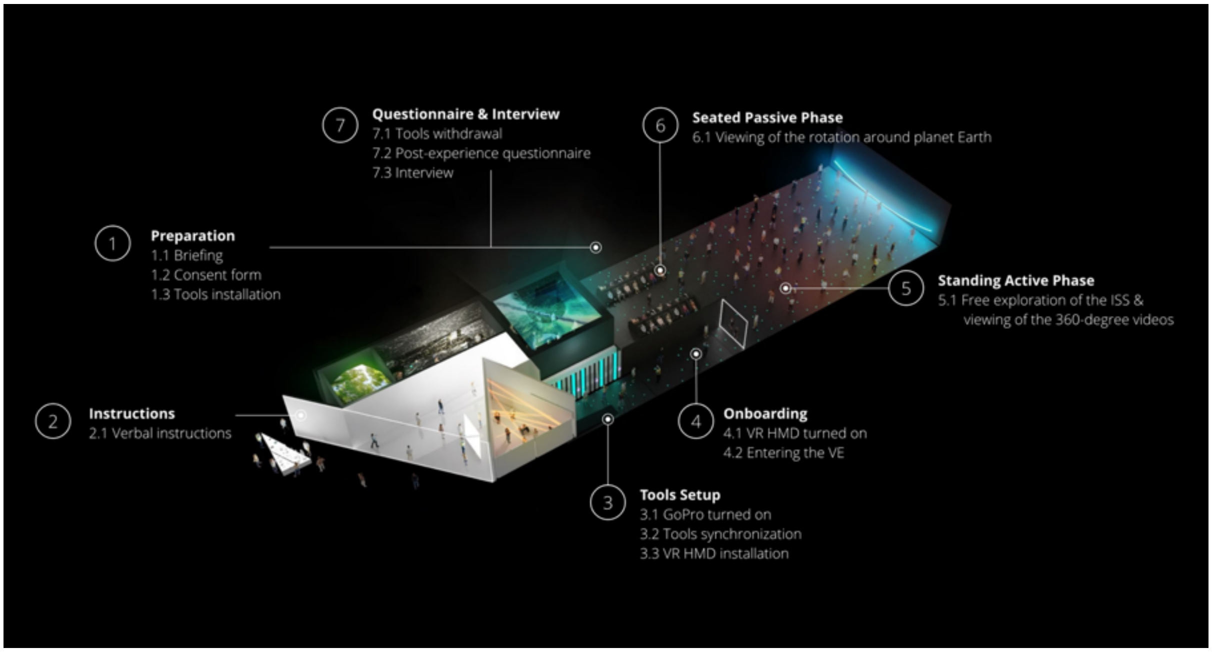

Figure 3. Experimental procedure detailed along the exhibition room plan.
Source: Retrieved from https://phi.ca/fr/evenements/infini-montreal/, modified with the permission of PHI.

3.5 Measures & Tools

3.5.1 Psychometric self-reports

To assess perceived experience, a self-report post-experience questionnaire comprised the following measures recorded on a 7-point Likert scale ranging from (1) not at all to (7) completely* / extremely** / very much so***. *Co-presence** was assessed through 7 items.[35] *Presence* was assessed through 6 items ranging from (1) not feeling there at all to (7) feeling as present as in the real world.[36] Immersion was assessed through two sub-dimensions: 8 items on *Adaptive Immersion** [37] and 6 items on *Sensory Immersion***.[38] *Flow*** and *Positive affect*** were both assessed through 5 items.[38] *State anxiety**** was assessed through 5 items, i.e.., feeling upset, frightened, nervous, jittery and confused.[19] Scales' internal consistency ranged from acceptable (α = 0.706) to excellent (α = 0.937).

3.5.2 Psychophysiological and motion sensors

To assess lived experience, *Exploration Behavior* was measured through a non-invasive 64Hz accelerometer embedded in the Hexoskin. A record of unexpected events or technical issues was provided by the GoPro. *Emotional Arousal* was inferred from HR recorded by a 256 Hz ECG embedded in the Hexoskin, and EDA measured via disposable Ag/AgCl sensors.

