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WEARABLES AND MULTISENSORY NATURE IMMERSION FOR MENTAL HEALTH MANAGEMENT

DISPOSITIFS PORTABLES ET IMMERSION MULTISENSORIELLE DANS LA NATURE POUR LA GESTION DE LA SANTÉ MENTALE

Par

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RÉSUMÉ

Les troubles liés au stress et aux traumatismes affectent de plus en plus les individus, les milieux de travail et les systèmes de santé, ce qui crée un besoin d'interventions qui soient accessibles, tolérables lors d'utilisations répétées et mesurables au-delà du simple auto-questionnaire. L'exposition à la nature constitue une approche non pharmacologique largement utilisée pour favoriser la relaxation et la régulation du stress, mais l'accès à des environnements restaurateurs est souvent limité par la géographie, le manque de temps, des contraintes de mobilité et le contexte clinique. La réalité virtuelle (RV) offre une alternative pratique en permettant de proposer des expériences de nature contrôlables et reproductibles. Toutefois, la plupart des systèmes de nature virtuelle stimulent principalement la vision et l'audition, ce qui peut réduire leur potentiel restaurateur comparativement à la nature réelle. Les avancées récentes en technologies olfactives et haptiques rendent possibles des expériences virtuelles multisensorielles, mais leurs bénéfices, leurs contraintes et les besoins de mesure dans des contextes réalistes et cliniques demeurent insuffisamment compris.

Cette thèse doctorale étudie l'immersion multisensorielle dans la nature virtuelle comme outil accessible pour favoriser la relaxation et soutenir la réduction du stress, tout en mettant l'accent sur des mesures objectives afin de quantifier les effets et d'orienter de futures personnalisations. Une revue systématique de la littérature (janvier 2016 à avril 2023) a d'abord été menée pour caractériser la manière dont les systèmes de nature virtuelle intègrent différentes modalités sensorielles et comment les résultats sont évalués. Cette revue met en évidence une base de preuves limitée et hétérogène centrée sur la nature virtuelle audio-visuelle-olfactive, une forte variabilité des modalités de présentation et des baselines expérimentales, ainsi qu'un paysage de mesures fragmenté. Au travers des études, l'olfaction apparaît comme un levier prometteur mais méthodologiquement inconstant, et le domaine montre une standardisation limitée des conditions de contrôle, de la diffusion des odeurs et de l'évaluation physiologique objective, ce qui motive des évaluations plus rigoureuses et davantage guidées par des capteurs.

À partir de ces constats, la thèse propose une évaluation progressive sur trois populations et niveaux de validité écologique. Premièrement, une étude contrôlée auprès d'étudiants universitaires a testé si l'ajout de modalités au-delà de la RV audio-visuelle standard augmente la relaxation. Nous avons proposé Nat(UR)e, une expérience de shinrin-yoku numérique synchronisant des indices olfactifs, vibroacoustiques et somatosensoriels (flux d'air et chaleur) avec une courte immersion forestière présentée dans un POD multisensoriel. Seize participants ont complété quatre conditions contrebalancées (vidéo seule, audio-visuelle, audio-visuelle-olfactive, et une condition "ultra-réalité" combinant l'ensemble des indices). Sur le plan subjectif, les conditions multisensorielles ont augmenté la relaxation et amélioré des dimensions d'expérience utilisateur telles que le réalisme, la présence, l'immersion et l'émotion, l'odeur produisant les gains les plus marqués. Sur le plan objectif, des biosignaux issus de dispositifs portables (électrocardiographie, respiration, activité électrodermale, température cutanée et pouls volumique) ont montré des tendances compatibles avec une relaxation accrue en "ultra-réalité", et certaines caractéristiques électrodermales différaient significativement entre conditions et corrélaient avec la relaxation rapportée, ce qui soutient l'intérêt de mesures complémentaires.

Deuxièmement, l'approche a été transposée à un contexte professionnel exigeant via une étude en milieu hospitalier avec des infirmières travaillant dans une unité d'hospitalisation en santé

mentale. Le protocole comparait des expositions audio-visuelles versus audio-visuelles-olfactives à des scènes de nature à 360 degrés lors de sessions courtes, contraintes en temps. Vingt-sept infirmières ont participé pendant leurs quarts de travail. Pour dépasser les seuls questionnaires, nous avons utilisé un casque instrumenté développé en interne intégrant l'électroencéphalographie et la photopléthysmographie, permettant de suivre simultanément l'activité neurale et des marqueurs de variabilité de la fréquence cardiaque, en parallèle de mesures répétées d'auto-évaluation de la relaxation et de la qualité d'expérience. Les résultats montrent une augmentation globale de la relaxation après l'exposition à la nature virtuelle, mais la valeur ajoutée de l'olfaction dépend fortement de la congruence sensorielle entre la scène et le jeu d'odeurs. Les analyses par scénario et les retours des participantes indiquent que des odeurs non congruentes peuvent réduire la relaxation et altérer l'expérience, tandis que des odeurs cohérentes peuvent renforcer le réalisme et l'engagement. Les analyses neurophysiologiques révèlent des différences nettes entre conditions dans les dynamiques des sous-bandes EEG et des indices liés à l'attention, l'engagement et l'asymétrie alpha frontale. Les analyses HRV montrent des évolutions systématiques au cours de la session compatibles avec un engagement accru et une réduction de la variabilité à court terme au fil du temps, avec des trajectoires plus marquées en condition multisensorielle, soulignant que des expositions brèves peuvent être à la fois relaxantes et cognitivement engageantes. Ensemble, ces résultats indiquent que l'ajout multisensoriel, à lui seul, n'est pas suffisant : la congruence, les attentes et le contexte façonnent les réponses subjectives et objectives.

Troisièmement, la thèse a étendu l'immersion multisensorielle dans la nature virtuelle à une population clinique via des interventions à sessions répétées chez des patients diagnostiqués avec un trouble de stress post-traumatique (TSPT). Deux formats de diffusion ont été évalués : un système PORTABLE délivrant une stimulation olfactive via un dispositif attaché au casque de RV, et un POD multisensoriel en clinique augmentant le même type de contenu nature avec des odeurs synchronisées ainsi que des indices de vent et de vibration. Les données ont été collectées dans une clinique de psychothérapie à Sept-Îles (Québec), dix participants ayant complété les deux expériences et huit étant inclus dans les analyses EEG en raison de données manquantes. Chaque intervention comprenait douze sessions sur trois semaines, avec deux pré-tests, un post-test et un suivi à trois mois, complétés par des questionnaires cliniques standardisés, des tests cognitifs et des évaluations d'expérience au niveau des sessions. L'exposition répétée a été bien tolérée, avec une présence stable et une cybersickness faible au fil des sessions. Les résultats cliniques et cognitifs montrent des tendances encourageantes dépendantes du dispositif, incluant des réductions de symptômes dissociatifs et une amélioration de la vitesse de traitement en condition portable, ainsi que des tendances d'amélioration moyennes à fortes des symptômes dépressifs et de certains domaines cognitifs en condition pod. Malgré une puissance statistique limitée, les résultats neurophysiologiques montrent de façon cohérente une adaptation longitudinale au fil des sessions, avec des diminutions d'activité en basses fréquences et des augmentations en hautes fréquences, incluant une augmentation gamma robuste en condition pod. Les analyses intra-sujets relient les fluctuations de caractéristiques EEG à la présence perçue, la relaxation, l'immersion et les variations de stress, soutenant l'idée que les mesures objectives peuvent révéler des dynamiques mécanistiques et individuelles non captées par les questionnaires seuls.

Globalement, cette thèse soutient trois conclusions principales. Premièrement, l'immersion multisensorielle dans la nature virtuelle est faisable dans des environnements contrôlés, professionnels et cliniques, mais son efficacité dépend de la qualité et de la cohérence du design multisensoriel plutôt que de l'ajout de sensations en soi. Deuxièmement, l'ajout synchronisé d'indices olfactifs et somatosensoriels à une immersion nature audiovisuelle peut accroître la relaxation perçue et moduler de manière significative des marqueurs physiologiques et neuraux liés à l'acti-

vation, l'engagement et l'affect, même si les effets peuvent s'inverser en cas d'incongruence sensorielle. Troisièmement, l'intégration de mesures objectives dans les systèmes immersifs est non seulement possible, mais nécessaire pour renforcer l'évaluation, capturer les différences interindividuelles et permettre de futures interventions adaptatives. La thèse se conclut en identifiant des limites (tailles d'échantillons, fenêtres d'exposition courtes en contextes réalistes, personnalisation incomplète des odeurs) et en proposant des pistes futures, notamment une meilleure personnalisation des odeurs et du contenu, des protocoles plus longs et davantage standardisés lorsque possible, ainsi que des stratégies de biofeedback adaptatif et de génération de contenu pour maintenir la congruence et optimiser les résultats en déploiement réel.

Mots-clés : réalité virtuelle, multisensoriel, nature virtuelle, shinrin-yoku, olfaction, haptique, relaxation, réduction du stress, trouble de stress post-traumatique, infirmières, électroencéphalographie, variabilité de la fréquence cardiaque, dispositifs portables, qualité d'expérience.

ABSTRACT

Stress- and trauma-related conditions increasingly affect individuals, workplaces, and healthcare systems, creating a demand for interventions that are accessible, tolerable under repeated use, and measurable beyond self-report. Nature exposure is a widely used non-pharmacological approach for relaxation and stress regulation, yet access to restorative environments is often limited by geography, time, mobility constraints, and clinical context. Virtual reality (VR) offers a practical alternative by delivering controllable and repeatable nature experiences. However, most virtual nature systems primarily stimulate vision and audition, which may limit their restorative potential compared to real-world nature. Recent advances in olfactory and haptic technologies make multisensory virtual experiences feasible, but their benefits, constraints, and measurement needs in realistic and clinical settings remain insufficiently understood.

This doctoral thesis investigates multisensory virtual nature immersion as an accessible tool to promote relaxation and support stress reduction, while emphasizing objective sensing to quantify outcomes and guide future personalization. A systematic review of the literature (January 2016 to April 2023) was first conducted to characterize how virtual nature systems integrate sensory modalities and how outcomes are assessed. The review highlighted (i) a small and heterogeneous evidence base focused on audiovisual olfactory virtual nature immersion tools, (ii) large variability in presentation modalities and experimental baselines, and (iii) a fragmented outcomes measurement landscape. Across studies, olfaction emerged as a promising but methodologically inconsistent lever, and the field showed limited standardization in control conditions, scent delivery, and objective physiological assessment, motivating more rigorous, sensor-informed evaluations.

Building on these observations, this thesis provides a step-by-step evaluation across three populations and levels of ecological validity. First, a controlled university-student study tested whether adding modalities beyond standard audiovisual virtual reality increases relaxation. We proposed Nat(UR)e, a digital shinrin-yoku experience that synchronizes olfactory, vibroacoustic, and somatosensory cues (airflow and heat) with a short forest immersion presented in a multisensory pod. Sixteen participants completed four counterbalanced conditions (video-only, audiovisual, audiovisual-olfactory, and audiovisual-olfactory-haptic, which we call “ultra reality”). Subjectively, multisensory conditions increased relaxation and improved user-experience dimensions such as realism, presence, immersion, and emotion, with smell producing the largest gains. Objectively, wearable biosignals (electrocardiography, respiration, electrodermal activity, skin temperature, and blood volume pulse) exhibited trends consistent with relaxation in the full multisensory condition, and select electrodermal features differed significantly between conditions and were shown to be correlated with reported relaxation levels. These findings help support the added value of physiological sensing during virtual nature immersion.

Second, the approach was translated to a demanding occupational context through an in-hospital study with nurses working in a mental health inpatient ward. The protocol compared audiovisual versus audio-visual-olfactory exposures to 360-degree nature scenes during short, time-constrained sessions. Twenty-seven nurses participated during work shifts. To move beyond questionnaires, we used an in-house instrumented head-mounted display integrating electroencephalography and photoplethysmography, enabling simultaneous tracking of neural activity and heart-rate-variability markers alongside repeated self-reports of relaxation and quality of experience. Results showed that relaxation increased after virtual nature exposure overall, but the ad-

ded value of olfaction depended strongly on sensory congruence between the scene and the selected odor. Scenario-level analyses and participant feedback indicated that mismatched odors can reduce relaxation and alter experience, whereas coherent odors can enhance realism and engagement. Neurophysiological analyses revealed clear differences between conditions in electroencephalography subband dynamics and indices related to attention, engagement, and frontal alpha asymmetry. Heart-rate-variability analyses showed systematic within-session shifts consistent with increased engagement and reduced short-term variability over time, with stronger trajectories in the multisensory condition, highlighting that brief exposures can be simultaneously relaxing and cognitively engaging. Together, these findings emphasize that multisensory addition alone is not sufficient; congruence, expectations, and context shape both subjective and objective responses.

Lastly, the thesis extended multisensory virtual nature immersion to a clinical population through repeated-session interventions with patients diagnosed with post-traumatic stress disorder. Two delivery formats were evaluated : a portable system delivering olfactory stimulation via a device attached to the head-mounted display, and an in-clinic multisensory pod, augmenting the same type of nature content with synchronized odors plus wind and vibration stimuli. Data were collected in a psychotherapy clinic in Sept-Îles, Quebec, with ten participants completing both experiments and eight included in the electroencephalography analyses due to missing data. Each intervention comprised twelve sessions over three weeks, with two pre-tests, a post-test, and a three-month follow-up, complemented by standardized clinical questionnaires, cognitive testing, and session-level experience ratings. Repeated exposure was well tolerated, with stable presence and low cybersickness over sessions. Clinical and cognitive results showed encouraging, setup-dependent patterns, including reductions in dissociative symptoms and improvements in processing speed in the portable condition, and medium-to-large improvement trends in depressive symptoms and selected cognitive domains in the pod condition. While statistical power was limited, the neurophysiological results consistently showed longitudinal adaptation across sessions, with decreases in low-frequency activity and increases in higher-frequency activity, including a robust gamma increase in the pod condition. Within-subject analyses linked fluctuations in electroencephalography features to perceived presence, relaxation, immersion, and stress changes, supporting the premise that objective sensing can reveal mechanistic and individual-level dynamics not captured by questionnaires alone.

Overall, this thesis supports three central conclusions. First, multisensory virtual nature immersion is feasible across controlled, occupational, and clinical environments, but effectiveness depends on the quality and coherence of multisensory design rather than on sensory addition alone. Second, adding synchronized olfactory and somatosensory cues to audiovisual nature immersion can increase perceived relaxation and meaningfully modulate physiological and neural markers related to arousal, engagement, and affect, although effects can reverse under sensory incongruence. Third, integrating objective sensing into immersive systems is not only feasible but necessary to strengthen evaluation, capture individual differences, and enable future adaptive interventions. The thesis concludes by identifying limitations (sample sizes, short exposure windows in realistic settings, incomplete scent personalization) and by outlining future directions, including improved personalization of scent and content, longer and more standardized protocols when possible, and the use of adaptive biofeedback and content generation strategies to maintain congruence and optimize outcomes in real-world deployment.

Keywords : virtual reality, multisensory, virtual nature, shinrin-yoku, olfactory, haptics, relaxation, stress reduction, post-traumatic stress disorder, nurses, electroencephalography, heart rate variability, wearable devices, quality of experience.

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LIST OF ABBREVIATIONS

ASR	Artifact subspace reconstruction
AV	Audio-visual
AVO	Audio-visual-olfactory
BVP	Blood volume pulse
CAPS	Clinician-Administered PTSD Scale
DBP	diastolic blood pressure
DES	Dissociative Experiences Scale
ECG	Electrocardiogram
EDA	Electrodermal activity
EEG	Electroencephalography
EOG	Electro-oculography
FAA	Frontal alpha asymmetry
FC	Fréquence cardiaque
FDR	Benjamini–Hochberg false discovery rate
FT	Fourier transform
Gen-AI	Generative artificial intelligence
HF	High-frequency spectrum
HMD	Head mounted display
HR	Heart rate
HRV	Heart rate variability
IBI	Inter-beat interval
ICA	Independent component analysis
LF	Low-frequency spectrum
nHF	Normalized HF
NIRS	Near-infrared spectroscopy
nLF	Normalized LF
NN50	Successive differences above 50ms
PANAS	Positive and Negative Affect Schedule
PCL	Post-traumatic Stress Disorder Checklist
PDEQ	Peritraumatic Dissociative Experiences Questionnaire

PHQ	Patient Health Questionnaire
pNN50	Proportion of successive differences above 50ms
POMS	Profile of Mood States
PP	pulse pressure difference
PPG	Photoplethysmography
PRS	Perceived Restorativeness Scale
PSD	Power spectral density
PTSD	Post-traumatic stress disorder
QoE	Quality-of-Experience/Qualité d'expérience
RMSSD	Root mean square of successive differences
ROS	Restoration Outcomes Scale
RRS	Relaxation Rating Scale
RV	Réalité virtuelle
SAM	Self-Assessment Manikin
SBP	systolic blood pressure
SC	Skin conductance
SD1	Standard deviation perpendicular to identity line
SD2	Standard deviation along identity line
SDNN	Standard deviation of NN intervals
SDSD	Standard deviation of successive differences
SSPT/TSPT	Syndrome/Trouble de stress post-traumatique
STAI	State-Trait Anxiety Inventory
UR	Ultra-reality
VA	Vibroacoustic therapy
VAS	Visual Analogue Scale
VFC	variabilité de la fréquence cardiaque
VO	Video-only
VR	Virtual reality
WHO	World Health Organization

SYNTHÈSE

0.1 Introduction

0.1.1 Stress and anxiety

Le stress et l'anxiété renvoient à des phénomènes liés mais distincts : le stress correspond à une réponse adaptative face à une demande, alors que l'anxiété relève davantage de l'anticipation et peut se manifester par une inquiétude persistante, parfois disproportionnée. Un stress aigu peut être mobilisateur, mais sa chronicisation est associée à des effets négatifs sur la santé (Selye, 1972). L'anxiété, lorsqu'elle devient durable et envahissante, peut s'inscrire dans un cadre psychopathologique (Barlow, 2004). Dans les deux cas, l'impact est multidimensionnel : atteintes physiques (p. ex. troubles cardiovasculaires, insomnie, douleurs), psychologiques (p. ex. dépression, attaques de panique), cognitives (p. ex. mémoire et attention), et professionnelles (p. ex. burnout).

À l'échelle mondiale, ces problématiques se sont amplifiées, notamment après la pandémie de COVID-19, en lien avec des facteurs tels que l'instabilité de l'emploi, l'isolement social et les pressions économiques (Pietrabissa et al., 2020; Smith et al., 2020a; Millroth et al., 2021). Des travaux rapportent une hausse marquée des troubles anxieux et dépressifs par rapport à la période pré-pandémique, soulignant l'urgence de développer des interventions efficaces, en particulier non pharmacologiques (Kotera et al., 2021b; Santomauro et al., 2021; Hawes et al., 2021).

Parmi ces approches, l'exposition à la nature apparaît comme une stratégie robuste pour réduire stress et anxiété, avec des bénéfices psychologiques et des changements physiologiques documentés (Kotera et al., 2021a; Giannico et al., 2021; Yao et al., 2021; Fu et al., 2022; Corazon et al., 2019). Le *shinrin-yoku* (bain de forêt) illustre cette logique d'immersion multisensorielle dans un environnement naturel (Hansen et al., 2017). Cependant, l'accès à la nature reste inégal : limitations de mobilité, hospitalisation, urbanisation croissante et obstacles physiques et psychosociaux réduisent la possibilité de recourir à cette ressource (Ritchie et al., 2018; Biernacka et al., 2018, 2019). Ce constat motive la recherche de solutions plus inclusives.

La réalité virtuelle (RV) immersive constitue une alternative prometteuse en permettant de simuler des environnements naturels et de générer un sentiment de présence, avec des applications déjà explorées en santé (Birckhead et al., 2019; Hao et al., 2022). Le *digital Shinrin-yoku* vise ainsi à reproduire l'exposition à la nature dans un cadre virtuel (Reese et al., 2022). Néanmoins, la plupart des dispositifs actuels restent centrés sur l'audio-visuel (vidéos 360°, images panoramiques, projections), et le niveau d'immersion dépend fortement de la qualité des contenus (p. ex. résolution, réalisme, audio 3D). Or, les bénéfices attribués au shinrin-yoku reposent sur une stimulation

multisensorielle complète, ce qui suggère que les expériences uniquement audiovisuelles pourraient ne pas maximiser les effets.

Dans cette perspective, l'intégration d'autres modalités sensorielles, en particulier l'olfaction, apparaît déterminante : elle influence la présence et la mémoire, et est associée à la relaxation, à l'attention et à des réponses émotionnelles, y compris en RV (Herz, 1998; Chu et al., 2002; Munyan III et al., 2016; Igarashi et al., 2014a,b; Amores et al., 2018; Dozio et al., 2021; Raudenbush et al., 2009; Vernet-Maury et al., 1999; Carulli et al., 2019; Flavián et al., 2021; Brengman et al., 2022; Khan et al., 2023).Plus largement, un système de RV véritablement multisensoriel (olfaction, stimuli thermiques, toucher) pourrait ouvrir la voie à des interventions à domicile, plus largement accessibles, malgré la mobilité réduite, les contraintes médicales, l'éloignement des environnements naturels ou des conditions météorologiques difficiles, ce qui s'inscrit dans les objectifs de cette recherche doctorale.

0.1.2 Effects of nature exposure : real and virtual

Les travaux sur l'exposition à la nature convergent vers l'idée d'un effet thérapeutique sur le stress et l'anxiété, avec des retombées positives sur la santé mentale et certains indicateurs de santé globale. Le *shinrin-yoku* constitue un cadre de référence important, car il formalise une immersion multisensorielle dans un environnement naturel, associée à des améliorations à la fois subjectives (stress/anxiété) et objectives (Hansen et al., 2017; Fu et al., 2022; Muro et al., 2022).

En parallèle, la littérature sur la nature virtuelle se développe et suggère des bénéfices subjectifs, ainsi que des modifications des marqueurs neurophysiologiques liés au stress et à l'anxiété (Anderson et al., 2017; Kotera et al., 2021a). Cette approche répond à des besoins concrets (patients hospitalisés, soins de longue durée) et pourrait soutenir des prises en charge à domicile dans un contexte de délais d'accès aux soins en santé mentale (American Psychological Association, 2023). Des résultats indiquent même que certains environnements de nature virtuelle peuvent produire des effets restaurateurs proches de ceux de l'exposition réelle (Browning et al., 2020).

Enfin, l'enjeu central devient l'optimisation de l'immersion : l'ajout d'olfaction améliore l'expérience et le sentiment de présence (Comşa et al., 2019; Narciso et al., 2020), tandis que l'haptique, notamment via la thérapie vibroacoustique, est associée à une diminution du stress et à une relaxation accrue (Delmastro et al., 2018). Dans le cadre de cette thèse doctorale, l'objectif est d'évaluer si une exposition à la nature virtuelle *multisensorielle* (olfaction, vibrations à basse fréquence, chaleur, simulation de vent) permet d'amplifier les bénéfices thérapeutiques des interventions de type immersion numérique en nature.

0.1.3 Limitations des applications de RV multisensorielle

Les travaux portant sur des environnements naturels immersifs en RV multisensorielle restent récents et hétérogènes, ce qui indique un domaine encore en structuration et laisse apparaître des marges nettes d'amélioration méthodologique. D'un point de vue de validité externe, plusieurs études reposent sur des échantillons démographiquement restreints (âge, genre, origine, statut socioéconomique), limitant la généralisation des résultats à des populations variées, et intègrent rarement des patients ou des groupes exposés à un stress quotidien élevé (p. ex. professions à forte charge), alors même que ces publics pourraient bénéficier en priorité d'interventions de réduction du stress (Zhang et al., 2023; Shin et al., 2022; Qi et al., 2022; Sona et al., 2019; Song et al., 2019).

Sur le plan expérimental, une limite récurrente concerne l'absence de comparaisons systématiques entre modalités sensorielles et stratégies d'intégration permettant d'évaluer leur effet propre et leurs synergies. Certaines études se concentrent sur un sous-ensemble de modalités (souvent visuel–olfactif), tandis que d'autres mobilisent plusieurs sens sans établir de plan factoriel clair ni de comparaison explicite entre conditions unimodales, bimodales et multimodales, ce qui fragmente l'interprétation des effets combinés (Zhang et al., 2023; Song et al., 2019; Takayama et al., 2022; Putrino et al., 2020; Amores et al., 2018). À cela s'ajoute un manque de mesures complémentaires : une partie de la littérature privilégie exclusivement des indicateurs physiologiques, d'autres s'appuient principalement sur des auto-questionnaires, et plusieurs travaux recourent à un seul indicateur, objectif ou subjectif. Cette approche unidimensionnelle peut masquer des interactions clés entre systèmes central et autonome et, plus largement, fournir une vision incomplète de l'impact psychologique, physiologique et expérientiel des interventions (Zhang et al., 2023; Shin et al., 2022; Abbott et al., 2022; Putrino et al., 2020; Sona et al., 2019; Serrano et al., 2016; Zhao et al., 2022; Hedblom et al., 2019; Amores et al., 2018; Qi et al., 2022).

Concernant l'olfaction, deux limites se dégagent. Premièrement, certains travaux adoptent un cadrage étroit du « paysage olfactif » (p. ex. focalisé sur des odeurs de jardins et d'espaces verts), ce qui réduit la portée des conclusions sur la diversité des expériences sensorielles possibles (Zhang et al., 2023). Deuxièmement, les stratégies de diffusion sont souvent peu variées (un seul dispositif ou une seule technique), rendant difficile l'extrapolation à d'autres méthodes (diffuseurs alternatifs, encens, arômes naturels) et limitant l'identification des conditions optimales de stimulation olfactive pour la récupération après stress (Zhao et al., 2022).

Le choix des environnements virtuels constitue également un frein : la majorité des études propose une gamme réduite de scènes (souvent un unique décor, typiquement forestier), sans tenir compte des préférences interindividuelles et des réponses potentiellement distinctes selon les contextes naturels (plage, cascade, champs, etc.). Seuls quelques travaux offrent plusieurs catégories d'environnements, ce qui laisse une question ouverte quant à l'adéquation scène–utilisateur et à la robustesse des effets selon le type de nature simulée (Qi et al., 2022; Putrino et al., 2020;

Hedblom et al., 2019; Serrano et al., 2016). À un niveau plus fin, la cohérence intermodale est parfois insuffisante : un décalage entre modalités (p. ex. odeur de lavande dans un scénario de plage) peut créer une dissonance sensorielle, perturber la cohérence perceptive et réduire l'immersion ainsi que l'effet recherché (relaxation, réduction du stress) (Amores et al., 2018; Serrano et al., 2016).

Enfin, la quantification objective des effets demeure limitée. Peu d'études exploitent des mesures instrumentées permettant un suivi quantitatif (quasi) en temps réel et l'identification de biomarqueurs utiles au pilotage et à l'évaluation longitudinale des interventions. Les objets connectés et capteurs portables sont pourtant pertinents pour des interventions de gestion du stress, tandis que l'acquisition de données neurales (p. ex. EEG) en RV, bien que plus complexe avec un casque HMD, pourrait apporter des informations uniques sur l'expérience immersive et ses impacts, notamment sur les réponses émotionnelles associées aux stimuli olfactifs (Smith et al., 2020b; Gomes et al., 2023; Song et al., 2019; Zhang et al., 2023; Qi et al., 2022; Amores et al., 2018; Abbasi et al., 2019; Wu et al., 2023).

Ces limites convergent vers une orientation claire : dépasser le paradigme principalement audiovisuel (et parfois olfactif) en explorant des configurations multisensorielles plus riches. Les résultats récents suggèrent qu'une stimulation plus large des sens peut accroître la présence, l'immersion et l'engagement, et potentiellement soutenir des mécanismes neurocognitifs favorables; de plus, des modalités telles que la vibroacoustique et la perception thermique montrent un intérêt pour le stress et la restauration. L'intégration du toucher/somesthésie, encore peu étudiée dans le contexte d'une nature virtuelle immersive, représente ainsi une opportunité méthodologique et applicative majeure pour renforcer le potentiel de relaxation de ces dispositifs (De Jesus Jr et al., 2022; Gougeh et al., 2022; Amini Gougeh et al., 2023; Boyd-Brewer, 2003; Lyu et al., 2022; Song et al., 2024).

0.1.4 Thesis objectives

Cette thèse vise à évaluer la faisabilité et l'intérêt d'une exposition à la nature médiée par une RV multisensorielle pour réduire le stress et l'anxiété, en favorisant un état de relaxation objectivable. L'enjeu n'est pas seulement de produire une expérience immersive, mais de démontrer des effets mesurables, reproductibles, et pertinents sur le plan clinique, en s'appuyant sur l'idée qu'une stimulation sensorielle plus riche et une conception multisensorielle congruente peuvent moduler la relaxation et la qualité de l'expérience.

Pour répondre aux limites fréquemment observées dans la littérature, la démarche adoptée est progressive et expérimentale : comparer de manière structurée les apports des modalités sensorielles, renforcer l'objectivation par des mesures physiologiques et neurales, diversifier les populations et les contextes (validité écologique) et traiter la question de la congruence/personalisation des stimuli. Les résultats attendus visent à soutenir le développement d'interventions non pharma-

cologiques innovantes et à faire avancer l'identification de biomarqueurs pertinents pour le stress et l'anxiété.

0.1.5 Thesis organization

La thèse est structurée en une suite de chapitres qui vont du cadre théorique aux validations expérimentales, puis aux implications cliniques et méthodologiques. L'organisation suit une logique d'accumulation de preuves : partir des bases conceptuelles et des choix de mesures, puis tester progressivement des configurations multisensorielles de plus en plus complètes, dans des contextes de plus en plus réalistes et exigeants, jusqu'à une évaluation longitudinale auprès d'une population clinique.

Le Chapitre 2 synthétise l'état de l'art et introduit les concepts et outils nécessaires (stress/anxiété, nature virtuelle, modalités sensorielles, mesures subjectives et objectives), en intégrant les résultats clés de la revue systématique (Lopes et al., 2024a). Le Chapitre 3 réalise une comparaison contrôlée de configurations sensorielles (du visuel seul à l'ajout successif de l'audio, de l'olfaction et de l'haptique) et quantifie leurs effets via questionnaires et signaux de capteurs. Le Chapitre 4 teste la RV multisensorielle dans un contexte de stress élevé (infirmières en unité psychiatrique), en analysant à la fois l'expérience et des mesures objectives, dont l'EEG et la PPG. Le Chapitre 5 étend l'évaluation à un suivi longitudinal chez des patients avec un trouble de stress post-traumatique (TSPT), en combinant questionnaires cliniques, tests neurocognitifs et monitoring neural, tout en comparant une solution portable à un dispositif multisensoriel en clinique. Enfin, le Chapitre 6 conclut en consolidant les contributions, en discutant les limites restantes et en proposant des perspectives, notamment vers la personnalisation (incluant une piste exploratoire avec l'IA générative) afin de réduire les décalages entre scènes virtuelles, indices sensoriels et attentes des utilisateurs.

0.2 Concepts de base et travaux connexes

0.2.1 Mental health

La santé mentale désigne le bien-être psychologique et la capacité à fonctionner au quotidien. Elle soutient l'adaptation au stress, l'apprentissage, le travail, ainsi que la qualité des relations sociales et la participation à la vie communautaire (World Health Organization, 2025; Organization, 2022). Dans cette thèse, nous considérons trois contextes où le stress est particulièrement élevé : le milieu académique, les environnements de travail exigeants et les situations cliniques après un événement traumatique. Dans ce dernier cas, l'exposition à un traumatisme peut entraîner des symptômes persistants altérant le fonctionnement, comme dans le TSPT (World Health Organization, 2024).

En milieux académiques et professionnels, le stress résulte souvent d'exigences répétées qui s'accumulent (échéances, évaluations, charge de travail, horaires, exposition à la souffrance, conflits) et d'un déséquilibre entre les pressions perçues et les ressources d'adaptation disponibles (Cho et al., 2020; Wells, 2024; Cranage et al., 2022; Chireh et al., 2025). Chez les étudiants, il interagit en outre avec des contraintes extra-universitaires (famille, finances), ce qui peut aggraver les symptômes dépressifs et nuire à la performance; des données longitudinales suggèrent également une augmentation du fardeau de santé mentale au cours du doctorat (Deng et al., 2022; Bergvall et al., 2025). Dans le contexte clinique, l'exposition à un traumatisme peut conduire à un TSPT caractérisé par des symptômes persistants (intrusions, évitement) altérant le fonctionnement (World Health Organization, 2024); bien que l'exposition thérapeutique soit efficace, l'accès aux soins spécialisés et l'adhésion au traitement demeurent des défis, et certaines situations sont difficiles à reproduire en sécurité (McLean et al., 2022). La RV offre alors des environnements contrôlés et répétables susceptibles de soutenir l'engagement (Gonçalves et al., 2012); dans cette thèse, ces constats motivent l'étude d'une immersion nature RV multisensorielle comme approche pratique de relaxation et de récupération du stress, testée auprès d'étudiants, de personnels soignants en contexte exigeant, et de patients TSPT.

0.2.2 Virtual reality

La RV est une simulation numérique tridimensionnelle qui permet à l'utilisateur d'interagir avec des environnements artificiels via des dispositifs dédiés, en sollicitant surtout la vision et l'audition. En générant un sentiment de présence et d'interaction crédible, elle peut reproduire une expérience proche du réel et soutenir des usages en santé et en bien-être (LaValle, 2023; Sherman et al., 2018; Dionisio et al., 2013).

Dans ce cadre, l'exposition à des environnements naturels en RV a popularisé le concept de *digital shinrin-yoku* (promenades de nature virtuelles), visant à recréer les effets restaurateurs des marches en nature sans accès direct à l'extérieur (Reese et al., 2022). La littérature rapporte des bénéfices sur la santé mentale, notamment une augmentation de la relaxation, une réduction du stress, une amélioration de l'humeur et une diminution de symptômes anxieux et dépressifs (Anderson et al., 2017; Kotera et al., 2021a). Cette approche est particulièrement pertinente pour les personnes hospitalisées, en soins de longue durée ou vivant en milieux urbains, et des résultats suggèrent que la nature virtuelle peut produire des effets comparables à ceux de l'exposition réelle, avec des impacts à la fois psychologiques et physiologiques (Browning et al., 2020; Jo et al., 2019; Lee et al., 2022; Syed Abdullah et al., 2021).

Enfin, des travaux récents indiquent que l'ajout de modalités sensorielles au-delà de l'audiovisuel peut renforcer l'immersion et potentiellement amplifier les effets thérapeutiques. L'olfaction, par exemple, accroît souvent la présence et peut préserver la qualité d'expérience même lorsque la fidélité visuelle diminue, tandis que certains ajouts comme le vent semblent moins déterminants

selon les protocoles (Comşa et al., 2019; Narciso et al., 2020). Dans l'esprit du shinrin-yoku, l'hypothèse est qu'une stimulation multisensorielle cohérente rend l'expérience plus authentique et plus efficace pour favoriser la relaxation et la réduction du stress; plusieurs études rapportent déjà des effets bénéfiques de l'intégration d'odeurs (Amores et al., 2018; Aiken et al., 2015; Pizzoli et al., 2021; Baus et al., 2010). De plus, la thérapie vibroacoustique (vibrations basse fréquence couplées à un retour haptique/somatique) est associée à la relaxation et à la diminution du stress, et son intégration à des paysages naturels en RV pourrait accroître l'effet global des interventions numériques basées sur la nature (Delmastro et al., 2018; Wigram et al., 2013; Naghdi et al., 2015).

0.2.3 Mesures subjectives

Les mesures subjectives du stress et de l'anxiété regroupent des questionnaires et échelles auto-rapportées visant à caractériser l'état psychologique et émotionnel des participants, en complément des indicateurs physiologiques. Dans cette thèse, nous utilisons principalement le «Profile of Mood States (POMS)» (McNair et al., 1964; Yokoyama et al., 1990) pour quantifier les fluctuations de l'humeur, le «Positive and Negative Affect Schedule (PANAS)» (Watson et al., 1988a,b; Sato, 2001) ainsi que la «Visual Analogue Scale (VAS)» (Gross et al., 1995; Wewers et al., 1990) pour évaluer des dimensions telles que stress perçu, anxiété, calme et bien-être, et le «State-Trait Anxiety Inventory (STAI)» (Bieling et al., 1998) afin de distinguer l'anxiété d'état (transitoire) de l'anxiété-trait (plus stable). Nous incluons également le «Self-Assessment Manikin (SAM)» et sa variante «Presence SAM» (Bradley et al., 1994) pour mesurer la valence/activation émotionnelle et le sentiment de présence en environnement immersif.

Pour documenter spécifiquement la relaxation et la restauration psychologique, nous mobilisons la «Relaxation Rating Scale (RRS)» (Labbé et al., 2007a) qui estime le niveau de relaxation ressenti, ainsi que des instruments centrés sur la qualité restauratrice des environnements : la «Perceived Restorativeness Scale (PRS)» (Hartig, 1996) et la «Restoration Outcomes Scale (ROS)» (Korpela et al., 2008, 2010). Enfin, pour les évaluations cliniques liées au SSPT, plusieurs tests normalisés sont utilisés : le «Peritraumatic Dissociative Experiences Questionnaire (PDEQ)» (Marmar et al., 2004), le «TSPT Checklist for DSM-5 (PCL-5)» (Weathers et al., 1993; Ashbaugh et al., 2016), le «Clinician-Administered TSPT Scale for DSM-5 (CAPS-5)» (Weathers et al., 2018; Rivest-Beauregard et al., 2022), le «Dissociative Experiences Scale (DES-II)» (Carlson et al., 1993; Larøi et al., 2013), ainsi que le «Patient Health Questionnaire (PHQ-9)» (Kroenke et al., 2001; Beard et al., 2016); la dimension cognitive est complétée par «CNS Vital Signs» (Gualtieri et al., 2006) pour une évaluation standardisée de la fonction cognitive.

0.2.4 Mesures objectives

Les mesures objectives du stress et de l'anxiété visent à quantifier des réponses physiologiques de manière fiable, idéalement sans recourir à des procédures invasives comme certains dosages hormonaux (p. ex. cortisol). Dans cette thèse, nous privilégions le suivi en temps réel via des capteurs portables, qui permet de collecter des biosignaux pendant les expériences et d'observer la dynamique de récupération au cours de l'immersion (Greene et al., 2016). Parmi ces biosignaux, les mesures cardio-vasculaires issues de l'ECG (fréquence cardiaque – FC, variabilité de la fréquence cardiaque – VFC) sont couramment associées au stress et à l'anxiété (Chalmers et al., 2014; Goessl et al., 2017; Dishman et al., 2000). Des informations similaires peuvent être obtenues avec la photopléthysmographie (PPG), qui fournit des marqueurs liés à la HRV via les variations de volume sanguin; certaines caractéristiques du signal BVP sont également reliées au stress/anxiété et à la relaxation (Parent et al., 2020; Kreibig et al., 2007).