3.6 Data preprocessing

Data synchronization and behavioral / stimuli coding was performed using Observer XT (Noldus, Wageningen, the Netherlands). GoPro recordings were visually inspected such that atypical events, e.g., technical problems or strangers' physical / verbal interruptions, were removed from the data.

3.7 Statistical analyses

Given the moderate sample size and a lack of normality observed in the psychophysiological data, differences across the social conditions with regards to dependent variables were examined using non-parametric Wilcoxon sum rank one-tailed tests. Additionally, the interaction between co-presence and the VE's interactivity on dependent variables was tested using linear and logistic regressions with random intercept. Statistical analyses were performed using SPSS Statistics (Version 28.0, IBM Corp., Armonk, NY, USA), with a threshold for significance set at $p < 0.05$.

4. RESULTS

4.1 Manipulation Check

To ensure that the social context was manipulated as desired, co-presence mean scores were compared between social conditions. Results confirmed that participants in dyads (M = 5.509, SD = 0.71) experienced significantly higher levels of co-presence than those in the solo condition (M = 4.536, SD = 0.95), (z = 2.722, p = 0.005).

4.2 Perceived UX Results

Results outlined in *Table 1* demonstrate that no significant difference in users' immersive experience emerged between social conditions, thus H1 is not supported. On the other hand, with regards to users' affective experience, positive affect was significantly higher for participants in dyads than solo (p = 0.010), while state anxiety did not significantly differ between social conditions. Accordingly, H2a is supported while H2b is not, offering partial support for H2 (*Table 2*). When investigating the moderating effect of interactivity, results showed that co-presence effect on adaptive immersion depends on the interactivity of the experience (p < 0.0001) therefore partially supporting H5a (*Table 3*). Specifically, participants in the solo group reported higher adaptive immersion during passive than active VR, while participants in the duo group reported higher adaptive immersion during active than passive VR (*Figure 4*).

Table 1. Co-Presence Effects on Perceived and Lived User Experience

	Presence					**Adaptive Immersion**					**Sensory Immersion**				
	M	Median	SD	Z	p	M	Median	SD	Z	p	M	Median	SD	Z	p
Solo	4.625	4.500	1.051	0.580	0.283	5.592	5.750	0.704	-0.116	0.454	5.962	6.333	0.859	-0.743	0.232
Duo	4.316	4.500	1.357			5.634	5.875	0.700			6.307	6.333	0.707		

	Flow					**Positive Affect**					**State Anxiety**				
	M	Median	SD	Z	p	M	Median	SD	Z	p	M	Median	SD	Z	p
Solo	5.471	5.600	1.305	-1.045	0.153	5.608	5.800	1.086	-2.491	0.010	2.016	1.800	0.859	-0.209	0.418
Duo	5.929	6.200	1.207			6.489	6.800	0.718			2.078	1.600	1.005		

	HR					**EDA**					**Motion**				
	M	Median	SD	Z	p	M	Median	SD	Z	p	M	Median	SD	Z	p
Solo	73.096	78.199	17.976	-0.489	0.315	1.562	1.409	0.672	-0.651	0.261	0.014	0.012	0.013	-1.414	0.085
Duo	73.501	80.300	27.306			1.489	1.472	0.232			0.016	0.014	0.012		

Results from Wilcoxon sum rank one-tailed tests investigating differences across social grouping conditions with regards to perceived experience (i.e., presence, adaptative immersion, sensory immersion, flow, state anxiety and positive affect) and lived experience (i.e., electrodermal activity, heart rate, motion).

4.3 Lived UX Results

Results outlined in *Table 1* show no significant difference in participants' emotional arousal and exploration behavior across social conditions. Hence, H3 and H4 are not supported (*Table 2*). When investigating the moderation effect of interactivity, results showed that co-presence effect on EDA depends on the interactivity of the experience (p = 0.006), therefore partially supporting H5c (*Table 3*). Specifically, EDA was higher during active than passive VR for participants in the solo group, whereas this significant effect was not detected in the duo group (*Figure 4*).