Au-delà du système autonome, l'activité neurale mesurée par EEG constitue une source complémentaire pour caractériser les états de stress/anxiété, via des descripteurs spectraux et de connectivité (p. ex. puissance alpha préfrontale, puissance theta, gamma relatif, asymétrie alpha, cohérence) (Katmah et al., 2021; Parent et al., 2020). D'autres modalités objectives sont aussi rapportées dans la littérature, comme la NIRS (variations de débit sanguin cérébral liées aux émotions) Hoshi et al. (2011), l'activité électrodermale (EDA/GSR) (Posada-Quintero et al., 2016), et des indices respiratoires (fréquence, variabilité, soupirs) (Vlemincx et al., 2013). Dans cette thèse, nous mettons particulièrement l'accent sur des caractéristiques dérivées de l'EEG et de la PPG, car elles sont compatibles avec l'immersion en RV et permettent de combiner une lecture du système central et du système autonome pour analyser l'effet de la nature virtuelle multisensorielle sur la relaxation et la récupération du stress dans les trois populations étudiées.

0.2.5 Travaux connexes

Une revue systématique (janv. 2016–avr. 2023) a interrogé six grandes bases de données à l'aide d'une requête ciblée reliant stress/anxiété/relaxation, RV, nature virtuelle (dont le *shinrin-yoku*), olfaction, et mesures physiologiques/biosignaux ou multisensorielles. Même sans inclure le terme « psychologique » parmi les mots-clés, les études reposant uniquement sur des questionnaires ont été conservées afin de caractériser les systèmes utilisés et d'identifier leurs limites, ce qui a conduit à la sélection de 13 articles clés portant sur la nature virtuelle audio-visuo-olfactive pour favoriser la relaxation ou réduire le stress/anxiété (Lopes et al., 2024a).

Dans ces travaux, l'immersion visuelle est mise en œuvre au moyen de scènes de nature variées et de dispositifs d'affichage hétérogènes : beaucoup utilisent des photos/vidéos à 360-degrés via un casque de RV (*head-mounted display*, HMD), tandis que d'autres s'appuient sur des projecteurs, des téléviseurs, des écrans LED ou des installations hybrides de type « fenêtre »,

parfois complétées par de vraies plantes. Les conditions de contrôle sont très diverses (mur blanc, absence de stimulus, scènes urbaines, voire induction de stress), ce qui complique la comparaison entre les études et suggère un manque de standardisation des lignes de base expérimentales.

La plupart des études ajoutent des paysages sonores naturels (oiseaux, eau), parfois avec de la musique relaxante, ou alignent les conditions urbaines avec des bruits de trafic. L'olfaction présente la plus forte variabilité méthodologique : certaines études utilisent des matériaux naturels (fleurs, échantillons végétaux) ou des huiles essentielles spécifiques, d'autres des diffuseurs commerciaux ou des générateurs d'odeurs, et quelques-unes des méthodes d'émission sur mesure (tampons de coton fixés au HMD, olfactomètres, colliers diffuseurs portés). Les stratégies de choix des odeurs vont de l'adéquation culturelle/écologique à des arômes « relaxants » appuyés par la littérature, parfois calibrés par capteurs ou par tests auprès de participants pour améliorer la congruence; les indices tactiles/thermiques restent rares, limités à quelques études ajoutant du vent, un contrôle de température ou du gazon artificiel pour aller au-delà du triptyque audio-visuel-olfactif.

Dans la littérature examinée, les expériences de nature virtuelle sont principalement proposées selon deux modalités de présentation : des « salles » immersives basées sur écrans/projection et des casques de RV (*head-mounted displays*, HMD). Les dispositifs écran/projection créent généralement un « espace » immersif en projetant des forêts ou des paysages sur les murs (parfois le plafond) ou via des installations multi-écrans de type « fenêtre ». Ils sont souvent combinés à des ambiances sonores, un éclairage contrôlé et une diffusion d'odeurs, et peuvent aussi intégrer un flux d'air, du chauffage ou des plantes réelles. Ces systèmes servent à tester des scénarios appliqués de relaxation ou de récupération dans des contextes réalistes (p. ex. salles de récupération pour soignants, amélioration du bien-être au bureau), avec des comparaisons telles que neutre versus forêt, avec ou sans odeur, et parfois des phases d'induction de stress.

Les études utilisant des HMD mettent plutôt l'accent sur une immersion individuelle et contrôlée, avec des scènes de nature présentées sous forme de photos panoramiques ou de vidéos immersives, accompagnées de paysages sonores naturels et, lorsque pertinent, d'odeurs synchronisées. Plusieurs travaux adoptent des plans factoriels explicites afin d'isoler la contribution des modalités (visuel seul, olfactif seul, audio-visuel, audio-visuo-olfactif) et insèrent parfois un stresseur standardisé entre les conditions pour examiner la dynamique de récupération. Globalement, ces expériences considèrent l'olfaction comme un levier central pour renforcer l'immersion et améliorer des indicateurs tels que l'affect négatif ou l'anxiété d'état, tout en maintenant l'environnement visuel constant et en réduisant les facteurs externes de confusion.

Un sous-ensemble plus restreint compare explicitement la nature virtuelle à des environnements urbains virtuels en utilisant des indices multisensoriels cohérents (sons, visuels et odeurs adaptés à chaque scène). Ces études rapportent une réduction du stress plus marquée dans les conditions nature que dans les contrôles urbains, et suggèrent que l'agrément perçu et la récupération pourraient dépendre davantage des composantes olfactives et auditives que du visuel

seul, ce qui renforce l'intérêt d'une conception multisensorielle cohérente pour les interventions de nature numérique.

Dans l'ensemble des études examinées, les résultats psychologiques ont été principalement évalués au moyen de questionnaires subjectifs, mais avec une variabilité méthodologique importante. Douze études ont suivi les changements d'humeur ou de restauration à l'aide d'outils tels que la PRS et la ROS (restauration perçue), la PANAS, la VAS, la POMS et le STAI (parfois sous forme abrégée), ainsi que des échelles picturales comme la SAM et la Presence-SAM; certaines ont également utilisé des mesures à item unique, comme la *Relaxation Rating Scale*. Les protocoles différaient notamment quant au moment des mesures (pré-post versus post uniquement) et quant à l'introduction d'un stresseur avant l'exposition virtuelle (p. ex. variantes du TSST, tâches cognitives, chocs légers, ou séquences de tâches multiples), rendant l'ensemble des preuves hétérogène.

Concernant les effets, l'ajout d'indices olfactifs à la nature virtuelle a conduit à des résultats contrastés : plusieurs études rapportent une restauration accrue, une diminution de l'affect négatif ou une baisse de l'anxiété d'état dans les conditions audio-visuo-olfactives, tandis que d'autres n'observent pas d'avantage net par rapport à l'exposition audio-visuelle, malgré une perception d'engagement plus élevé en multisensoriel. Lorsque la nature est comparée à des contrôles urbains ou à l'absence de stimulus, les conditions de nature virtuelle sont généralement jugées plus agréables et plus restauratrices, et elles sont plus susceptibles de réduire le stress perçu, en particulier lorsque les indices multisensoriels sont congruents avec la scène. Globalement, ces résultats suggèrent un potentiel bénéfice psychologique de la nature virtuelle multisensorielle (Shin et al., 2022; Takayama et al., 2022; Zhao et al., 2022; Sona et al., 2019; Qi et al., 2022; Song et al., 2019; Abbott et al., 2022; Schebella et al., 2020; Serrano et al., 2016; Amores et al., 2018; Hedblom et al., 2019; Putrino et al., 2020).

Dans la littérature examinée, l'évaluation physiologique des effets est moins fréquente que l'évaluation subjective : huit études ont collecté au moins une modalité physiologique, et seulement trois ont explicitement associé ces mesures à un paradigme d'induction de stress afin de quantifier la récupération. Les biosignaux analysés sont variés et incluent des mesures cardiovasculaires (FC et VFC), la pression artérielle et le pouls, l'activité électrodermale (EDA), la température cutanée, l'amylase salivaire, la spectroscopie proche infrarouge (NIRS) via l'oxyhémoglobine préfrontale, ainsi que l'activité neurale mesurée par EEG. Globalement, cela met en évidence un paysage de mesures fragmenté, où les études s'appuient souvent sur un sous-ensemble limité de signaux et utilisent des protocoles très hétérogènes (Zhang et al., 2023; Qi et al., 2022; Takayama et al., 2022; Zhao et al., 2022; Schebella et al., 2020; Song et al., 2019; Hedblom et al., 2019; Amores et al., 2018).

Concernant les résultats, plusieurs marqueurs évoluent dans un sens compatible avec un état de relaxation lors d'expositions multisensorielles ou de nature virtuelle, mais les effets ne sont pas uniformes selon les modalités et les conditions. Les indicateurs cardiovasculaires montrent

parfois une diminution de la FC et une amélioration d'indices parasympathiques lors de bains de forêt numériques multisensoriels, alors que d'autres travaux rapportent une HRV plus élevée sans odeur qu'avec odeur, et certaines comparaisons ne mettent en évidence aucune différence de FC entre conditions. Les résultats NIRS suggèrent un apaisement plus marqué sous stimulation visuo-olfactive combinée, via une diminution de l'oxyhémoglobine préfrontale, tandis que les résultats EDA sont contrastés et, dans certains cas, davantage associés à l'agrément olfactif qu'aux visuels. Les études EEG mettent surtout l'accent sur des variations de l'activité alpha (et parfois bêta/thêta) : certaines conditions montrent une augmentation de la puissance alpha/bêta ou des scores de relaxation améliorés, tout en indiquant que certaines combinaisons audio-olfactives ou certains paysages végétaux peuvent induire des profils d'activation moins favorables.

0.3 Impact des modalités sensorielles sur les états de relaxation : un cas d'usage avec des étudiants universitaires

L'étude présente un cas d'usage contrôlé mené auprès d'étudiants universitaires afin de tester si l'ajout de modalités sensorielles au-delà de la réalité virtuelle audio-visuelle standard peut accroître la relaxation lors d'une exposition à une nature virtuelle. En s'appuyant sur des travaux antérieurs suggérant que les odeurs peuvent réduire le stress et que le toucher peut renforcer le sentiment de présence, l'étude propose Nat(UR)e, une expérience de marche en nature de type « shinrin-yoku numérique » multisensorielle, qui enrichit une scène naturelle par des stimulations olfactives, vibroacoustiques et somatosensorielles synchronisées avec le contenu virtuel.

Seize participants issus d'un milieu académique (six femmes ; âge moyen d'environ vingt-sept ans) ont pris part à l'expérience avec l'approbation du comité d'éthique, en appliquant des mesures de sécurité supplémentaires liées à la COVID-19 (distanciation, port du masque, désinfection du matériel, et désinfection UV-C du casque et des dispositifs portés). Chaque participant a réalisé quatre conditions contrebalancées : vidéo seule, audio-visuel, audio-visuel-olfactif, et une condition « ultra-réalité » combinant audio et visuel avec l'odorat et des indices corporels.

Le dispositif expérimental reposait sur une cabine multisensorielle SENSIKS 3.1a équipée de ventilateurs, d'éléments chauffants, de haut-parleurs haute définition, d'un caisson de basses pour le retour vibroacoustique, et d'un diffuseur capable d'émettre plusieurs arômes. L'ensemble des stimuli était synchronisé temporellement avec une vidéo forestière à trois cent soixante degrés présentée au moyen d'un casque Oculus Quest 3.1b. La synchronisation associait les moments liés au vent à un flux d'air, les passages où le soleil traverse les arbres à la chaleur, les pas et le craquement des feuilles à des vibrations du siège, et des odeurs d'arrière-plan discrètes (p. ex., terre, forêt, herbe, fraîcheur de brume) à la modalité olfactive.

Le protocole mettait l'accent sur une immersion en forêt courte, d'environ une minute, utilisée pour comparer une condition audio-visuelle conventionnelle à la variante « ultra-réalité » complète, en tant que test principal du concept Nat(UR)e. En condition audio-visuelle, les participants rece-

vaient une bande sonore ambisonique ainsi qu'une voix chuchotée guidant la réflexion, en parallèle des stimuli visuels. En condition ultra-réalité, le même contenu était enrichi par des odeurs, un flux d'air aligné sur les sons de vent et le mouvement des feuilles, des vibrations vibroacoustiques alignées sur la marche et le craquement des feuilles, et une chaleur dynamique alignée sur les variations d'intensité lumineuse perçues.

La relaxation était évaluée à la fin de chaque session au moyen d'une échelle de relaxation à item unique (Relaxation Rating Scale) modifiée, allant de un (« pas du tout relaxé ») à cinq (« très relaxé »). En parallèle, les réponses physiologiques étaient enregistrées en continu à l'aide de deux dispositifs portés : une ceinture thoracique BioHarness3 3.1c mesurant l'électrocardiographie et la respiration, et un bracelet Empatica E4 3.1d mesurant la température cutanée, l'activité électrodermale et le pouls volumétrique (blood volume pulse). Plusieurs caractéristiques ont été extraites pour chaque modalité (résumées dans le tableau des caractéristiques du chapitre) afin de soutenir des comparaisons objectives entre conditions.

0.3.1 Résultats et discussion

La relaxation auto-rapportée des participants augmente avec l'ajout de modalités : les conditions audio-visuo-olfactives (AVO) et ultra-réelles (UR) ont été jugées significativement plus relaxantes que la condition audio-visuelle (AV), ce qui soutient l'idée qu'un « bain de forêt numérique » multisensoriel peut renforcer la relaxation 3.3. Les évaluations de l'expérience utilisateur se sont également améliorées avec les indices multisensoriels (à l'exception de la cybercinétose) : l'ajout d'odeurs a produit les gains les plus marqués en réalisme, présence, immersion et émotion, tandis que l'ajout d'indices haptiques en plus des odeurs a entraîné des augmentations supplémentaires (pas toujours significatives) du réalisme, de la présence et de l'état de *flow* 3.4.

Les analyses physiologiques ont porté sur la comparaison AV versus UR à partir de données issues de dispositifs portables, certaines acquisitions ayant été exclues en raison de problèmes de qualité ou de batterie. La condition UR a montré des tendances compatibles avec une diminution du stress et une augmentation de la relaxation (par exemple, une puissance haute fréquence de l'ECG plus élevée 3.5, une composante basse fréquence de l'EDA plus faible 3.6, et un maximum de BVP plus faible 3.7), bien que la plupart des différences ne soient pas statistiquement significatives dans les tests appariés. En revanche, des caractéristiques spécifiques dérivées de l'EDA (la moyenne de la première différence négative et l'écart-type) présentent des différences significatives entre conditions et sont connues pour aider à discriminer des états stressants de non-stressants. L'analyse de corrélation relie également des caractéristiques de biosignaux à la relaxation subjective : une caractéristique ECG (écart-type de la première différence absolue) devient négativement corrélée à la relaxation dans les conditions multisensorielles, avec une significativité atteinte en UR, en cohérence avec des associations rapportées avec le stress et l'anxiété 3.8.

0.3.2 Conclusion

Cette étude montre que l'enrichissement de promenades de nature virtuelle par des indices olfactifs synchronisés et des stimulations haptiques/vibroacoustiques peut produire des gains significatifs de relaxation subjective par rapport à une RV conventionnelle, tout en générant des signatures physiologiques allant dans la direction attendue et, pour certaines caractéristiques, des changements significatifs ou des corrélations avec les scores de relaxation. Ces résultats suggèrent que la RV multisensorielle pourrait constituer une alternative pratique à l'exposition réelle à la nature pour des personnes ayant un accès limité ou des contraintes de mobilité, et que le suivi par dispositifs portables pourrait permettre un monitoring en temps réel et, à terme, une personnalisation des scènes multisensorielles basée sur le biofeedback.

0.4 Expériences de RV multisensorielles en environnements réalistes : cas d'usage avec des infirmières en unité d'hospitalisation en santé mentale

Ce chapitre présente une étude réaliste menée à l'hôpital auprès d'infirmières travaillant en unité d'hospitalisation en santé mentale, afin d'examiner si l'ajout d'une couche olfactive à une exposition à la nature en RV modifie la relaxation par rapport à une RV audiovisuelle standard. Le protocole compare deux conditions lors d'une immersion dans une scène de nature à trois cent soixante degrés : audio-visuel seul (AV) et audio-visuo-olfactif (AVO). L'étude est motivée par les niveaux de stress durablement élevés dans la profession infirmière, en particulier dans des contextes exigeants d'hospitalisation en santé mentale, et vise à tester si des indices multisensoriels améliorent non seulement la restauration perçue, mais aussi des marqueurs physiologiques mesurables.

L'étude combine des évaluations subjectives et objectives. Après chaque courte exposition en RV, les infirmières ont évalué leur niveau de restauration/relaxation ainsi que plusieurs dimensions de qualité d'expérience (p. ex. engagement, immersion, distorsion temporelle, cinétose) à l'aide d'une échelle de Likert à onze points, répétée à différents moments du protocole. En parallèle, nous avons calculé des biomarqueurs dérivés de l'EEG (puissances par sous-bandes et indices de plus haut niveau tels que valence, activation, attention, engagement et charge mentale) ainsi que des métriques de VFC dérivées du PPG (mesures temporelles, fréquentielles et non linéaires). L'objectif est de déterminer si la condition AVO modifie ces marqueurs par rapport à AV et si les changements physiologiques suivent les évaluations rapportées par les participantes.

Vingt-sept infirmières ont participé à des sessions individuelles réalisées pendant les quarts de travail (environ trente minutes au total par participante), avec les approbations éthiques requises et des contraintes pratiques ayant façonné le protocole. Un dépistage a été effectué afin d'éviter les contre-indications à la RV et à l'exposition aux odeurs : les participantes porteuses d'un pacemaker, ayant des antécédents d'épilepsie/crises, ou ayant perdu l'odorat (p. ex. post-COVID) ont

été exclues, et des ajustements ont été réalisés pour les lunettes de prescription afin d'assurer une visualisation nette. Étant donné la variabilité de la qualité des signaux en contexte hospitalier, les analyses sont rapportées sur des échantillons spécifiques à chaque modalité : les résultats EEG reposent sur 22 participantes après exclusions et arrêts précoces, tandis que les résultats HRV dérivés du PPG reposent sur 14 participantes en raison de pertes fréquentes du PPG, souvent liées au contact casque–front. Ainsi, les résultats EEG et HRV doivent être interprétés dans leurs échantillons respectifs, sans supposer qu'ils reflètent exactement les mêmes participantes.

L'expérience s'est déroulée dans une salle de pause du personnel infirmier, en présence uniquement de la participante et de deux évaluateurs. Chaque infirmière choisissait l'une des trois vidéos de nature (plage, lac ou forêt) et la vivait deux fois : une fois en AV et une fois en AVO, avec un ordre randomisé pour réduire les biais. Chaque exposition durait deux minutes et trente secondes, pour un total de cinq minutes d'interaction en RV. Afin de limiter la persistance des odeurs entre conditions, la pièce était ventilée en ouvrant une fenêtre avant et entre les conditions, puis refermée pendant l'exposition. Un questionnaire final, administré hors casque, a permis de recueillir les impressions globales et des suggestions pratiques pour affiner le protocole en vue d'applications futures auprès de populations cliniques 4.1.

Sur le plan matériel, l'étude a utilisé un casque Meta Oculus Quest 2 instrumenté en interne, intégrant des capteurs EEG/EOG/PPG. L'acquisition EEG s'appuyait sur les bioamplificateurs OpenBCI Cyton et Daisy pour collecter des signaux ExG, avec onze canaux EEG positionnés afin de cibler des régions fréquemment associées au stress, à l'anxiété et à la relaxation dans la littérature. La stimulation olfactive était fournie par un diffuseur OVR ION2 fixé au casque 4.4, dispersant des arômes au plus près du nez à partir d'une cartouche « Nature » prédéfinie. Pour des raisons de sécurité et d'acceptabilité en milieu hospitalier, l'intensité était maintenue faible et des ensembles d'odeurs spécifiques à chaque scène étaient utilisés (p. ex. *beach* et *ocean breeze* pour la scène plage; fleurs, terre, forêt et herbe pour la scène lac; avec ajout de bois pour la scène cascade/forêt) .

Pour le traitement des signaux, l'extraction des métriques HRV commence par une réduction des artéfacts de mouvement sur le PPG à l'aide d'une approche basée sur la décomposition en valeurs singulières, puis calcule plusieurs caractéristiques HRV sur l'ensemble de l'exposition (deux minutes et trente secondes) ainsi que sur des fenêtres précoces versus tardives afin de capturer la dynamique intra-session. Le traitement EEG utilise volontairement une chaîne minimale pour éviter de retirer une information potentiellement discriminante : filtre coupe-bande pour éliminer le bruit secteur, filtrage passe-haut pour réduire les dérives, puis segmentation en époques de deux secondes. Les capteurs frontaux intégrés à la mousse du casque étant particulièrement bruités, les canaux les plus contaminés sont écartés, laissant huit canaux pour l'analyse. Les caractéristiques incluent les puissances normalisées dans les bandes delta, thêta, alpha, bêta et gamma, ainsi que des indices dérivés tels que l'engagement, la valence, l'activation, l'attention, la charge mentale et l'asymétrie frontale alpha.

Enfin, une régression linéaire a été utilisée pour tester si les neuromarqueurs et les caractéristiques HRV présentent des tendances positives, négatives ou nulles au sein des sessions AV et AVO, et pour comparer les trajectoires entre conditions. La significativité de ces tendances est évaluée statistiquement (via un test de Wald), avec pour objectif plus large d'identifier des marqueurs robustes pouvant soutenir un suivi automatique de la relaxation, en temps réel et pendant l'immersion, et d'orienter des protocoles futurs plus fiables et plus facilement déployables en contexte clinique réel.

0.4.1 Résultats et discussion

Sur le plan subjectif, la relaxation s'est significativement améliorée entre le niveau de base et l'après-exposition dans les deux conditions AV et AVO ($p < 0.01$), mais la comparaison directe AV versus AVO n'était pas significative lorsque l'on regroupe l'ensemble des scénarios. En analysant séparément chaque scénario, les effets dépendaient de la congruence sensorielle : le scénario *lac* montrait une augmentation significative du niveau de base vers la condition AV ($p < 0.01$), et le scénario *cascade* une augmentation significative du niveau de base vers la condition AVO ($p < 0.001$). Le scénario *plage* faisait exception, sans changement significatif par rapport au niveau de base et avec une tendance à une relaxation plus faible en AVO qu'en AV 4.7. Les évaluations de qualité d'expérience (engagement, immersion, oubli des préoccupations, distorsion temporelle, cinétose) ne différaient pas significativement entre AV et AVO au global ; entre scénarios, seule la mesure « engagement des sens » en AV variait significativement. Les commentaires des participants suggéraient qu'un décalage entre des odeurs attendues de « plage tropicale » et une scène de « plage arctique » pourrait expliquer l'effet observé pour la plage, tandis que les odeurs associées au lac et à la cascade étaient jugées plus cohérentes et plus « réalistes » Table 4.4.

Sur le plan objectif, les analyses EEG ont combiné des pentes de régression linéaire au cours du temps et des tests non paramétriques pour comparer AV et AVO et pour évaluer les effets des scénarios. La plupart des canaux montraient des diminutions significatives pendant l'exposition dans plusieurs bandes de fréquence, avec des profils variables selon la bande et la région ; des diminutions plus marquées apparaissaient souvent en AVO. Des différences entre conditions (AV vs AVO) ont été détectées sur plusieurs canaux pour les bandes delta, thêta, alpha, bêta et gamma, et des différences dépendantes du scénario étaient également fréquentes au sein de chaque condition Table 4.5. Les indices EEG de plus haut niveau mettaient en évidence des contrastes AV–AVO nets : l'attention différait fortement entre conditions ($p \leq 0.001$), l'asymétrie alpha frontale passait d'une moyenne négative en AV à une moyenne positive en AVO ($p < 0.001$), et l'engagement augmentait d'AV vers AVO ($p \leq 0.003$), tandis que la valence, l'activation et la charge mentale ne présentaient pas de différences significatives. Les cartes topographiques 4.8 suggéraient qu'en AVO, l'asymétrie alpha pouvait s'inverser entre les participants ayant rapporté (ou non) un gain de relaxation, ce qui est compatible avec des interprétations de type approche-évitement et renforce l'importance de la congruence et de la personnalisation.

Les analyses de VFC se sont concentrées sur l'évolution intra-session (première minute versus dernière minute) plutôt que sur des différences précoces AV–AVO. Les métriques temporelles et non linéaires diminuaient globalement au cours du temps dans les deux conditions (avec une augmentation de la FC), indiquant une réduction de la variabilité à court terme et un retrait parasympathique à mesure que la session progressait ; ces effets étaient souvent plus marqués en AVO et s'accompagnaient de tailles d'effet notables. Les mesures fréquentielles étaient plus variables : AV tendait vers de légères augmentations des puissances LF et HF, alors qu'AVO tendait vers des diminutions, avec un ratio LF/HF légèrement plus élevé en AVO Table 4.6. Les analyses de corrélation reliaient des caractéristiques HRV aux évaluations de relaxation et de qualité d'expérience, avec des associations plus fortes et plus nombreuses en AVO (en particulier en fin de session), suggérant que la présence et la relaxation peuvent covarier avec la régulation autonome lors d'une exposition multisensorielle (Table 4.7 et 4.8).

0.4.2 Conclusions

Dans un contexte clinique réel, les expositions à la nature virtuelle en AV et en AVO ont amélioré la relaxation des infirmiers et ont produit des changements mesurables des marqueurs cérébraux et autonomes, mais l'avantage de l'olfaction dépendait du scénario. Lorsque l'on agrège l'ensemble des scènes, AV conduisait globalement à une relaxation plus élevée ; en revanche, pour le lac et la cascade, AVO tendait à produire de meilleurs gains de relaxation et de meilleures évaluations d'expérience (par exemple immersion et engagement), tandis que la plage montrait la tendance opposée. Les retours des participants et les mesures objectives convergent vers la congruence sensorielle comme facteur clé : des odeurs non concordantes peuvent dégrader la relaxation et orienter l'expérience vers l'évitement plutôt que vers l'approche.

Sur le plan physiologique, le casque instrumenté a mis en évidence des différences AV–AVO que les questionnaires seuls ne permettraient pas de détecter, notamment des changements dans la dynamique des sous-bandes EEG et des variations significatives d'indices liés à l'attention, à l'engagement et à l'asymétrie alpha frontale. L'HRV a montré des diminutions intra-session cohérentes de la variabilité associée au parasympathique et une augmentation de la FC, ce qui peut refléter le fait que de courtes expositions immersives peuvent être à la fois relaxantes et fortement engageantes ; AVO semblait intensifier cette trajectoire d'engagement et d'activation au fil du temps. Malgré des limites (taille d'échantillon, durée brève, personnalisation olfactive incomplète, et pertes de données dépendantes de la modalité), ces résultats soutiennent l'intérêt de la mesure en temps réel pour suivre relaxation, engagement et incongruence olfactive potentielle, et pour permettre à terme des systèmes multisensoriels adaptatifs et de biofeedback, optimisés selon l'utilisateur et le contexte.

0.5 Immersion multisensorielle en nature : une nouvelle intervention pour les patients atteints de SSPT

Ce chapitre présente l'immersion multisensorielle en nature virtuelle comme une approche pratique et complémentaire aux prises en charge conventionnelles du trouble de stress post-traumatique (SSPT). Si les traitements centrés sur le traumatisme, tels que les thérapies d'exposition, peuvent être efficaces, ils restent souvent difficiles d'accès et éprouvants sur le plan émotionnel, ce qui contribue à des taux d'abandon élevés. La RV a été proposée pour rendre l'exposition plus contrôlable et répétable, et la RV multisensorielle (p. ex., ajout d'odeurs ou de vibrations) pourrait encore renforcer les effets. Cependant, elle peut aussi nécessiter une forte personnalisation et s'avérer trop intense pour certains patients, d'où l'intérêt d'évaluer une immersion en nature multisensorielle potentiellement mieux tolérée pour soutenir la gestion du stress et la relaxation.

L'étude évalue deux systèmes de délivrance multisensorielle chez des patients SSPT : (1) un dispositif PORTABLE apportant une stimulation olfactive via un module fixé au casque de RV, et (2) un système POD en clinique, qui enrichit un contenu nature audio-visuel présenté au casque par des odeurs synchronisées et des indices haptiques (vent et vibration). L'objectif n'est pas seulement de comparer ces deux modalités, mais aussi de caractériser l'évolution de l'activité neurale au cours de l'intervention et d'examiner ses liens avec l'expérience subjective, les symptômes cliniques et la cognition.

Les données ont été recueillies dans une clinique de psychothérapie à Sept-Îles (Québec). Dix adultes présentant un SSPT ont participé aux deux expériences, mais les analyses présentées ici portent sur huit participants en raison de données EEG manquantes dans deux cas ; les résultats doivent donc être considérés comme préliminaires. Le protocole s'étend sur plusieurs semaines et comprend deux pré-tests, une intervention de trois semaines, un post-test et un suivi à trois mois ; une longue période de pause séparait également les deux expériences. Chaque intervention comportait douze séances sur trois semaines (quatre séances par semaine), d'une durée de quinze minutes chacune, avec une présentation randomisée de scènes de nature apaisantes et visuellement stables (p. ex., plages, lacs/forêts, parcs), associées soit à une augmentation olfactive seule (PORTABLE), soit à une combinaison odeurs, flux d'air et vibroacoustique (POD) 5.1.

L'évaluation des effets combine des auto-questionnaires cliniques et des mesures au niveau des séances, des tests cognitifs et l'EEG. Les participants ont rempli des questionnaires standardisés de sévérité du SSPT et de détresse psychologique (p. ex., PCL-5, CAPS-5, PDEQ, DES-II, PHQ-9), participé à des entretiens semi-structurés et réalisé une évaluation neurocognitive via *CNS Vital Signs*. Après chaque séance de RV, ils ont également noté des dimensions de l'expérience telles que la présence et la cybercinétose ; dans l'étude POD, ils ont en plus fourni des évaluations de stress avant/après séance, ainsi que des notes de relaxation et d'immersion après séance.

Le traitement EEG s'appuie sur EEGLAB, avec filtrage, atténuation des artefacts (ASR), analyse en composantes indépendantes (ICA) avec ICLabel, puis extraction de caractéristiques sur des époques de deux secondes. Les variables incluent des puissances spectrales normalisées pour les bandes delta, thêta, alpha, bêta (avec sous-bandes bêta un et bêta deux) et gamma, ainsi que des indices dérivés liés au traitement affectif et cognitif (engagement, valence, activation, attention et asymétrie alpha frontale). L'analyse statistique couvre des tests à mesures répétées pour les comparaisons pré/post, le suivi intra-sujet des relations EEG–expérience au fil des séances (corrélation à mesures répétées et modèles mixtes), ainsi que la modélisation longitudinale des tendances neurales (pentes individuelles et comparaisons mixtes entre début et fin d'intervention). Le cadre examine aussi si les changements EEG sont associés aux améliorations cliniques et cognitives, et si les évolutions de l'expérience subjective coïncident avec celles des marqueurs neuraux au cours de l'intervention.

0.5.1 Résultats et discussion

0.5.1.1 Évaluations subjectives du SSPT et évaluations cognitives

Les questionnaires cliniques et les tests cognitifs ont été suivis sur l'ensemble du protocole et rapportés séparément pour les deux dispositifs (PORTABLE et POD). Dans l'expérience PORTABLE, les symptômes dissociatifs (DES-II) ont diminué au fil du temps, avec un effet global significatif en mesures répétées et de grandes tailles d'effet intra-individuelles, bien que certains contrastes post-hoc aient été atténués après correction du taux de fausses découvertes. Dans l'expérience POD, les symptômes dépressifs (PHQ-9) ont diminué au suivi par rapport au post-test (avec une tendance similaire par rapport au pré-test tardif), et le DES-II a également montré une tendance à la diminution ; globalement, les résultats POD suggèrent des améliorations intra-individuelles de magnitude moyenne à grande, mais avec un soutien statistique plus faible que PORTABLE.

Sur le plan cognitif, PORTABLE a montré les gains les plus clairs et les plus cohérents, en particulier pour la vitesse et l'efficacité de traitement, qui ont augmenté significativement entre le premier pré-test et le post-test, avec également un effet global significatif en mesures répétées. Toutefois, l'amélioration observée entre le premier et le deuxième pré-test suggère qu'une partie du gain cognitif pourrait refléter la psychothérapie en cours plutôt que l'exposition à la RV seule. À l'inverse, POD n'a pas montré de changement cognitif large et systématique, mais a présenté des indices d'amélioration avec de grandes tailles d'effet dans certains domaines, tels que la mémoire de travail et l'efficacité, ainsi que l'attention soutenue et la vigilance, même si ces comparaisons ne restent pas significatives après correction (Figures 5.2-5.9).

0.5.1.2 Réponses subjectives au fil des sessions

Sur les 12 sessions, les évaluations de l'expérience rapportées après chaque session sont restées globalement stables dans les deux interventions. Dans PORTABLE (Figure 5.10), la cybersickness est demeurée faible, sans signe d'accumulation, tandis que la présence est restée élevée, indiquant qu'une exposition répétée n'a pas réduit l'immersion perçue. Dans POD (Figure 5.11), l'immersion et la relaxation ont montré une variabilité modeste d'une session à l'autre, mais sont restées globalement stables, et les niveaux de stress rapportés après session étaient systématiquement inférieurs aux niveaux rapportés avant session, même si aucune tendance longitudinale n'a résisté à la correction. Lorsque les participants ont évalué l'appréciation des différentes modalités sensorielles dans POD, les modalités audio, visuelle et haptique ont été les plus appréciées, tandis que l'olfaction a reçu la plus faible appréciation en moyenne.

0.5.1.3 Expérience en réalité virtuelle et activité neuronale

Les associations intra-sujets entre les évaluations de l'expérience et les caractéristiques EEG ont été examinées à l'aide de corrélations en mesures répétées et de modèles à effets mixtes. Dans PORTABLE, une cybersickness plus élevée covariait avec une puissance delta frontale plus élevée et une puissance bêta un plus faible aux régions frontales et occipitales, et s'accompagnait également d'un score d'excitation physiologique plus faible ; à l'inverse, une présence plus élevée montrait une tendance opposée, avec des puissances thêta et alpha plus élevées et une diminution de la bêta un en région centrale. Dans POD, une relaxation plus élevée au fil des sessions était associée à une puissance alpha plus élevée sur de larges régions, des diminutions de stress plus importantes suivaient une thêta plus élevée au frontal droit, et une immersion plus élevée était associée à une baisse de l'engagement au sein d'un même participant au cours du temps.

Les modèles à effets mixtes ont globalement renforcé ces tendances : dans PORTABLE, la présence était positivement liée à de nombreuses caractéristiques de basse fréquence (thêta et alpha), tandis que la cybersickness présentait des relations négatives avec plusieurs caractéristiques en bandes bêta et alpha. Dans POD, une puissance bêta et bêta un plus élevée au frontal prédisait une immersion plus faible (et un comportement similaire était observé pour le biomarqueur d'engagement), alors qu'une puissance alpha frontale plus élevée prédisait une relaxation plus élevée ; les variations de stress étaient également liées à des caractéristiques en bande gamma et à l'excitation physiologique. Des analyses exploratoires ont ensuite relié l'amélioration des symptômes à des changements EEG longitudinaux : dans PORTABLE, l'amélioration de la dépression (PHQ-9) était fortement associée à des pentes croissantes de thêta et d'alpha aux régions frontales et centrales, tandis que l'amélioration des symptômes de SSPT (PCL-5) s'alignait avec des pentes décroissantes de bêta et de bêta un en région centrale ainsi qu'avec une diminution de l'indice d'attention. Dans POD, les corrélations entre amélioration des symptômes et

pentes de puissance occipitale et pariétale montraient des motifs cohérents, mais n'ont pas résisté à la correction.

0.5.1.4 Changements EEG entre la première et la dernière session et corrélations sur scores de changement

Les modèles longitudinaux à effets mixtes comparant la première et la dernière session indiquent une adaptation neurophysiologique nette sur l'ensemble du protocole. Dans PORTABLE, la puissance delta diminuait de façon étendue tandis que l'activité de plus haute fréquence augmentait, en particulier dans des sous-bandes bêta aux régions frontales droites, pariétales et occipitales, avec des effets restant significatifs après correction. Dans POD, la puissance gamma augmentait fortement et de manière robuste sur l'ensemble des régions (tous coefficients positifs et résistant à la correction), la puissance thêta diminuait principalement sur les sites occipitaux et pariétaux, et la bêta deux augmentait plus modestement, suggérant une signature d'adaptation distincte pour la condition pod multisensorielle. Les corrélations entre les changements subjectifs (première moins dernière session) et l'EEG étaient exploratoires : dans PORTABLE elles ne résistaient pas à la correction, tandis que dans POD plusieurs associations fortes reliaient une immersion accrue à une baisse de la bêta deux et de la gamma et à une hausse du delta pariétal et occipital, compatible avec une immersion plus calme et moins coûteuse en effort dans un contexte relaxant.

0.5.2 Conclusions

Sur deux protocoles d'immersion multisensorielle en nature virtuelle chez des patients atteints de SSPT, les mesures subjectives d'expérience (présence, immersion, relaxation, cybersickness, et niveaux de stress lorsqu'ils étaient disponibles) sont restées largement stables au fil des expositions répétées, suggérant une bonne tolérabilité, sans indice d'inconfort cumulatif ni de dégradation de la qualité immersive perçue. Les résultats cliniques et cognitifs sont encourageants mais dépendent du dispositif : PORTABLE montre des diminutions plus nettes de la dissociation et des gains plus marqués en vitesse de traitement, tandis que POD montre des tendances d'amélioration de magnitude moyenne à grande pour les symptômes dépressifs et certains domaines cognitifs, mais avec une robustesse statistique plus faible après correction.

À l'inverse de la stabilité des auto-évaluations d'une session à l'autre, l'EEG met en évidence des changements longitudinaux cohérents, suggérant une adaptation plutôt qu'une fatigue : l'activité de basse fréquence tend à diminuer, tandis que l'activité de plus haute fréquence augmente, avec dans PORTABLE une augmentation marquée en bande bêta concomitante à une diminution du delta, et dans POD une augmentation particulièrement robuste de la gamma. Malgré un échantillon limité et les contraintes liées aux comparaisons multiples, la convergence des résul-

tats EEG motive des études à plus grande échelle afin de confirmer si ces trajectoires neuronales peuvent servir de marqueurs fiables d'adaptation à la RV multisensorielle et aider à comprendre comment des immersions répétées et apaisantes interagissent avec l'évolution des symptômes et l'immersion perçue chez des populations atteintes de SSPT.

0.6 Conclusion et travaux futurs

0.6.1 Conclusion

Les troubles liés au stress et aux traumatismes deviennent plus fréquents et ont des impacts croissants sur les individus, les milieux de travail et les systèmes de santé. Du stress quotidien à l'épuisement professionnel, jusqu'au trouble de stress post-traumatique (TSPT) en contexte clinique, il existe un besoin d'interventions qui soient (i) accessibles, (ii) tolérables lors d'expositions répétées, et (iii) mesurables à l'aide d'indicateurs objectifs pouvant compléter les autoquestionnaires. L'exposition à la nature (par ex., le *shinrin-yoku*) constitue une approche non pharmacologique, mais l'accès à des environnements naturels restaurateurs demeure limité pour de nombreuses personnes en raison de contraintes géographiques, temporelles, de mobilité et de contexte clinique.