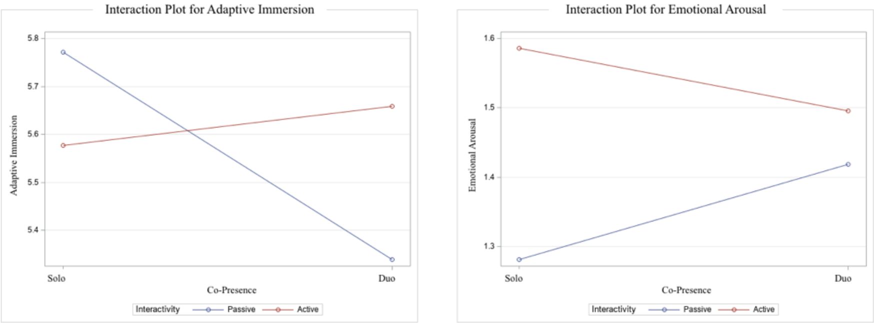

Figure 4. Interaction plots of the interaction effect between co-presence and a VE's interactivity on measures of adaptive immersion and electrodermal activity.

Table 2. Table of Hypotheses Testing for RQ1

H	From	Directionality	To	Z	p-value	Status
1a	Co-presence	↓	Presence	0.580	0.567	Not supported
1b	Co-presence	↓	Adaptive Immersion	-0.116	0.909	Not supported
1c	Co-presence	↓	Sensory Immersion	-0.743	0.464	Not supported
1d	Co-presence	↓	Flow	-1.045	0.306	Not supported
2a	Co-presence	↑	Positive Affect	-2.491	0.019	Supported
2b	Co-presence	↓	State Anxiety	-0.209	0.836	Not supported
3a	Co-presence	↓	Electrodermal Activity	-0.651	0.522	Not supported
3b	Co-presence	↓	Heart Rate	-0.489	0.629	Not supported
4	Co-presence	↑	Exploration	-1.414	0.170	Not supported

Table 3. Table of Hypotheses Testing for RQ2

H	From	Directionality	To	b	SE	DF	t-value	p-value	Status	Lower	Upper
5a	CP x Interactivity	↓	Presence	0.054	0.113	300	0.480	0.631	Not supported	-0.167	0.276
	CP x Interactivity	↓	Adaptive Immersion	0.549	0.105	300	5.230	<.0001	Supported	0.343	0.756
	CP x Interactivity	↓	Sensory Immersion	19.105	13.353	300	1.430	0.154	Not supported	-7.172	45.382
	CP x Interactivity	↓	Flow	2.129	1.785	300	1.190	0.234	Not supported	-1.385	5.642
5b	CP x Interactivity	↑	Positive Affect	3.542	2.090	300	1.690	0.091	Not supported	-0.571	7.655
	CP x Interactivity	↓	State Anxiety	-1098.100	0.000	300	M	<.0001	Not supported	.	.
5c	CP x Interactivity	↓	Electrodermal Activity	-0.217	0.079	260	-2.760	0.006	Supported	-0.372	-0.062
	CP x Interactivity	↓	Heart Rate	-3.604	4.124	299	-0.870	0.383	Not supported	-11.720	4.511
5d	CP x Interactivity	↑	Exploration	-0.002	0.004	299	-0.450	0.656	Not supported	-0.010	0.006

CP: Co-Presence

4.4 Qualitative Results

4.4.1 Shared experience elicits greater positive affect though avatar tracking and gamification

The majority of the sample, i.e., 20/28 participants, reported they preferred or would have preferred (if in the solo group) performing the experience in dyads (*Table 4*). The main justification being the physical proximity afforded by a real-world partner, as participants "would try to avoid other strangers, simply touching or following [their] companion made [the overall experience] more pleasant" (P19). Additionally, what participants preferred was "to see the avatars walking around while being connected with a friend" (P05). Thus, positive affect was elevated through the VE's sophisticated tracking system, becoming more salient in the shared condition and fueling a greater feeling of gamification: "being accompanied, felt a bit more like a game" (P27).