Dans cette thèse, nous avons exploré l'immersion multisensorielle en nature virtuelle comme un outil accessible et potentiellement thérapeutique pour favoriser la relaxation et améliorer la régulation du stress. Une hypothèse centrale est que la nature virtuelle audio-visuelle (AV) ne reproduit pas entièrement la qualité restauratrice de la nature réelle, et que l'augmentation de l'immersion par la stimulation de sens additionnels (olfaction et indices somatosensoriels tels que le vent, la chaleur et la vibroacoustique) pourrait améliorer à la fois l'expérience utilisateur et l'engagement physiologique. En parallèle, à mesure que les interventions multisensorielles se rapprochent des contextes réels et cliniques, les cliniciens et les chercheurs ont besoin de moyens pratiques pour quantifier les effets et suivre l'évolution; cette thèse met donc également l'accent sur un suivi objectif au moyen de mesures physiologiques et neurophysiologiques, incluant des biosignaux intégrés aux systèmes de RV et des capteurs portables.

Une contribution majeure de ce travail doctoral est son évaluation progressive, étape par étape, auprès de trois populations distinctes. Premièrement, nous avons testé les hypothèses principales dans une population majoritairement académique, dans des conditions pilotes contrôlées. Deuxièmement, nous avons appliqué l'approche à un environnement de travail exigeant en étudiant des infirmières dans un contexte hospitalier d'unité d'hospitalisation, où les contraintes de temps, la fatigue et la validité écologique sont centrales. Troisièmement, nous avons étendu l'approche à une population clinique, en menant des études d'expositions répétées à la nature virtuelle multisensorielle auprès de participants diagnostiqués avec un TSPT.

Le Chapitre 1 a introduit la motivation et les objectifs de la thèse. Le Chapitre 2 a ensuite présenté le contexte et les travaux connexes. Le Chapitre 3 a présenté la première expérimentation, dans laquelle nous avons testé l'expérience de nature virtuelle multisensorielle en synchronisant des stimuli additionnels, tels que l'olfaction, le vent, la chaleur et la vibroacoustique, avec une vidéo de nature à trois cent soixante degrés. Cette étude a fourni des premières preuves indiquant que l'augmentation de la stimulation sensorielle peut améliorer de manière significative la relaxation perçue par rapport à une condition AV conventionnelle, et que des réponses physiologiques cohérentes avec un état de relaxation peuvent être observées.

Le Chapitre 4 a examiné si ces effets apparaissent également dans un contexte professionnel exigeant, en se concentrant sur des infirmières. Ce travail a étudié comment la stimulation multisensorielle interagit avec le contexte et le contenu (par ex., des scènes naturelles spécifiques) et a mis en évidence que l'augmentation olfactive n'est pas uniformément bénéfique : la congruence sensorielle et les attentes propres à l'utilisateur peuvent influencer à la fois l'expérience subjective et les patrons neuronaux. Des analyses complémentaires basées sur la VFC ont fourni une perspective objective sur les dynamiques de régulation à court terme et ont renforcé l'importance de mesures robustes lors du déploiement d'interventions en RV sur le terrain.

Le Chapitre 5 a étendu l'exposition à la nature virtuelle multisensorielle à des populations atteintes de TSPT au moyen de protocoles multi-sessions et de plusieurs formats de délivrance (PORTABLE et POD multisensoriel). Ce chapitre a évalué si les participants pouvaient utiliser l'intervention de manière répétée et confortable, et si celle-ci était associée à des changements des symptômes cliniques et des mesures cognitives. Il a également examiné les changements neurophysiologiques associés à l'exposition répétée. Au travers des études TSPT, un thème central est que la nature virtuelle multisensorielle peut être utilisée de façon répétée dans un flux de travail clinique, tout en produisant des changements mesurables des symptômes et/ou des marqueurs objectifs.

Globalement, les résultats présentés dans cette thèse soutiennent trois conclusions générales. Premièrement, l'immersion multisensorielle en nature virtuelle est faisable dans des environnements contrôlés, professionnels et cliniques, mais son efficacité dépend de la qualité du contenu et de la congruence sensorielle plutôt que de l'ajout de modalités sensorielles en soi. Deuxièmement, l'ajout d'odeurs synchronisées et de sensations corporelles (telles que le vent ou la vibration) à une expérience de nature virtuelle audio-visuelle peut augmenter la relaxation auto-rapportée et modifier des signaux physiologiques et cérébraux liés à l'activation, à l'engagement et aux émotions. Troisièmement, l'intégration de mesures objectives dans les systèmes immersifs est non seulement possible, mais nécessaire : elle permet une évaluation plus riche, met en évidence les différences interindividuelles et ouvre la voie à des interventions adaptatives ajustables à l'utilisateur et au contexte.

0.6.2 Limites et travaux futurs

Malgré des résultats prometteurs, les études de cette thèse ne sont pas exemptes de limites. La première étude a été affectée par la pandémie de COVID-19. La collecte de données a eu lieu en 2021, durant des périodes de confinement, à un moment où le recrutement et l'accès expérimental étaient fortement restreints. La deuxième étude a été réalisée dans un contexte hospitalier auprès d'infirmières. En raison d'horaires très exigeants et de la courte période pendant laquelle nous avons eu accès aux locaux, nous n'avons pu recruter qu'un nombre limité de participantes et participants. Ces mêmes contraintes ont également limité la durée du protocole : nous n'avons testé que deux conditions (AV et AVO), avec des expositions de deux minutes et demie chacune. Ces sessions courtes réduisent aussi la sensibilité des mesures subjectives et objectives, en particulier pour les métriques physiologiques qui bénéficient de fenêtres d'observation plus longues. De plus, la nécessité de maintenir un protocole bref a conduit à l'utilisation de mesures auto-rapportées simplifiées, moins fiables que des questionnaires standardisés multi-items.

La troisième étude a également été influencée par la COVID-19 et par des limites pratiques de recrutement. Notre partenaire clinique est situé à Sept-Îles, au Québec, où le bassin de personnes éligibles atteintes de TSPT est plus restreint. Par ailleurs, comme nous avons comparé deux formats expérimentaux, les analyses ont reposé sur un sous-ensemble de participantes et participants, à savoir ceux ayant complété les deux formats. Cela a réduit davantage la taille d'échantillon pour les comparaisons directes.

Les travaux futurs devraient viser une augmentation du nombre de participants afin d'assurer une puissance statistique plus élevée, ainsi que l'utilisation d'une mesure de référence (*baseline*) pour caractériser l'état initial des participants, tant sur le plan subjectif qu'objectif.

Une autre limite concerne l'utilisation d'intensités et de types d'odeurs pré-sélectionnés. L'absence de personnalisation a entraîné, chez certains sujets, un abandon en raison d'une sensibilité aux odeurs, tandis que d'autres ont peu apprécié la non-congruence entre l'odeur présentée pour la scène de plage et ce qu'ils s'attendaient à percevoir. Cela a introduit des biais dans les évaluations subjectives et objectives. Des travaux futurs devraient explorer des mécanismes de personnalisation des odeurs afin de réduire ces effets indésirables.

L'enjeu de congruence motive également des travaux futurs. Une approche prometteuse consiste à exploiter l'IA générative pour créer ou adapter des environnements immersifs à trois cent soixante degrés en fonction des préférences de l'utilisateur, de sorte que le contenu visuel corresponde mieux à ce que l'utilisateur attend et à ce que le système multisensoriel peut délivrer. Bien que les outils génératifs actuels présentent encore des limites pour produire du contenu long, de haute qualité, à trois cent soixante degrés, pleinement cohérent et adapté à des sessions de RV prolongées, nous avons commencé à explorer ces possibilités et rapporté des étapes préliminaires dans Lopes et al. (2025b). À terme, les avancées des modèles génératifs et du rendu en temps réel devraient permettre de concevoir des expériences de nature virtuelle plus flexibles et personna-

lisées, susceptibles d'améliorer à la fois l'expérience utilisateur et la fiabilité des résultats auprès d'utilisateurs divers.

1 INTRODUCTION

1.1 Stress and anxiety

Stress and anxiety, though often used interchangeably, have distinct nuances. Stress generally refers to the body's response to any demand or challenge, whereas anxiety is the body's reaction to stress, often characterized by persistent worry or fear in non-threatening situations. Stress is a natural reaction to situations perceived as threatening or demanding. While acute stress can act as a motivator or even enhance performance in some cases, chronic stress can have detrimental effects on health and well-being (Selye, 1972). Anxiety, while related to stress, is more about anticipation. It's a feeling of unease, such as worry or fear, which can be mild or severe (Barlow, 2004). Everyone experiences moments of anxiety, but persistent, excessive worry about everyday situations is often indicative of an anxiety disorder. Both conditions have a huge impact on quality of life and can affect the person physically (e.g., cardiovascular problems, such as high blood pressure, heart disease, stroke; insomnia; chronic pain, such as headaches or muscle pain), mentally (e.g. depression; panic attacks; generalized anxiety disorder, etc), cognitively (e.g. memory problems; concentration problems, etc), and through occupational challenges, such as burnout.

In today's world, stress and anxiety have emerged as pervasive global problems, particularly in the wake of the COVID-19 pandemic, which further contributed to the crisis with employment instability, reduced socialization, and increased financial pressures. Several studies have reported an increase in mental health disorders (Pietrabissa et al., 2020; Smith et al., 2020a; Millroth et al., 2021). For example, relative to the pre-COVID-19 era, there has been a global rise of 25.6% in anxiety and 27.6% in depression, highlighting the urgency and significance of addressing mental health issues (Kotera et al., 2021b; Santomauro et al., 2021; Hawes et al., 2021). The detrimental impact of these psychological challenges on mental well-being and overall quality of life has prompted a growing need for effective interventions, especially non-pharmacological ones.

One non-pharmacological intervention that has shown great promise is to immerse oneself in nature, which has been shown to reduce stress/anxiety states and to provide different mental health benefits (Kotera et al., 2021a; Giannico et al., 2021; Yao et al., 2021), as well as changes in physiological signals (Fu et al., 2022; Corazon et al., 2019). In Japan, for example, the practice of engaging in multisensory nature immersion has been embraced for many years and is known as 'forest bathing' (Shinrin-yoku) (Hansen et al., 2017), where one spends time in a forest to enhance health, wellness, and happiness. Despite these well-documented benefits, exposure in natural environments may not be accessible to many, such as individuals with limited mobility or hospitalized patients. The World Health Organization (WHO) estimates that about 15% of the world's population faces disability, including limited mobility. Additionally, it is known that approximately 55% (in 2017) of the global population resides in urban areas, where access to natural surroundings can

be challenging. Projections suggest that this percentage will rise to 68% by the year 2050 (Ritchie et al., 2018).

For example, physical barriers such as busy streets, railways, and fences impede direct access, while psychological barriers, such as social norms and hostile environments, can discourage individuals from visiting and using urban green spaces (Biernacka et al., 2018). Moreover, even when these spaces are accessible, their attractiveness may be compromised by issues such as poor maintenance, noise, congestion, and a lack of necessary amenities, further reducing their usability (Biernacka et al., 2019). This has highlighted the need for alternative strategies that are more accessible.

One promising solution that has emerged that provides more inclusive access to nature is that of immersive virtual reality (VR). Immersive VR experiences can simulate real-life environments, allowing users to feel present and replacing their real surroundings with virtual reproductions. Numerous studies have explored the effects of VR in medical and healthcare (e.g., (Birckhead et al., 2019; Hao et al., 2022)). More recently, the concept of virtual nature bathing has also emerged. The approach is commonly referred to as 'digital Shinrin-yoku' (Reese et al., 2022) and aims to recreate the experience of nature exposure but in a virtual setting.

Virtual nature bathing experiences can vary widely and may involve 360-degree videos of nature environments projected onto head-mounted displays (HMDs), panoramic photos shown on computer screens, or projections on walls, where users can feel immersed in the forest. These experiences primarily focus on visual and auditory stimuli, where nature scenes (e.g., forests, beaches, waterfalls, lavender fields) and sounds (e.g., birds chirping, leaves rustling, and water flowing) are present. Of course, the sense of immersion and presence are usually modulated by manipulating the quality of the visual (e.g., 8k-resolution high-fidelity 360-degree videos versus human-generated synthetic environments) and auditory (e.g., stereo versus 3D-audio) inputs.

Based on the principles of shinrin-yoku, however, the health benefits are believed to arise from the stimulation of all senses and complete immersion in nature. Since current VR systems offer only audio-visual stimuli, existing experiences may not be fully immersive and may not provide maximal benefits to users. Indeed, research has revealed remarkable sensitivity of memory and the sense of presence to olfactory stimuli (Herz, 1998; Chu et al., 2002; Munyan III et al., 2016), as well as to relaxation (Igarashi et al., 2014a,b; Amores et al., 2018). Smells have also shown to improve attention (Dozio et al., 2021; Raudenbush et al., 2009) and to elicit basic emotions, such as happiness (Vernet-Maury et al., 1999). In VR, it has also been shown to improve relaxation states (Carulli et al., 2019), to positively influence affective and behavioral reactions to the virtual environment (Flavián et al., 2021), as well as to increase user engagement (Brengman et al., 2022) and the sense of realism (Khan et al., 2023).

To investigate the use of multisensory virtual reality, a new system is needed where not only audio and visual systems are engaged, but also olfactory, thermoreception, and touch. Such multisensory systems can open a new window into stress and anxiety treatment from home that can

be accessible to all, despite limited mobility issues, health conditions, access to nature in urban environments, and even extreme weather conditions. These are some of the goals of this Doctoral research.

1.2 Effects of nature exposure : real and virtual

Research has consistently highlighted the therapeutic benefits of nature immersion in alleviating stress and anxiety. Exposure to nature has been identified as an effective non-pharmacological intervention that produces substantial mental health benefits (e.g., improves mood stability, decreases the likelihood of mental health disorders, and improves heart health). A notable example of this practice is Japan's tradition of 'shinrin-yoku' or forest bathing. This approach entails a multisensory experience within natural environments, emphasizing a deep, mindful connection with nature (Hansen et al., 2017). Improvements in subjective assessments of stress and anxiety, as well as in objective metrics, have been reported in the literature as a result of forest bathing (e.g., (Fu et al., 2022; Muro et al., 2022)).

Similarly, studies are starting to emerge showing that exposure to nature in a virtual environment may also have subjective benefits, as well as documented changes in neurophysiological markers of stress and anxiety (Anderson et al., 2017; Kotera et al., 2021a). While this can be particularly beneficial for hospitalized patients and those in long-term care facilities who cannot easily access real outdoor spaces, it may also have a greater potential for at-home treatment, given the long wait times seen for mental health treatments (American Psychological Association, 2023). The work in Browning et al. (2020), for example, showed that virtual nature environments led to similar positive effects and restorative outcomes as being in real nature.

Moreover, as olfactory elements are being incorporated, research is showing that improved experiences can be achieved (Comşa et al., 2019), with a heightened sense of immersion (Narciso et al., 2020). Haptics has also shown to play a key role in mental health management. Vibroacoustic therapy (VA), for example, has been shown to alleviate stress and foster relaxation. VA harnesses the energy of musical sound waves, channeled directly onto the body, eliciting both physiological relaxation and psychological tranquility (Delmastro et al., 2018).

In this doctoral research, one of our goals is to investigate the benefits of integrating olfactory and low-frequency sound vibrations, heat elements, and wind simulation into a new multisensory virtual nature exposure. We will investigate if it is possible to amplify the therapeutic mental health benefits of such digital nature immersion based interventions.

1.3 Limitations in multisensory VR applications

Studies exploring immersive nature environments in VR have only recently begun to integrate multiple sensory stimuli beyond vision and sound, which suggests the field is still maturing and leaves clear room for methodological improvement. In the subsections that follow, we outline key limitations observed in prior multisensory VR studies, which serve as motivation for some of the key innovations developed as part of this doctoral research.

The text in this next section was extracted from (Lopes et al., 2024a).

1.3.1 Population

Several studies have faced limitations due to demographic constraints (e.g., (Zhang et al., 2023; Shin et al., 2022; Qi et al., 2022; Sona et al., 2019)). These studies often do not account for the full spectrum of diversity in age, gender, ethnicity, or socioeconomic status. This lack of diversity can hinder the generalizability of the findings, potentially leading to conclusions that may not apply broadly across different demographic groups. As such, studies should strive to include a more diverse sample, including from a patient population, to enhance the generalizability of the findings.

Another significant limitation, as noted by Song et al. (2019), is the lack of studies with populations with heightened daily stress (e.g., first responders). Overlooking high-stress groups can lead to a gap in understanding of their specific needs and responses.

1.3.2 Lack of stimuli comparisons

Studies, such as those by Zhang et al. (2023); Song et al. (2019), focused predominantly on visual and olfactory stimuli, while works, such as Takayama et al. (2022); Putrino et al. (2020); Amores et al. (2018), emphasized multisensory experiences. The absence of a comprehensive integration strategy and comparison of the three sensory inputs can lead to a fragmented understanding of their synergistic potential and impact.

1.3.3 Lack of complementary measures

A critical limitation noted in studies, such as that by Zhang et al. (2023), is the exclusive focus on physiological indicators, neglecting psychological aspects. Conversely, research by Shin et al. (2022); Abbott et al. (2022); Putrino et al. (2020); Sona et al. (2019); Serrano et al. (2016) have primarily relied on subjective analyses. This one-dimensional approach can result in an incomplete

understanding of the study subject, as it fails to capture the holistic impact of the interventions or phenomena being studied.

In fact, several studies relied on a single objective measurement (e.g., (Zhao et al., 2022; Hedblom et al., 2019; Amores et al., 2018)), thus may have missed some important interactions between the central and nervous systems, which have been linked to different emotional states and behaviors. In turn, the work by Qi et al. (2022) relied on a single subjective measurement, which can result in a narrow understanding of participant experiences.

1.3.4 Narrow focus on odor elements and on scent diffusion strategies

Research, such as in Zhang et al. (2023), focused mainly on odor elements in garden green spaces, overlooking the broader spectrum of sensory experiences in olfactory environments. This limited perspective may not fully capture how various sensory inputs together enhance environmental quality and health benefits.

Moreover, the study by Zhao et al. (2022) highlighted a limitation in using a single method for olfactory stimulation (using the Aroma Shooter device), leading to uncertain conclusions about other techniques, such as other diffusion devices, incenses, or the use of natural plant aromas. This limits the understanding of the impact of different smell stimulation methods on stress recovery and health.

1.3.5 Virtual environment choices

Most studies offered a limited range of nature scenes, often focusing on a single type of environment (e.g., a forest). This limited range fails to consider the diverse preferences and responses individuals might have to different natural settings. Only a few works (e.g., (Qi et al., 2022; Putrino et al., 2020; Hedblom et al., 2019; Serrano et al., 2016)) offered different types of nature scenes.

1.3.6 Modality mismatch

Studies such as Amores et al. (2018) and Serrano et al. (2016) highlight a crucial limitation : the mismatch of sensory modalities. For instance, using lavender essential oil in a beach scenario can create sensory dissonance. This inconsistency can disrupt the coherence of the user experience, potentially diminishing the intended effect of the environment, whether it be for relaxation, stress reduction, or immersion.

1.3.7 Limited objective measurements

Very few studies have utilized objective measurements to quantitatively assess the effects of sensory stimuli. Objective measurement via wearables, for example, may allow for close to real-time monitoring of user affective states, as well as the development of biomarkers that could be used to quantitatively monitor intervention outcomes in the long term. Wearables have been shown to be a useful ally for stress management interventions (e.g., (Smith et al., 2020b; Gomes et al., 2023)).