4.4.2 Active VR elicits greater presence through interactivity

The majority of the sample, i.e., 16/28 participants, reported feeling more present during the active phase, a feeling repeatedly attributed to the greater interactivity afforded by the VE (*Table 4*). Oppositely, "as soon as [they] sat down, no interaction allowed [them] to stay focused on what [they were] experiencing in VR, so [their] attention was automatically turned to their own thoughts" (P12). This suggests that interacting with the VE helps in remaining connected to the on-hand experience, therefore optimizing users' presence.

4.4.3 The overall experience elicits positive states of mind, but can appear physically strenuous

When queried about their overall state post-experience, 12/28 participants reported feeling more excited and awake than they did prior to beginning the experience (*Table 4*). Despite this seemingly general positive trend, some important nuances were raised by participants mentioning how they felt "a little more excited and awake (post-experience), [but] "a little physically drained" (P03) as "the standing phase asked for more energy, (…) [specifically] having to always pay attention to collisions" (P04).

Table 4. Qualitative Insights Summary

Qualitative Insight	Solo Frequency	Duo Frequency	Total Frequency
Preference for having shared the experience	6/12 participants	14/16 participants	20/28 participants
Feeling more present during the active VR phase	6/12 participants	9/16 participants	16/28 participants
Feeling more excited and awake post-experience	4/12 participants	8/16 participants	12/28 participants

Frequency of each qualitative insight per social grouping condition.

5. DISCUSSION

5.1 Implications

This field study investigated the effects of social and interactive dimensions of VR on UX. The most relevant implications are addressed next through theoretical, practical, and methodological lenses.

Revisiting RQ1, and the effect of the social context on affective UX, results showed that shared, rather than individual, active VR elicits greater positive affect (H2a). Not only does this finding support existing social theories, namely Zajonc's social facilitation theory[20], but also prior research on other immersive media showing that shared gaming experiences elicit greater enjoyment and fun.[39,22] While results pertaining to immersive UX offered an opposite directionality than the one hypothesized, i.e., no significant difference in users' presence, immersion, and flow between social conditions, qualitative results help in explaining this unexpected trend; per user interviews, it seems like the sophisticated tracking system was successful in integrating real-world partners to a point where their presence became a seamless part of the VE, which is aligned with previous research showing that presence is facilitated when VR elicits genuine emotional and behavioral responses.[40] Considering the growing eagerness to develop social MUVEs for the Metaverse[41], this is a notable practical implication for VR developers as it supports that VR, contingent upon well-designed real-time tracking, can be successfully shared, such that the introduction of a real-world partner is not a threat to the elicited immersive UX.

Revisiting RQ2, and the effect of a VE's interactivity, results suggest that the interactivity afforded by the VE moderates the effects of co-presence on adaptive immersion and electrodermal activity. Specifically, adaptive immersion was greater during passive VR for solos while it was greater in active VR for dyads. This implies that adaptive immersion is reinforced through greater VE interactivity in contexts of shared VR, thus serving as a motivation for VR developers to prioritize a VE's interactivity when designing shared experiences. From a methodological point of view, our successful mixed methods approach combining a variety of psychophysiological measures via advanced wearable technology appears as a notable contribution towards the ecological evaluation of VR experiences for a variety of real-life entertainment applications.

5.2 Limitations & Future Research

Load sharing, measured through emotional arousal, is mediated by physical contact.[42] In the present study, however, although dyads were made of close friends or romantic partners, the strength of their relationship, along with the extent to which they talked, touched or remained physically close during their experience, was not controlled for. While this is a limitation to our results, it also sets path to further research to further investigate the effects of dyadic relationships on lived and perceived UX.

6. CONCLUSION

Overall, this field study sheds light onto the social and interactive dimensions of VR, by evaluating immersive and affective experiences. It successfully leverages a mixed methods approach in taking UX VR research out of controlled laboratory settings, into the field. Hence, ecologically valid results provide confidence to VR developers that VR can be shared with a real-world partner without diminishing the immersive experience, and that immersion is partly reinforced through a VE's interactivity during shared VR. Our results point in a direction that agrees with Palmer Luckey, founder of the Oculus, claiming that "VR is a way to escape the real world into something more fantastic. It has the potential to be the most social technology of all time".[43]

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Appendix C: Literature Review Method

A thorough method was employed to ensure a complete assessment of the literature and uncover the existing literature gaps in UX VR research. That is, considering the research's aim to measure users' cognitive and affective states while immersed in VR, the body of previous research that have used neurophysiological measures, i.e., electroencephalography, in combination with a VR head-mounted display, was reviewed. Beyond providing a thorough overview of the research that has evaluated cognitive and affective states of users in VR, the goal of this literature review was also to identify unexplored areas of research as to reveal interesting and novel research opportunities. Per this regard, the method of Boolean search was employed; a systematic process comprising a series of search queries in scientific databases including Google Scholar, Science Direct, AIS e-Library, Frontiers, Elsevier, and Springer Link.

A first Boolean search was performed using the set of predetermined keywords listed in Table C.1, and to answer the rather general question: *What comprises the current literature body of research combining EEG and a head-mounted VR display?* Results from this search provided a general overview of potential combinations of the two wireless devices, the associated physical constraints and important limitations to be considered in the research design. While this search was very insightful and inspired important methodological pillars of our research, the gap in literature relating to users' immersion in VR remained vague, therefore raising the need for a second and more precise search as detailed next.

Table C.1 Methodological Search Terms Associated with the First Boolean Search

Search term 1		Search term 2
"EEG"	***" AND "***	"VR" or "Virtual reality"
"Electroencephalography"		"VE" or "Virtual environment"
"Electro-encephalography"		"IR" or "Immersive reality"
"Electroencephalogram"		"Immersive experience"
"Electro-encephalogram"		"HMD" or "Head-mounted display"

Search terms that were combined to yield results of the first Boolean search.

Accordingly, a second Boolean search was performed using the set of predetermined keywords listed in Table C.2, and to answer the more specific questions: *What do empirically validated results from previous research suggest about the impact of VR immersion in relation to a user's cognitive state? What do empirically validated results from previous research suggest about the impact of VR immersion in relation to a user's affective state?* Where *cognitive state* refers to concepts of attention, decision-making, engagement, consciousness, learnability, while *affective state* refers to concepts of emotional valence, arousal, embeddedness, flow. Results from this search were rich and offered an important overview of previous studies that had employed virtual reality, and evaluated related user experience, for a variety of application purposes.

Table C.2 User Experience Search Terms Associated with the Second Boolean Search

Search term 1		**Search term 2**
"Cognition" or "Cognitive state"		“VR” or "Virtual reality"
"Attention" or "Attentional state"		"VE" or "Virtual environment"
"Decision-making" or "Engagement"		"IR" or "Immersive reality"
"Consciousness" or "Conscious state"		"Immersive experience"
"Learning" or "Learning affordances"	***" AND "***	"HMD" or "Head-mounted display"
"Education" or "Educational"		
"Affective state"		
"Arousal" or "Valence"		
"Emotion" or "Emotional state"		
"Embeddedness" or "Flow"		

Search terms that were combined to yield results of the second Boolean search.

The scientific articles emerging from both search queries were first screened through a review of their abstract. Then, the selection process was based on the quality / completeness of the presented methodology, the reliability / number of citations, the appropriateness of the chosen sample size, the relevance of results / limitations in relation to our research objectives, and the predetermined set of inclusion and exclusion criteria detailed in Table C.3.

Table C.3 Selection Criteria for Scientific Articles

Inclusion Criteria	**Exclusion Criteria**
Published in the last decade (2011-2021)	Research-in-progress articles
Published in the English language	Short papers from conferences or workshops
Published in a peer-reviewed journal, conference of workshop	Lack of empirical evidence (e.g., theoretical or conceptual articles, essays, tool demonstrations, technical reports, etc.)

Inclusion and exclusion criteria for retaining or rejecting an article from the literature review.