A handful of studies have relied on monitoring neural data while the user was immersed in the virtual environment (Song et al., 2019; Zhang et al., 2023; Qi et al., 2022; Amores et al., 2018). Unlike other wearable devices that are typically placed on wrists, chests, or arms, the collection of neural data while the user is wearing a head-mounted display may be challenging. Physiological measures derived from electroencephalography (EEG) can provide new insights into the immersive experience and its mental health impact. For instance, the works by Abbasi et al. (2019); Wu et al. (2023) showed the use of EEG to study emotional responses to olfactory stimuli.

1.3.8 Beyond audio-visual-olfactory

Recent studies are showing that as more senses are stimulated, a greater sense of presence, immersion, and engagement can be achieved (De Jesus Jr et al., 2022; Gougeh et al., 2022), as well as improved neural plasticity (Amini Gougeh et al., 2023). Vibroacoustic therapy has shown to be useful for stress management (Boyd-Brewer, 2003). Additionally, the effects of thermal perception have been shown to have restorative benefits (Lyu et al., 2022; Song et al., 2024). Exploring the inclusion of tactile/somatosensory stimuli to further enhance the relaxation potential of immersive nature immersion is an untapped territory that could lead to interesting outcomes.

1.4 Thesis objectives

The primary aim of this doctoral research is to investigate the feasibility and benefits of combining nature exposure with multisensory virtual reality experiences to reduce stress and anxiety by promoting a measurable state of relaxation. Building on evidence that richer sensory stimulation and congruent multisensory design can influence relaxation and user experience, this thesis adopts a stepwise experimental strategy that progressively addresses key limitations identified in prior multisensory VR studies : incomplete sensory comparisons, limited objective sensing, limited population diversity and ecological validity, insufficient attention to sensory congruence/ personalization, and a lack of longitudinal/clinical evaluations. Insights from this study will not only contribute

to the design of novel treatments for anxiety but also advance research in the field of biomarkers for anxiety/stress.

In Chapter 3, a comparison is made between conventional digital nature exposure and a multisensory configuration that adds olfactory, vibroacoustic, and somatosensory cues, while tracking multiple physiological signals via wearables. It primarily addresses the issue of a lack of multi-stimuli comparisons and the scarcity of objective biomarkers in existing solutions.

Chapter 4 moves beyond typical convenience samples by studying nurses working in a mental-health inpatient unit, a group exposed to higher daily stress and strong practical constraints (limited time, limited flexibility, real work context). The chapter compares an audio-visual (AV) nature experience with an audio-visual-olfactory (AVO) version, and examines both subjective outcomes (relaxation and quality of experience) and objective signals collected during immersion. In particular, it reports neural responses measured with an instrumented VR headset (EEG) and cardiovascular responses, photoplethysmography (PPG), including heart rate variability (HRV) related metrics. A key result is that the added benefit of olfaction depends on how well the smell matches the virtual scene. When the scent feels inconsistent with the environment, relaxation can decrease for some participants, and the overall effect becomes harder to interpret. Overall, Chapter 4 addresses limitations related to studying relevant target groups and shows why stimulus congruence and measurement choice are critical when interventions are short and must fit real-world constraints.

Chapter 5 brings the work closer to clinical use by evaluating multisensory VR nature immersion with patients diagnosed with post-traumatic stress disorder (PTSD) over repeated sessions across several weeks. The protocol includes pre- and post-assessments and a follow-up, and it combines standardized clinical questionnaires and neurocognitive tests with neural monitoring during immersion. The chapter also compares two ways of delivering the intervention : a portable headset-based experience with synchronized olfaction, and an in-clinic multisensory pod that adds synchronized scents and additional physical cues (e.g., wind and vibroacoustic feedback) to the audio-visual content. Overall, Chapter 5 addresses several common gaps in the literature by studying a patient population, using a longitudinal design with standardized psychological measures, and incorporating neural data, while also discussing issues related to portability and at-home treatments versus a more clinical setup. Lastly, Chapter 6 presents the conclusions and potential future research directions.

Overall, this doctoral research will aim to support three main research questions : (1) Do multisensory virtual nature experiences provide measurable benefits in terms of improved relaxation and mental health management compared to conventional audio-visual experiences? (2) Are multisensory experiences viable across controlled, occupational, and clinical environments? And if so, what are some potential issues and limitations, and (3) What role can wearable neurophysiological devices and instrumented VR headsets play in capturing biomarkers that complement self-report?

1.5 Publications

The work in this thesis has been published, or is under review, in numerous journals and conference proceedings, both as the main author and as a collaborating author. The next subsections list these publications, respectively.

Publications as first author

1. **LOPES, M. K. S.;** Jesus, B.; Moinnereau, M. A.; Gougeh, R. A.; Rosanne, O. M.; Schubert, W.; Oliveira, A. A.; Falk, T. H.; "Nat(UR)e : Quantifying the Relaxation Potential of Ultra-Reality Multisensory Nature Walk Experiences," Proceedings of the 2022 IEEE International Conference on Metrology for Extended Reality, Artificial Intelligence, and Neural Engineering (Lopes et al., 2022) [Chapter 3].
2. **LOPES, M. K. S.;** Falk, T. H.; "Audio-Visual-Olfactory Immersive Digital Nature Exposure for Stress and Anxiety Reduction : A Systematic Review on Systems, Outcomes, and Challenges," Frontiers in Virtual Reality, 2024 (Lopes et al., 2024a) [Chapters 1, 2, 6].
3. **LOPES, M. K. S.;** Jesus, B.; Rosanne, O. M., Pardini, S; Appel, L; Smith, C; Falk, T. H.; "Stop to Smell the Virtual Roses : A Mixed-methods Pilot Study on the Impact of Multisensory Virtual Reality Nature Experiences on Feelings of Relaxation," Frontiers in Virtual Reality, 2024 (Lopes et al., 2024b) [Chapter 4].
4. **LOPES, M. K. S.;** Falk, T. H.; "Generative AI for Personalized Multisensory Immersive Experiences : Challenges and Opportunities for Stress Reduction," Proceedings of the 2025 IEEE VR Conference, Workshop on Generative Artificial Intelligence meets Extended Reality (Lopes et al., 2025b) [Chapter 6].
5. **LOPES, M. K. S.;** Jesus, B.; Rosanne, O. M., Pardini, S; Appel, L.; Smith, C; Falk, T. H.; "Changes in Heart Rate Variability During Immersive Multisensory Forest Bathing Experiences," Proceedings of the 2025 Applied Human Factors and Ergonomics Conference Lopes et al. (2025a) [Chapter 4].
6. **LOPES, M. K. S.;** Perreault, L.; Jesus, B.; Roberge, M.; Falk, T. H.; "Subjective and Objective Evaluation of the Benefits of Multisensory Virtual Nature Immersion for Patients with Post-Traumatic Stress Disorder," Proceedings of the 2025 International Conference on Quality of Multimedia Experience (Lopes et al., 2025c) [Chapter 5].
7. **LOPES, M. K. S.;** Tiwari, A.; Perreault, L.; Jesus, B.; Roberge, M.; Falk, T. H.; "Neural and Clinical Effects of Multisensory Virtual Nature Immersion in PTSD," Proceedings of the 2026 International Conference on Acoustics, Speech, and Signal Processing [Accepted, to appear]Lopes et al. (2026b) [Chapter 5].
8. **LOPES, M. K. S.;** Perreault, L.; Jesus, B.; Roberge, M.; Falk, T. H.; "Neural and Subjective Effects of Repeated Multisensory Virtual Nature Exposure in PTSD", submitted to the

2026 Annual Conference of the IEEE Engineering in Medicine and Biology Society [Under Review] Lopes et al. (2026a)[Chapter 5].

Publications as collaborating author

1. De Jesus Jr, B., **Lopes, M.**, Moinnereau, M.A., Gougeh, R.A., Rosanne, O.M., Schubert, W., Oliveira, A.A. and Falk, T.H., 2022, June. Quantifying multisensory immersive experiences using wearables : is (stimulating) more (senses) always merrier?. In Proceedings of the Workshop on Multisensory Experiences (SensoryX), 2022 IMX. (De Jesus Jr et al., 2022).
2. De Jesus Junior, B.J., Perreault, L., **Lopes, M.K.**, Roberge, M.C., Oliveira, A.A. and Falk, T.H., 2023. Using Multisensory virtual reality nature immersion as a therapeutic modality for improving HRV and cognitive functions in post-traumatic stress disorder : a pilot-study. Frontiers in Virtual Reality, 4. (De Jesus Junior et al., 2023).
3. De Jesus Junior, B.J., **Lopes, M.K.**, Perreault, L., Roberge, M.C., Oliveira, A.A. and Falk, T.H., 2025. Instrumenting a Virtual Reality Headset to Monitor Changes in Electroencephalograms of PTSD Patients During Multisensory Immersion, IEEE Journal of Selected Areas in Sensors (2025).
4. De Jesus Junior, B.J., **Lopes, M.K.**, Perreault, L., Roberge, M.C., Oliveira, A.A. and Falk, T.H., 2025. Electroencephalography Neuromarkers to Predict the Response of a Multisensory Virtual Reality Nature Immersion Intervention for Patients Diagnosed with Post-Traumatic Stress Disorder. In IEEE International Conference on Systems, Man, and Cybernetics (SMC), pp. 6033-6038. IEEE, 2025.
5. Pardini, S., Kim, S., de Jesus, B., **Lopes, M.K.**, Leggett, K., Falk, T.H., Smith, C. and Appel, L., 2024. SafeVRwards : Designing a complementary virtual reality module to the Safewards framework intended to relax and manage conflict in mental health wards. BMJ open quality, 13(2). (Pardini et al., 2024).
6. Perreault, L.,De Jesus Junior, B.J., **Lopes, M.K.**, Roberge, M.C., Oliveira, A.A. and Falk, T.H., 2024. Using multisensory virtual reality nature immersion as a therapeutic modality for improving HRV and cognitive functions in post-traumatic stress disorder : a pilot-study, Proceedings of the 35th Annual Boston Trauma Conference, abstract, May 1-4.
7. Gougeh, R.A., De Jesus, B.J., **Lopes, M.K.**, Moinnereau, M.A., Schubert, W. and Falk, T.H., 2022, October. Quantifying user behaviour in multisensory immersive experiences. In Proceedings of the 2022 IEEE International conference on metrology for extended reality, artificial intelligence and neural engineering (MetroXRAINE) (pp. 64-68). (Gougeh et al., 2022).
8. Falk, T.H., Gougeh, R.A., Ivanescu, L., De Jesus Jr, B., **Lopes, M.**, Mohamed, N., Moinnereau, M.A., Schubert, W., and Oliveira, A.A., 2022. Neuroergonomics Meets the Metaverse : Biosensor-Instrumented VR Headsets for Real-time Multisensory Immersive Expe-

rience Assessment “In the Wild”. Proceedings of the Neuroergonomics Conference & NYC Neuromodulation Conference 2022.

1.6 Thesis organization

The remainder of this thesis is comprised of six additional chapters, as detailed next.

- **Chapter 2 – Background concepts and related works.** This chapter introduces the main concepts needed for the thesis, including stress and anxiety assessment, virtual nature exposure, multisensory stimulation (audio, olfaction, and haptic cues), and the main subjective and objective measures used to quantify relaxation and stress reduction. It also presents key results from the systematic review conducted during the PhD research (Lopes et al., 2024a).
- **Chapter 3 – Impact of sensory modalities on relaxation states : A use-case with university students.** This chapter presents a controlled study that compares different sensory configurations (from visual-only and audio-visual to audio-visual-olfactory and audio-visual-olfactory-haptic). It quantifies how adding modalities changes relaxation using self-reports and wearable physiological signals.
- **Chapter 4 – Multisensory VR experiences in realistic environments : A use case with nurses in a mental health inpatient ward.** This chapter evaluates audio-visual versus audio-visual-olfactory VR nature exposure with nurses working in a mental-health inpatient unit. It reports relaxation and quality-of-experience outcomes, and analyzes objective data collected during immersion, including EEG and PPG-derived measures.
- **Chapter 5 – Multisensory nature immersion : A new intervention for PTSD patients.** This chapter studies multisensory VR nature immersion with patients diagnosed with PTSD across repeated sessions over multiple weeks. It combines standardized clinical questionnaires and neurocognitive tests with in-session neural monitoring, and compares a PORTABLE headset-based experience with an in-clinic multisensory POD that adds additional haptic cues.
- **Chapter 6 – Conclusions and future research directions.** This chapter summarizes the main findings of the thesis and highlights its overall contributions. It also discusses remaining challenges that must be addressed to further develop and deploy multisensory VR nature interventions, including personalization and larger participant pools.

2 BACKGROUND CONCEPTS AND RELATED WORKS

2.1 Preamble

This chapter presents background concepts and related works that are essential for the full understanding of this dissertation. The text included here was compiled from the work published in Lopes et al. (2024a).

2.2 Mental health

Mental health refers to a person's psychological well-being and their ability to function in everyday life. It supports coping with stress, developing and using one's abilities, learning and working effectively, and maintaining social relationships and participation in the community (World Health Organization, 2025; Organization, 2022).

Mental well-being is shaped by both personal experiences and the broader contexts people face in daily life. In this thesis, we focus on three contexts where stress can be particularly high : academic settings, demanding work environments, and clinical situations following traumatic experiences. In particular, exposure to traumatic events can lead to persistent symptoms that interfere with daily functioning, as in post-traumatic stress disorder (PTSD) (World Health Organization, 2024).

2.2.1 Stress in academic environments

Academic settings can expose students to repeated demands, such as deadlines, evaluations, peer competition, and uncertainty, that may accumulate over time. In this context, stress is often described as an imbalance between the pressures of the environment and an individual's perceived ability to cope with them (Cho et al., 2020). In practice, this imbalance can appear as a persistent feeling of being overloaded, which is frequently linked to poorer mental-health outcomes in academic populations.

Academic stress also interacts with stressors outside the university. Deng et al. (2022) examined academic and family stress together and reported that both contribute to higher depression levels, which in turn are associated with poorer academic performance. This supports the idea that academic stress should be understood within a broader life context, especially for students balancing studies with family responsibilities and financial constraints.

Longitudinal evidence also suggests that mental-health burden can increase during PhD training. The work in Bergvall et al. (2025) found that psychiatric medication use rises substantially after the start of PhD studies and continues to increase across the PhD period, reaching about a 40% increase by the fifth year compared to pre-PhD levels (Bergvall et al., 2025). Together, these findings motivate the need for practical, scalable approaches that can support stress recovery in academic contexts. This motivation is aligned with this thesis's goals, i.e., to investigate multisensory virtual nature immersion within an academic graduate student population.

2.2.2 Stress in demanding work environments

Demanding work environments can also expose people to repeated stressors that accumulate over time and reduce opportunities for recovery. In healthcare, nursing is often described as a high-stress profession because it combines long hours, heavy mental and physical workload, rotating shifts, frequent exposure to suffering, and difficult interactions with patients and families (Wells, 2024). These challenges can be even more pronounced in mental-health inpatient settings, where nurses report high rates of conflict, violence, and aggression (Cranage et al., 2022). More broadly, evidence from care-work settings has shown consistent links between major work stressors (e.g., high workload, role ambiguity, inadequate resources, aggressive client behavior) and outcomes such as burnout, anxiety, and depression (Chireh et al., 2025). In this thesis, we examine the use of multisensory nature immersion as a real-world intervention for nurses working in a mental-health inpatient unit, supporting them with short stress-recovery periods that can be taken multiple times a day within their demanding schedules.

2.2.3 Post-traumatic stress disorder

Post-traumatic stress disorder (PTSD) is a mental health condition that can develop after exposure to a traumatic event. While many people experience stress reactions after trauma, PTSD refers to symptoms that persist and can interfere with daily functioning (World Health Organization, 2024). People diagnosed with PTSD may experience intrusive memories, nightmares, or flashbacks, and may avoid reminders of the event.

Treatment of PTSD symptoms can be difficult to deliver and to complete for many patients. Exposure therapy, for example, where patients gradually face trauma-related memories and cues in a safe setting, is considered an effective approach (McLean et al., 2022). However, access to specialized care is often limited, and dropout remains an important issue. Practical constraints also exist : some events are hard to reproduce safely and realistically in real life (e.g., severe car accidents).

As such, virtual reality (VR) has gained popularity as a therapeutic tool, because it can create controlled and repeatable simulated situations that support engagement and can help reduce dropout (Gonçalves et al., 2012). In this thesis, we build on this motivation by studying multisensory VR-based interventions with PTSD patients, with the goal of supporting relaxation and stress recovery.

2.3 Virtual reality

Virtual Reality is a computer-generated, three-dimensional simulation that enables users to interact with and experience artificial environments through select senses, primarily vision and hearing, using specialized electronic devices. This immersive technology creates a digital experience that simulates real-world interactions, making it feel authentic in its engagement (LaValle, 2023; Sherman et al., 2018; Dionisio et al., 2013).

The experience of VR can be broken down into three primary categories based on the degree of immersion (Mandal, 2013; Bamodu et al., 2013) :

— Non-immersive VR : This is the least immersive version of virtual reality. In non-immersive VR, only a subset of the user's senses is engaged, and it often feels more like a computer game. A typical example might be a 3D graphics application on a personal computer, where the user can interact with the environment using standard input devices, like a keyboard and mouse. The environment can be viewed on a regular monitor without the need for any special equipment.
— Semi-immersive VR : This type bridges the gap between non-immersive and fully-immersive VR. In semi-immersive VR, the environment is both digital and physical. Users might be in a room with large projection screens that display a virtual environment, and they might use some specialized equipment to interact. Flight simulators, where pilots train, are a good example of semi-immersive VR.
— Fully-immersive VR : As the name suggests, this is the most immersive form of virtual reality. Here, the user becomes fully immersed in a computer-generated environment. This typically requires advanced equipment, such as HMD and motion sensing devices. These tools help stimulate the user and make the digital experience closer to reality.

In all its forms, VR has applications across numerous domains, from entertainment and gaming to training, education, and therapeutic intervention. As the technology continues to advance, the line between our physical reality and virtual reality becomes increasingly blurred, offering vast possibilities for the future.

2.3.1 Effects of natural environment using virtual reality

Studies show that exposure to natural environments using VR has great mental health benefit and the concept of virtual nature walks has emerged. Also known as ”digital shinrin-yoku" (or digital nature walks) (Reese et al., 2022), the paradigm aims to recreate the experience of nature walks but in a virtual setting. Findings indicate that nature walks may be effective for mental health, as virtual nature experiences induce relaxation and reduce stress levels. In addition, exposure to virtual natural settings can elevate mood and help combat symptoms of anxiety and depression (Anderson et al., 2017; Kotera et al., 2021a). This can be particularly beneficial for hospitalized patients, those in long-term care facilities who cannot easily access real outdoor environments or are confined indoors, or those located in urban areas without easy access to natural settings. In Browning et al. (2020), the authors showed that virtual nature environments and actual nature can both lead to similar positive effects and restorative outcomes. Furthermore, VR-simulated nature walks have been shown to have an impact on psychological and physiological outcomes (Jo et al., 2019; Lee et al., 2022; Syed Abdullah et al., 2021), reinforcing that this technique can be used as a treatment without pharmacological intervention.

2.3.2 Multisensory experiences

Recent investigations have delved deeper into the potential of multisensory integrations. For instance, Comşa et al. (2019) revealed that when olfactory elements are incorporated, there’s flexibility to diminish VR video quality without detracting from the user’s overall experience. Additionally, the study from Narciso et al. (2020) confirmed that scents significantly heightened the user’s immersion, whereas adding wind elements had minimal impact.

Drawing inspiration from the concept of shinrin-yoku, or forest bathing, the restorative advantages of immersive experiences in natural settings are attributed to the engagement of all senses, facilitating a profound connection with the environment. As present-day VR systems predominantly cater to visual and auditory senses, they may not provide maximum benefits to users by achieving immersive quality by not fully engaging the multisensory spectrum. Incorporating multisensory elements into the VR environments may amplify the therapeutic mental health benefits of digital nature-based interventions, making them more authentic and impactful.