As a result of the above, a total of 52 articles were retained from combined searches; all of which were carefully read and reviewed, with their key concepts analyzed. That is, all selected articles were codified based on their underlying theme (e.g., immersion, emotion, health applications of VR) and categorized in an Excel spreadsheet for ease of use. The basic information pertaining to the article's title, year of publication, research question, sample size, and experimental design was noted. Furthermore, the specific questionnaires used, chosen electrodes positioning, EEG preprocessing methods, and statistical analyses were indicated. Then, the central results from each article were retained, along with important limitations identified by the authors. Finally, an indicator of the article's overall quality was added for quick recall and indexing purposes.

Altogether, this meticulous literature review process allowed to confirm that the body of existing studies combining EEG and VR had, in majority, been limited to controlled laboratory-based environments. While limiting user movements to ensure the quality of brain activity, previous research had also been restricting the ecological validity of obtained results. As explained in Chapter 1 of this thesis, this general conclusion arising from our literature review served as a central motivation and ended up guiding both phases of our research project.

Appendix D: Ethics Approval

HEC MONTRĒAL

Comité d'éthique de la recherche

May 13, 2021

To the attention of:
Pierre-Majorique Léger
HEC Montréal

Re: Ethics approval of your research project

Project No.: 2022-4458

Title of research project: Meditative immersion in Virtual Reality (VR): Utilization of psychophysiological data to evaluate the user's cognitive and affective experience during immersion in a meditative VR environment.

Funding source : CRSNG (C. Coursaris) - CCS : R2579

Title of the grant : Envisioning and Enacting UX Evaluation of Augmented Reality: A Multimethod Approach

---

Your research project has been evaluated in accordance with ethical conduct for research involving human subjects by the Research Ethics Board (REB) of HEC Montréal.

A Certificate of Ethics Approval attesting that your research complies with HEC Montréal's *Policy on Ethical Conduct for Research Involving Humans* has been issued, effective May 14, 2021. This certificate is **valid until May 01, 2022.**

In the current context of the COVID-19 pandemic, you must ensure that you comply with the directives issued by the Government of Quebec, the Government of Canada and those of HEC Montréal in effect during the state of health emergency.

Please note that you are nonetheless required to renew your ethics approval before your certificate expires using Form *F7 – Annual Renewal*. You will receive an automatic reminder by email a few weeks before your certificate expires.

If any changes are made to your project before the certificate expires, you must complete *F8 – Project Modification* and obtain REB approval before implementing those changes. If your project is completed before the certificate expires, you must complete Form *F9 – Termination of Project* or *F9a – Termination of Student Project*, as applicable.

Under the *Policy on Ethical Conduct for Research Involving Humans*, researchers are responsible for ensuring that their research projects maintain ethics approval for the entire duration of the research work, and for informing the REB of its completion. In addition, any significant changes to the project must be submitted to the REB for approval before they are implemented.

You may now begin the data collection for which you obtained this certificate.

We wish you every success in your research work.

REB of HEC Montréal

HEC MONTRĒAL

Comité d'éthique de la recherche

CERTIFICAT D'APPROBATION ÉTHIQUE

La présente atteste que le projet de recherche décrit ci-dessous a fait l'objet d'une évaluation en matière d'éthique de la recherche avec des êtres humains et qu'il satisfait aux exigences de notre politique en cette matière.

Projet # : 2022-4458

Titre du projet de recherche : Meditative immersion in Virtual Reality (VR): Utilization of psychophysiological data to evaluate the user's cognitive and affective experience during immersion in a meditative VR environment.

Chercheur principal :
Pierre-Majorique Léger,
Professeur titulaire, Technologies de l'information, HEC Montréal

Cochercheurs :
Constantinos-K Coursaris; Shady Guertin-Lahoud; David Brieugne; Emma Rucco; Salima Tazi; Jared Boasen; Sylvain Sénécal; Shang-Lin Chen; Marc Fredette

Date d'approbation du projet : 14 mai 2021

Date d'entrée en vigueur du certificat : 14 mai 2021

Date d'échéance du certificat : 01 mai 2022

Maurice Lemelin
Président
CER de HEC Montréal

HEC MONTRĒAL

Comité d'éthique de la recherche

September 28, 2021

To the attention of:
Pierre-Majorique Leger
Technologies de l'information, HEC Montréal

Co-researchers:
Constantinos-K Coursaris; Shady Guertin-Lahoud; David Brieugne; Emma Rucco; Salima Tazi; Jared Boasen; Sylvain Senecal; Shang-Lin Chen; Marc Fredette; Bella Tadson

Project No.: 2022-4458

Project title:
Meditative immersion in Virtual Reality (VR): Utilization of psychophysiological data to evaluate the user's cognitive and affective experience during immersion in a meditative VR environment.

Further to the evaluation of your Form F8 – Project Modification, the Research Ethics Board (REB) of HEC Montréal wishes to inform you of its decision:

The changes have been noted in the file. The current certificate will remain valid until the next renewal.

Thank you.

REB of HEC Montréal

HEC MONTRÉAL

Comité d’éthique de la recherche

ATTESTATION D'APPROBATION ÉTHIQUE COMPLÉTÉE

La présente atteste que le projet de recherche décrit ci-dessous a fait l'objet des approbations en matière d'éthique de la recherche avec des êtres humains nécessaires selon les exigences de HEC Montréal.

La période de validité du certificat d'approbation éthique émis pour ce projet est maintenant terminée. Si vous devez reprendre contact avec les participants ou reprendre une collecte de données pour ce projet, la certification éthique doit être réactivée préalablement. Vous devez alors prendre contact avec le secrétariat du CER de HEC Montréal.

Nom de l'étudiant : Shady Guertin-Lahoud

Titre du projet supervisé/mémoire/thèse : Meditative immersion in Virtual Reality (VR): Utilization of psychophysiological data to evaluate the user’s cognitive and affective experience during immersion in a meditative VR environment.

Titre du projet sur le certificat :
Meditative immersion in Virtual Reality (VR): Utilization of psychophysiological data to evaluate the user’s cognitive and affective experience during immersion in a meditative VR environment.

Projet # : 2022-4458

Chercheur principal / directeur de recherche :
Pierre-Majorique Léger

Cochercheurs :
Constantinos K. Coursaris; Shady Guertin-Lahoud; David Brieugne; Emma Rucco; Salima Tazi; Jared Boasen; Sylvain Sénécal; Shang Lin Chen; Marc Fredette; Bella Tadson

Date d'approbation initiale du projet : May 14, 2021

Date de fermeture de l'approbation éthique pour l'étudiant(e) : August 17, 2022

Maurice Lemelin
Président
CER de HEC Montréal

Signé le 2022-08-17 à 13:25

Appendix E: Thesis in English Approval

Retrait d’une ou des pages pouvant contenir des renseignements personnels

Appendix F: Thesis by Articles Approval

Retrait d’une ou des pages pouvant contenir des renseignements personnels

Appendix G: Co-Authors Authorization

Authorization by co-authors of an article included in a master's thesis or doctoral dissertation

Office
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HEC MONTRĒAL

When a student is not the sole author of an article to be included in his/her thesis or dissertation, he/she must obtain the authorization of all the other co-authors for this purpose and attach the signed authorization to the article in question. **There must be a separate authorization form for each article included in the thesis or dissertation.**

1. Student

Guertin-Lahoud, Shady	11290655
Last name, First name	HEC ID number
Master of science in Administration (I	Information Technologies
Program of study	Specialisation

2. Article

Authors: Guertin-Lahoud, S., Coursaris, C., Boasen, J., Demazure, T., Chen, S. L., Dababn

Title : Evaluating User Experience in Multisensory Meditative Virtual Reality: A Pilot Study

Publication : Special Interest Group on Human Computer Interaction (SIGHCI) 2021 Conferenc

Current status of article : ☒ published ☐ submitted for publication ☐ in preparation

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As first author, I take responsibility for the experimental design, execution, writing, and publication of this article. Dr. Coursaris, Dr. Léger and Dr. Sénécal supervised the project. Dr. Boasen and Mr. Demazure provided guidance on neurophysiological methods &

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From the Laboratory to the Field: Evaluating User Experience in Virtual Reality for Tomorrow ' s Metaverse

(Title of thesis or dissertation)

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