Previous studies have shown that it is possible to promote relaxation and reduce stress when smells are integrated (Amores et al., 2018; Aiken et al., 2015; Pizzoli et al., 2021; Baus et al., 2010). By integrating olfactory stimuli, there’s a promising potential to enhance the restorative and therapeutic effects of natural virtual environments on stress and anxiety. Moreover, vibroacoustic therapy (VA) has emerged as a promising tool to alleviate stress and foster relaxation. VA harnesses the energy of musical sound waves, channeled directly onto the body, eliciting both physiological relaxation and psychological tranquility (Delmastro et al., 2018). Integrating VA into multisensory VR

landscapes can be achieved by coupling somatic/haptic feedback with low-frequency sound vibrations. As users immerse themselves in VR renditions of serene natural settings, complemented by nature-inspired auditory cues via headsets, they are simultaneously bathed in these therapeutic low-frequency waves. The synergistic effect not only elevates the overall sensory experience but also significantly amplifies feelings of well-being and stress reduction (Wigram et al., 2013; Naghdi et al., 2015). The integration of these multisensory experiences in VR platforms could redefine the effectiveness and impact of digital nature-based interventions. Validating this hypothesis is a main objective of this thesis.

2.4 Subjective assessments

Various methods have been employed to measure stress and anxiety levels. Typically, these methods fall into two primary categories : subjective assessments, which evaluate psychological effects, and objective evaluations, which focus on physiological impacts. Although researchers have the liberty to choose their assessment tools, some instruments are commonly favored due to their proven reliability and comprehensive nature. Subjective methods help us better understand the various psychological states, which can be used in combination with physiological measures to enrich the analysis. Below are some common subjective assessment tools used :

- **Profile of Mood States (POMS) (McNair et al., 1964; Yokoyama et al., 1990) :** This is a widely recognized tool specifically designed to measure mood fluctuations. It aids researchers and clinicians in identifying and quantifying specific mood states, thus facilitating a deeper understanding of emotional changes over time.
- **Positive and Negative Affect Schedule (PANAS) (Watson et al., 1988a,b; Sato, 2001) and Visual Analogue Scale (VAS) (Gross et al., 1995; Wewers et al., 1990) :** Both PANAS and VAS are instrumental in gauging perceived stress levels, anxiety, feelings of insecurity, calmness, and overall happiness. PANAS, in particular, distinguishes between positive and negative emotions, allowing for a comprehensive evaluation of an individual's emotional state.
- **State-Trait Anxiety Inventory (STAI) (Bieling et al., 1998) :** This inventory focuses specifically on differentiating between state anxiety (temporary condition) and trait anxiety (more permanent disposition). This differentiation is pivotal as it helps in understanding whether an individual's anxiety is situational or a more ingrained characteristic.
- **Self-Assessment Manikin (SAM) and Presence Self-Assessment Manikin (Bradley et al., 1994) :** SAM is a non-verbal pictorial assessment that gauges the respondent's affective reaction to a range of stimuli. The Presence variant further extends this to understand how "present" or immersed an individual feels in a given environment or scenario.

— **Relaxation Rating Scale (RRS) (Labbé et al., 2007a) :** As the name suggests, this scale is tailored to evaluate an individual's relaxation levels. It's particularly useful when gauging the efficacy of relaxation interventions or therapeutic sessions.
— **Perceived Restorativeness Scale (PRS) (Hartig, 1996) :** This tool assesses how rejuvenating or restorative an environment feels to an individual. It can be instrumental when studying the impact of certain environments, like nature or therapeutic spaces, on psychological well-being.
— **Restoration Outcomes Scale (ROS) (Korpela et al., 2008, 2010) :** This scale complements the PRS by focusing on subjective restorativeness, giving researchers insights into how certain interventions or environments can aid in psychological restoration.

2.4.1 PTSD – Psychological measures

Several standardized instruments are also available for PTSD-related symptoms. This subsection briefly summarizes the questionnaires and clinical measures used in this thesis.

The *Peritraumatic Dissociative Experiences Questionnaire* (PDEQ) (Marmar et al., 2004) assesses dissociative experiences that may have occurred during or shortly after the traumatic event (e.g., depersonalization, derealization, amnesia). It includes 10 items rated from 1 to 5, and scores above 15 are commonly interpreted as indicating clinically significant peritraumatic dissociation.

The *PTSD Checklist for DSM-5* (PCL-5) (Weathers et al., 1993; Ashbaugh et al., 2016) is a 20-item self-report measure of PTSD symptom severity over the main DSM-5 symptom clusters. Items are rated from 0 to 4; a total score of around 33 or higher is often used as a threshold for a provisional PTSD diagnosis and for tracking symptom change over time. The *Clinician-Administered PTSD Scale for DSM-5* (CAPS-5) (Weathers et al., 2018; Rivest-Beauregard et al., 2022) is a semi-structured clinical interview that evaluates symptom presence and severity. It is commonly used as a reference measure for PTSD and provides a clinician-rated estimate of symptom severity based on DSM-5 criteria.

The *Dissociative Experiences Scale* (DES-II) (Carlson et al., 1993; Larøi et al., 2013) measures everyday dissociative symptoms (dissociation, amnesia, absorption) using 28 items. Responses are given as a percentage of time (0–100), and a mean score above 30 is often considered indicative of clinically significant dissociation. Lastly, depressive symptoms were assessed with the *Patient Health Questionnaire* (PHQ-9) (Kroenke et al., 2001; Beard et al., 2016), a 9-item self-report scale rated from 0 to 3 that is widely used to quantify depression severity and monitor change.

2.4.1.1 Cognitive measures

Cognitive function of PTSD patients was assessed using *CNS Vital Signs*[1], a computerized battery composed of seven tasks (e.g., verbal/visual memory, processing speed, attention, and executive function). Standard scores are interpreted using normative categories(Above average = $>$ 109; Average = 90 to 109; Low average = 80 to 89; Low = 70 to 79; Very low = $<$ 70).

2.5 Objective measures

The complexities of stress and anxiety have encouraged the search for reliable detection methods. While traditional methods, such as cortisol tests, provide reliable measures, they can be very invasive. In turn, the advent of real-time biosignal monitoring via wearable devices has opened doors for non-invasive monitoring (Greene et al., 2016). As the modern age embraces technological innovation, wearable devices, designed to track physiological metrics, are becoming mainstream. These wearable devices are advantageous as they allow real-time physiological monitoring during experiments.

Within biosignal modalities captured by wearables, several indicators can provide physiological measures of stress. Using electrocardiogram (ECG) signals, for example, measurement of heart rate and heart rate variability (HRV) is possible; these measures have been associated with stress and anxiety (Chalmers et al., 2014; Goessl et al., 2017; Dishman et al., 2000). Photoplethysmography (PPG) also provides insights into HRV by tracking blood volume changes in our arteries with each heartbeat. Moreover, certain attributes of blood volume pulse (BVP) signals have been linked to stress and anxiety (Parent et al., 2020), as well as relaxation level measurement (Kreibig et al., 2007).

Neural activity, captured by electroencephalography (EEG), is another valuable source of stress and/or anxiety information. Several spectral and modulation spectral features computed from EEG readings have been tied to stress and anxiety levels (Katmah et al., 2021; Parent et al., 2020). Some representative feature examples include (but are not limited to) : prefrontal alpha band power, theta band absolute power, relative gamma band power, prefrontal alpha asymmetry, and coherence (alpha and beta band from the parietal and occipital regions). Near-infrared spectroscopy (NIRS) has also been shown to detect emotional states by measuring emotion-related changes in cerebral blood flow Hoshi et al. (2011). Other signal modalities can also be used to detect high stress states, including electrodermal activity (EDA) or galvanic skin responses (Posada-Quintero et al., 2016), as well as breathing rate, breathing rate variability, and sigh frequency(Vlemincx et al., 2013).

1. https://www.cnsvs.com/

In this thesis, we will focus particularly on features derived from EEG and PPG signals, as they can be collected during immersive VR exposure and provide complementary information on neural and autonomic responses. We use these features to study how multisensory virtual nature immersion influences relaxation and stress recovery across the three different populations investigated in this doctoral research. More details on these signal modalities and features used are given in the subsections to follow.

2.5.1 Photoplethysmography

PPG is an optical technique that measures changes in blood volume in the microvascular bed. In wearable devices, a light source and photodetector record a pulse waveform (often referred to as blood volume pulse, BVP), from which beat-to-beat timing can be extracted. By detecting successive pulse peaks, it is possible to estimate heart rate and derive pulse-to-pulse interval series, often called pulse rate variability (PRV). In many resting conditions, PRV can be a reasonable approximation of ECG-based heart rate variability (HRV), but the match depends on signal quality and context (e.g., movement, vasomotor changes) (Schäfer et al., 2013; Castaneda et al., 2018).

HRV refers to the natural variability in the time interval between consecutive heartbeats and is widely used as an index of autonomic nervous system regulation (Electrophysiology, 1996; Shaffer et al., 2017). Common time-domain features include the mean heart rate, SDNN (overall variability), and RMSSD (short-term variability). Frequency-domain features typically quantify power in standard bands (e.g., low frequency and high frequency), where RMSSD and high-frequency power are often used as markers of parasympathetic (vagal) activity (Electrophysiology, 1996; Shaffer et al., 2017).

A key advantage of PPG is that it can be integrated into consumer wearables and instrumented headsets, enabling continuous monitoring during experiments and interventions (Castaneda et al., 2018; Charlton et al., 2022). In this thesis, we use PPG-derived features to quantify autonomic responses during immersive VR exposure.

2.5.2 Electroencephalography

EEG is a non-invasive technique that measures the electrical activity produced by neuronal populations in the brain. EEG signals are recorded by placing electrodes on the scalp at predefined locations to capture cortical activity (Binnie et al., 1994). Because head size and shape vary across individuals, electrode placement is usually standardized to improve comparability. A widely used layout is the international 10–20 system, where electrode positions are defined as fixed percentages of the distances between anatomical landmarks (front–back : nasion to inion; left–right :

preauricular points), ensuring coverage across the scalp. Once recorded, EEG signals can be processed to extract features that summarize relevant aspects of brain activity.

Among the most common EEG features reported in the literature are power spectral density (PSD) measures, which quantify how signal power is distributed across frequency bands (Ifeachor et al., 2002). PSD can be computed over short epoched segments of the time-domain signal, as well as via time-frequency mappings, such as the Fourier transform. For a band-limited signal $s(k)$ with m samples, the band power computation can be expressed as :

$$power = \frac{1}{m} \sum_{k=1}^{m} s^2(k). \tag{2.1}$$

To support comparisons across participants, sessions, or datasets, power values are often normalized. A common approach is to normalize each band power by the total (full-band) power, which reduces between-subject variability and helps control for overall amplitude differences. EEG power is typically summarized in five frequency bands : delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (>30 Hz).

2.6 Related work

A comprehensive literature review was conducted across six databases, including PubMed, Science Direct, Web of Science, Scopus, Google Scholar, and IEEE Xplore, between January 2016 to April 2023. The following keywords were used : (stress OR anxiety OR relaxation) AND (“virtual reality”) AND (“nature scene” OR “digital nature” OR “digital forest” OR “virtual forest” OR “virtual nature” OR “forest bathing” OR “forest therapy” OR “nature therapy” OR “shinrin-yoku” OR “natural environment”) AND (olfactory OR aromatherapy OR olfaction) AND (EEG OR biosignal OR physiological OR multisensory). Keywords were searched throughout the title, abstract, and full text of the articles. Although we have not included the term “psychological” as a keyword, we have kept articles that only used subjective measurements through questionnaires, so that we can analyze the systems that were used and quantify any limitations (Lopes et al., 2024a). In this section, we will highlight the 13 key articles that emerged from the review, and that focus on multisensory nature immersion using audio-visual-olfactory stimuli for relaxation or reducing stress/anxiety.

2.6.1 Multi-sensory stimuli and systems

2.6.1.1 Visual stimuli

The reviewed studies relied on different scenes of nature for relaxation. In Zhang et al. (2023), a panorama photo of Osmanthus trees (a common Chinese garden plant) was used for the inter-

vention, and a white wall without any smells was used as a group control. In Qi et al. (2022), four different environments were used, each presented as a three-dimensional 360-degree panoramic photo. The nature scenes included a lawn, a rose garden, an Osmanthus tree garden, and a pine forest. As in the other study, a white wall with no smell or audio was used for the control group. The environment used in Abbott et al. (2022) was a forested area including a campsite, a river, and a wooden cabin; for the control condition, subjects were exposed to a stressful stimulus. In Schebella et al. (2020), a 360-degree video of low biodiversity, moderate biodiversity, and high biodiversity nature scenes was used, along with a virtual urban environment as a control condition. In Hedblom et al. (2019), 360-degree photos of a park and forest were used, while for the control condition, an urban environment was used. Lastly, in Amores et al. (2018), a beach scene was presented in 360-degree video format. For the control condition, it was mentioned that no stimulus was presented and no specific instructions were given to the participants, other than to not close their eyes.

While the studies above used HMDs as the display modality, other studies relied on projectors and display screens/TVs to provide the virtual experience. In Takayama et al. (2022), a video image of a forest environment was projected in a room. In Shin et al. (2022), a 270-degree video of a busy cafe scene was presented under three conditions, two of which included a nature scene. In Zhao et al. (2022), an LED display screen was used to transmit a video of a forest in autumn colors; the control condition had no stimulus. In Putrino et al. (2020), a high-definition projector was used to show a soothing natural landscape, comprised of either ocean scenes or forest scenes. In Song et al. (2019), a 4K-compatible display television was used, and the visual stimulus was a photograph view of a forest landscape. The work in Sona et al. (2019), utilized an artificial window comprised of three high-resolution 4K LED screens with speakers to present a park scene and a lounge scenario. In Serrano et al. (2016), an HD video projector was used where participants could watch relaxing scenes, including a beach and a landscape covered in snow. Lastly, the studies in Putrino et al. (2020); Sona et al. (2019) relied on a hybrid setting, where real plants were also used. More details about the virtual environment presentation modality can be seen in Section 2.6.2

2.6.1.2 Auditory stimuli

Audio stimuli were used in most of the studies, with only two studies focusing on the visual-olfactory senses (Zhang et al., 2023; Song et al., 2019). The audio was related to nature and often included bird and water sounds. Among the selected articles, only three studies used complementary sounds, in addition to nature ones : (Putrino et al., 2020) and (Serrano et al., 2016) included relaxing music. For the studies that used the control condition with urban environments (i.e., (Hedblom et al., 2019; Schebella et al., 2020)), it was common for traffic sounds to match the environment. In Sona et al. (2019), only instrumental music was played. Finally, the work in Shin et al. (2022) compared an open window (with virtual nature) condition versus a closed window (with/without nature) in a coffee shop. In the open window condition, sounds of nature could be

heard. In all three conditions, background babble noise, typical of a coffee shop, was also presented at a moderate volume level.

2.6.1.3 Olfactory stimuli

All scents used in the studies were related to nature for the intervention conditions in the natural environments. Some relied on natural scents, such as the work in (Zhang et al., 2023), which used real osmanthus flowers to produce the olfactory stimulus, and the work in Qi et al. (2022), which used real samples of lawn, rose flowers, osmanthus flowers, and pine. In Song et al. (2019), the authorsused Hinoki cypress leaf oil (Kiseitec Co., Wakayama, Japan) extracted by steam distillation from leaves and twigs of Hinoki cypress trees. On the other hand, eight studies used different types of diffusers to emit smells. In Takayama et al. (2022), the essential oil of Abies sachalinensis (Sakhalin fir) was used. The authors in Shin et al. (2022) used two ultrasonic essential oil diffusers with the aroma of coffee and wet dirt (nature condition). In Zhao et al. (2022), the Aroma Shooter device was used to provide a forest scent. In Abbott et al. (2022), scents were produced with the Olorama Scent Generator (Olorama Technology Ltd, Spain) and smells of sausage, coffee, wet ground, pine, woods, roses, lavender, and honey were used. In Putrino et al. (2020), yuzu, hinoki, roman chamomile, and lavender essential oils were used. In Sona et al. (2019), scents of rosewood, geranium, ylang-ylang, olibanum (frankincense), and hyssop were used in the natural outdoor condition and composition of rosewood and cardamom in the indoor condition. In Serrano et al. (2016), a lavender scent was distributed with a ceramic diffuser.

Three studies used customized methods of aroma emission. In Schebella et al. (2020), scents were applied to cotton pads and attached to the HMD, a range of 16 nature scents (e.g., several types of grass, soil, leaves, and flowers) and four urban scents (e.g., dust and turpentine) were initially tested on a convenience sample of 11 people. In the end, they used only one scent in the urban and low biodiversity scenes, and three different natural scents in the high biodiversity scene; however, the authors did not specify the exact name of the aroma. All scents were selected from the Demeter Fragrance Library[2]. In Hedblom et al. (2019), the authors used their own computer-controlled olfactometer (Lundström et al., 2010), where city odors included diesel, tar, and gunpowder, and for park odors, they used grass and different forest odors, including two evergreen species and mushrooms. In Amores et al. (2018), an essence necklace was used to emit a lavender essential oil scent.

As can be seen, the methodology for selecting scents in multisensory VR studies varies, often reflecting the unique objectives and contexts of each research project. For instance, (Zhang et al., 2023) selected the scent of Osmanthus, a flower renowned as one of the ten most famous flowers in China, where the study took place, thus highlighting the cultural relevance of scent choice. Takayama et al. (2022); Song et al. (2019) focused on scents from trees that complemented the

2. http://www.demeterfragrance.com/

visual aspects of the VR environment, thus enhancing the sensory congruence for users. Other studies, however, such as those conducted by Putrino et al. (2020); Amores et al. (2018); Serrano et al. (2016), opted for scents such as lavender and Roman chamomile essential oils, chosen for their documented effects in reducing anxiety and stress in the scientific literature.

Qi et al. (2022) took it one step further and used a portable odor sensor (COSMOS XP-329 III R; Rank Value, range 0–2000) to measure and select odor concentrations that closely mimicked the landscapes used in the virtual environments. Schebella et al. (2020) engaged participants in the scent selection process, where 11 subjects identified which scents they found to more closely match the natural or urban settings in the experiment. Seven scents were accurately recognized and subsequently utilized in corresponding VR environments, ensuring the olfactory experience matched the visual setting. Moreover, Sona et al. (2019) not only referenced literature for scent selection but also conducted preliminary tests with 12 subjects to determine the intensity of ambient scents and identify perception thresholds. Other studies (e.g., (Shin et al., 2022; Zhao et al., 2022; Abbott et al., 2022; Hedblom et al., 2019)) chose scents based on the landscapes present in their virtual environments.

2.6.1.4 Tactile and somatosensory stimuli

In addition to the audio-visual-olfactory stimuli detailed above, three studies also investigated tactile/somatosensory stimuli. In Zhao et al. (2022), fans were mounted on the top of the table, pointing toward the user's head and table surface, as well as infrared lights underneath the table were used for temperature control. Lastly, in Serrano et al. (2016), artificial grass was installed on the ground, allowing the participant to touch and feel it during the immersive VR experience.

2.6.2 Presentation modality and virtual nature experiences

2.6.2.1 Display/Projector-based experiences

Among the selected studies, seven presented the virtual reality experience using display/projectors in an indoor setting (Shin et al., 2022; Takayama et al., 2022; Zhao et al., 2022; Putrino et al., 2020; Hedblom et al., 2019; Sona et al., 2019; Serrano et al., 2016). In Shin et al. (2022), three conditions were tested : no window (brick wall), closed window (nature view), and open window (nature view), with all conditions including the scene of a coffee shop. Participants were randomized into one of three groups. Participants were immersed in a 270-degree VR simulation within the laboratory. The participant's viewpoint featured a lifelike projection of the student union coffee shop, spanning the front and left walls. Additionally, the right wall showcased three distinct conditions. Throughout all conditions, a coffee fragrance and ambient conversation noises were used at a moderate volume level. In the open window condition, the immersive experience was further enhanced by the sounds

of birds chirping/singing in the background, accompanied by the aroma of wet dirt. In Takayama et al. (2022), participants were exposed to a 20-minute digital shinrin-yoku environment that reproduced visual, auditory, and olfactory elements. Each session accommodated a maximum of five subjects, and an adequate distance between individuals was maintained. Video images of a forest were projected onto three walls and the ceiling of the experimental room.

The work in Zhao et al. (2022) focused on multimodal augmentation via lighting, audio, video, airflow, heating, and scent elements to improve the productivity and well-being of workers in an open-plan office. In this work, a comparison was made between three conditions (neutral vs. unscented forest vs. scented forest), and a stress induction phase was also performed. For the neutral condition, LED panels displayed no visuals, whereas for the other two conditions (with scent and without scent), a forest scene was displayed. Another study created a *recharge room* with multisensory (visual, auditory, and olfactory) nature-inspired experiences where healthcare workers could relax and reduce stress (Putrino et al., 2020). The environment was carefully designed to evoke a serene natural setting. Silk imitation plants were strategically placed to simulate lush greenery, while scenes of natural landscapes were projected onto a blank wall. The ambiance was further enhanced by soft, color-matched lighting, which complemented the projected landscapes. High-definition audio recordings of nature sounds were combined with relaxing music. To complete the multisensory immersion, essential oils and calming scents were diffused using an essential oil diffuser, heightening the impression of being fully surrounded by a natural environment.

The study in Song et al. (2019) employed four different conditions, each lasting 90 seconds, namely : a forest landscape image featuring Hinoki cypress trees without any accompanying odor (visual-only), a gray image infused with Hinoki cypress leaf essential oil (olfactory-only), a forest landscape image of Hinoki cypress trees combined with the scent of Hinoki cypress leaf essential oil (combined stimulus), and a gray image without any odor (control condition). The study conducted by Sona et al. (2019) examined five distinct conditions, including a control condition with no window, sound, or scent. Additionally, two audio-visual conditions were assessed : a nature condition with a window displaying nature scenes, accompanied by bird sounds and neutralizing air/no scent, and a lounge condition featuring a window displaying a lounge scene, instrumental music, and neutralizing air/no scent. Furthermore, the study explored two audio-visual-olfactory conditions where scents were introduced as an additional element.

In Serrano et al. (2016), the experiment was performed in a VR room, in which a virtual reality environment was created where participants were immersed inside a two-story house called *House of Relaxation*. The goal was to induce relaxation and a sense of presence and to analyze whether adding touch and smell altered the experience outcomes. Inside the environment, users could perform different actions, such as modifying the house's decoration, watching a video clip through a projector, changing the intensity of the lights and the color of the walls, opening or closing doors and windows, moving between the two floors of the house, moving or adding furniture, changing the ground to grass or sand, or change the exterior landscape to reflect another natural context

(e.g., beach or snow). The lavender scent was used to stimulate the olfactory sense, and for the tactile stimulus, they used artificial grass. They compared four conditions : audio-visual, audio-visual-olfactory, audio-visual-tactile, and audio-visual-olfactory-tactile.

2.6.2.2 HMD-based experiences

The other six studies relied on VR HMDs to present the visual stimuli (Zhang et al., 2023; Qi et al., 2022; Abbott et al., 2022; Schebella et al., 2020; Hedblom et al., 2019; Amores et al., 2018). The most recent study compared three conditions, i.e., olfactory-only, visual-only, and visual-olfactory, to a control condition (Zhang et al., 2023). The experiment took place in a room with white walls and ceilings, ensuring a consistent indoor environment to prevent the subjects' moods from being influenced by external factors, such as weather and light. In the control group, an odorless condition was maintained, with participants exposed to an image of a white wall, devoid of any stimuli associated with plant smells or garden landscapes. In the olfactory condition, participants experienced a natural concentration of fragrance emitted from Osmanthus fragrans. For the visual stimulus, a panoramic photo of Osmanthus trees was displayed. The visual-olfactory condition involved the combination of both visual and olfactory stimuli.

In Qi et al. (2022), a total of 308 volunteers participated in the study and were divided into 14 independent groups. These groups were designed to explore three different stimulus scenarios : audio-visual, audio-olfactory, and audio-visual-olfactory. Four plant landscapes (lawn, rose garden, osmanthus tree garden, and pine forest), with each landscape accompanied by its respective scent when olfactory stimuli were integrated, plus a single birdsong group (1 group) that visualized a white wall and received no odor stimulus, and a control group (1 group) of participants who viewed only a white wall (no birdsong and no odor). Each condition comprised 22 participants, ensuring an equal distribution across the study.

Another study that showed a positive impact of introducing olfactory stimuli to reduce negative affect and state anxiety levels was the work in Abbott et al. (2022). There, the authors analyzed an audio-visual and an audio-visual-olfactory condition with a task to induce stress between conditions. They built two VR environments using Unreal Engine 4. The first VR environment was designed as a nature-inspired forested area, complete with a campsite, a river, and a wooden cabin. To enhance the immersion, realistic sounds of nature, such as a rushing river and chirping birds, were incorporated. Additionally, when olfactory stimuli were required, scents of nature were introduced. The second VR environment was specifically tailored for the stress induction portion of the experiment, known as the Trier Social Stress Test (TSST). This environment was modeled after a small auditorium, featuring approximately 30 static audience members. These virtual audience members remained passive throughout the session, providing no feedback to the subjects, whether positive or negative. Lastly, in Amores et al. (2018), a baseline condition (no stimulus) was compared to an audio-visual-olfactory condition. The participant was comfortably seated while wearing

the Essence necklace, which emitted a fragrance of lavender. Participants were presented with a 360-degree video of a beach setting and the audio accompanying the video.

2.6.2.3 Nature vs. urban virtual environments

Two studies compared between a natural and an urban environment (Schebella et al., 2020; Hedblom et al., 2019). In Schebella et al. (2020), three natural environments, with different levels of biodiversity (low, moderate, and high), were compared to an urban environment control condition. A significant effect of multisensory biodiversity was observed on stress recovery related to the urban environment. Moreover, in Hedblom et al. (2019), an urban area was compared to an urban park and an urban forest. Each condition included audio-visual-olfactory stimuli appropriate for the scenes. The two virtual nature conditions resulted in greater stress reduction relative to the urban environment. The perceived pleasantness was associated with the olfactory and auditory stimuli, but not with the visual stimulus. The study suggested that olfactory stimuli may be better at facilitating stress reduction than visual stimuli and highlights the relevance of multisensory approaches for stress reduction.

2.6.3 Outcome assessments (psychological)

2.6.3.1 Subjective measures

In total, 12 studies performed subjective measurements to analyze the mood changes associated with multisensory VR exposure. Four studies administered the PRS to measure how restorative an environment was (Shin et al., 2022; Takayama et al., 2022; Zhao et al., 2022; Sona et al., 2019). In Sona et al. (2019), questions about mood, fatigue, and arousal (before and after exposure) were also measured. Two studies used the ROS to analyze the subjective restorativeness, where (Shin et al., 2022) requested the questionnaire only after VR exposure, while in Takayama et al. (2022) the measurement was requested before and after exposure. Two other studies used a semantic differential method. In Qi et al. (2022), a survey concerning the overall quality evaluation of the environment was used, while in Song et al. (2019), the participants' subjective spatial impressions were collected via a questionnaire with four opposite adjectives, each evaluated on 13 scales.

Two studies measured mood with the PANAS (Takayama et al., 2022; Abbott et al., 2022). Two studies used the VAS before and after exposure. While in Schebella et al. (2020) VAS was used to measure the perceived stress, anxiety, insecurity, calmness, and happiness levels of the participants, in Serrano et al. (2016) it was used to evaluate levels of sadness, joy, anxiety, and relaxation moods. One study used the Profile of Mood States (Takayama et al., 2022). STAI was used in two studies : in Qi et al. (2022), the full 20-item version was used, whereas in Abbott et al. (2022) a modified version including only 6-items was used. The work in (Serrano et al., 2016)

mentioned using the state scale of the STAI but did not report the results; instead, it reported results using the SAM (before and after exposure) and the PSAM (after exposure).

Single-item measures were also used across different studies, including the RRS, which was collected in Amores et al. (2018) before and after the exposure. Overall, four studies acquired some type of subjective measure only after the virtual experience (Shin et al., 2022; Zhao et al., 2022; Song et al., 2019; Hedblom et al., 2019). Moreover, five studies used tasks to induce stress prior to exposure. In Zhao et al. (2022), participants were given a 3-minute reading comprehension task similar to those given on a graduate standardized test. In Abbott et al. (2022) and Schebella et al. (2020), the modified trier social stress test was used. In Hedblom et al. (2019), mild electric shocks were used as a stress trigger. Finally, in Sona et al. (2019), a sequence of tasks was used to induce stress, including a single N-back task, a Stroop task, and an Attention Network Task.

2.6.3.2 Emotional restoration, mood, and perceived stress

The addition of olfactory stimuli in virtual nature experiences resulted in inconsistent outcomes concerning effects on emotional restoration and positive/negative emotion. While some studies reported an improvement in mood and stress reduction, others reported no significant differences. For example, in Shin et al. (2022), the conditions where the participants looked out the window at nature showed greater restorative qualities than the absence of nature, but comparisons between the closed window condition (only view of nature) and the open window condition (sight, smell, and sounds of nature) showed no significant differences. Several participants did, however, report the open window condition to be more captivating. Results of one-way ANOVAs showed significant restorativeness/restoration across conditions for the ROS subscales 'Being Away' and 'Fascination' ($p < 0.05$).

In Qi et al. (2022), the audio-visual-olfactory stimuli led to an increased physiological restoration and overall perceived quality, whereas the audio-olfactory stimuli, despite having no significant effect on psychological restoration, showed an increase in perceived overall feelings of attraction to the landscape and a sense of overall harmony. For the audio-visual and audio-visual-olfactory conditions, no significant differences in psychological effects were found. Only for the auditory stimulus was the STAI-S value significantly lower than the control group ($p = 0.04$). In another study (Zhao et al., 2022), in turn, after the two virtual forest conditions (with and without nature smell), ratings of perceived restoration and focus were significantly $p < 0.05$ higher than the neutral condition (i.e., post-hoc comparisons, using a Wilcoxon signed-rank test, audio-visual-olfactory, $Z = 17.50$, $p = 0.000$ and audio-visual $Z = 13.0$, $p = 0.000$). However, stress development was slower, and recovery was greater in the forest without scent condition compared to the other conditions. In addition, Friedman's test showed a significant ($p < 0.05$) difference in restoration perception among the three conditions ($\mathcal{X}^2(36) = 39.78$, $p = 0.000$). Also, in Takayama et al. (2022), negative mood states (measured using POMS), significantly decreased ($p < 0.01$) after the experience

(i.e., tension-anxiety, depression, anger-hostility, fatigue, and confusion). In addition, psychological restorative effects were confirmed, with a significant decrease ($p < 0.01$) in "negative affect" (measured using PANAS) and a significant increase ($p < 0.01$) in the sense of restoration (measured using ROS) after the experience.

Regarding negative emotions, in Abbott et al. (2022), participants experienced a notable reduction in STAI-6 scores following the audio-visual-olfactory condition compared to the audio-visual condition ($p = 0.03$). Furthermore, when contrasted with their stressed state, there was a significant decrease in both PANAS Negative Affect ($p = 0.003$) and STAI-6 scores ($p = 0.001$) after the audio-visual-olfactory. Additionally, STAI-6 scores showed a significant decline from the baseline in the audio-visual-olfactory condition ($p = 0.013$). Results suggested that the addition of olfactory stimuli to the VR environment aided in reducing negative affect and state anxiety levels.

For positive emotions, significant improvements in relaxation were reported in Amores et al. (2018). In Amores et al. (2018), the results showed that the multisensory VR experience was able to promote increased relaxation relative to the baseline condition, although not a significant difference. The findings corroborate previous studies that showed forest-related stimuli significantly increase the participants' feelings of comfort and relaxation relative to a control condition ($p < 0.05$) (Song et al., 2019). Moreover, the work in Sona et al. (2019) showed that the correlation between the two multisensory environment experiences showed that nature views were perceived as more pleasant ($r = 0.74$, $p < 0.01$) and restorative ($r = 39$, $p < 0.01$) than the control group (no stimulus). Adding nature smells facilitated the recovery of personal resources (mood, fatigue, arousal) via greater scent pleasantness and fascination ($r = 0.18$, $p < 0.10$). Moreover, correlation analyses between experiences showed that the view was perceived as more pleasant ($r = 0.53$, $p < 0.01$) and the environment as more restorative ($r = 0.22$, $p < 0.05$) in the nature simulations than in the lounge simulations.

In Serrano et al. (2016), the results showed that the VR experience was effective in inducing relaxation, $F(1,132) = 90.31$, $p < 0.001$, where positive moods and the sense of presence increased. Moreover, a significant decrease in arousal ($F(1,132) = 92.04$, $p < 0.001$) was observed after all four VR experiences. However, no statistical differences were found between the four groups on emotions and sense of presence. In Hedblom et al. (2019), the perceived pleasantness, average over environments and sensory stimuli rated on a 1–100 scale, was significantly higher in the park environment (Mean = 69.21, SD = $\pm$11.1) compared to both the forest (Mean = 62.7, SD = $\pm$12.74; $p = 0.01$) and the urban area ($p < 0.001$). Perceived pleasantness was also higher for the forest relative to the urban area (Mean = 37.19, SD = $\pm$14.22; $p < 0.001$). There were significant differences in the ratings of perceived pleasantness among the three environments, as indicated by the sensory stimuli ($t = 90.01$; $p < 0.001$; pairwise comparisons).

Regarding perceived stress, (Schebella et al., 2020) showed that a multisensory experience (visual, auditory, and olfactory) was associated with better recovery in all measures of well-being relative to a visual-only experience. Median anxiety recovery scores were significantly greater in

the audio-visual-olfactory high biodiversity environment (33.00) than in the visual-only (17.50) using a Mann–Whitney test (U = 90.50, z = 1.971, p = 0.047). When compared to the virtual urban environment, stress recovery was most effective in a low-biodiversity environment ($p < 0.05$). In Putrino et al. (2020), a greater reduction in perceived stress after the multisensory immersive experience was reported ($p < 0.001$), where the level of stress had an average reduction of 59.6% in the self-reported ratings. Similarly, in Hedblom et al. (2019), the park and forest conditions resulted in significant stress reduction, whereas the urban area condition did not.

2.6.4 Outcome assessment (physiological)

In total, eight articles performed some type of physiological measurement and assessment (Zhang et al., 2023; Qi et al., 2022; Takayama et al., 2022; Zhao et al., 2022; Schebella et al., 2020; Song et al., 2019; Hedblom et al., 2019; Amores et al., 2018). Only three of them, however, measured physiological stress through stress induction (Zhao et al., 2022; Schebella et al., 2020; Hedblom et al., 2019). In particular, four studies measured cardiovascular data (Takayama et al., 2022; Zhao et al., 2022; Schebella et al., 2020; Song et al., 2019), two measured blood pressure and pulse (Zhang et al., 2023; Takayama et al., 2022), one measured salivary amylase activity (Takayama et al., 2022), three assessed electrodermal activity (EDA) (Zhang et al., 2023; Qi et al., 2022; Hedblom et al., 2019), one measured skin temperature (Qi et al., 2022), one measured oxy-hemoglobin concentration in left and right prefrontal cortices as an indicator of brain activity using near-infrared spectroscopy (Song et al., 2019), and three used EEG to measure neural activity (Zhang et al., 2023; Qi et al., 2022; Amores et al., 2018). More details about each modality are presented next.

2.6.4.1 Blood pressure and pulse

The study described in Zhang et al. (2023) investigated the effects of olfactory and olfactory-visual stimulation on blood pressure and pulse. During the stimulation, it was observed that systolic blood pressure (SBP) values remained relatively unchanged. However, diastolic blood pressure (DBP) values exhibited a significant increase (ΔDBP = 4.37 $\pm$ 1.69 mmHg, $p < 0.05$). Additionally, the pulse pressure difference (PP) values demonstrated a notable decrease during both stimulations (ΔPP = -4.56 $\pm$ 1.24 mmHg, $p < 0.05$). Furthermore, during olfactory stimulation, pulse values also showed a significant decrease (ΔP = -2.34 $\pm$ 1.16 bmp, $p < 0.05$). In contrast, visual stimulation did not lead to significant changes in SBP, DBP, or PP. These findings suggest that the physiological effects were greater when the olfactory system was stimulated. Conversely, in Takayama et al. (2022), no significant differences in DBP, SBP, or pulse rate were seen before and after experiencing the digital forest bathing environment.

2.6.4.2 Skin temperature and salivary amylase

Only one study looked at skin temperature (ST) changes (Qi et al., 2022). While the results did not show significance, the restorative tendency for auditory stimuli was greater than in the control group.

Similarly, only one study measured salivary amylase (Takayama et al., 2022). No significant effect was observed when comparing the data before and after the multisensory digital forest experience.

2.6.4.3 Near-infrared spectroscopy (NIRS)

The study described in Song et al. (2019) demonstrated that the combined visual and olfactory stimuli yielded significantly reduced oxygenated hemoglobin (oxy-Hb) concentrations in both the left (control, -0.08 $\pm$ 0.10 μM; visual-olfactory, -0.48 $\pm$ 0.09 μM; $p < 0.05$) and right (control, 0.02 $\pm$ 0.10 μM; visual-olfactory, -0.46 $\pm$ 0.08 μM; $p < 0.05$;) prefrontal cortices, compared to the control condition. Additionally, when exposed to the olfactory stimulus alone, a significant decrease in oxy-Hb concentration was observed in the right prefrontal cortex compared to the control condition (olfactory, -0.32 $\pm$ 0.12 μM). This decrease in oxy-Hb concentration aligns with previous literature suggesting its association with physiological calming (Hoshi et al., 2011). Overall, these findings suggest greater relaxation effects resulting from the combined visual and olfactory stimuli.

2.6.4.4 Cardiovascular data

Regarding the cardiovascular system, there were four studies that show results related to relaxation and stress reduction in multisensory experience (Takayama et al., 2022; Zhao et al., 2022; Schebella et al., 2020; Song et al., 2019).

In Takayama et al. (2022), the heart rate significantly decreased ($p < 0.01$), and HF was significantly higher ($p = 0.014$) during the exposure to multisensory forest bathing compared with that during the resting state. On the other hand, the study in Zhao et al. (2022) used HRV to compare three conditions during stress-inducing and recovery tasks. They found significant differences ($p < 0.05$) in HRV among these conditions. Specifically, the audio-visual condition showed a notably higher HRV than the neutral condition across all metrics. Additionally, HRV in the audio-visual condition was generally higher than in the audio-visual-olfactory condition. The results suggest that the nature experience without scent was the most effective in promoting relaxation.

Regarding the comparison between urban and natural environments, in Schebella et al. (2020), results showed that there were no significant differences in recovery from stress induction in terms of heart rate and HRV. However, regarding the stimulus in the experience, the multisensory expe-

rience showed that the recovery from stress induction relative to a visual-only condition was higher in terms of reduced heart rate and HRV. Moreover, the greatest recovery from stress induction based on median HR recovery scores ($\mathcal{X}^2(2)$ = 9.234, p = 0.007) was found in the low biodiversity condition, relative to the moderate biodiversity natural environment. Lastly, in Song et al. (2019), findings derived from HRV (i.e., $ln(LF/HF)$) showed that only the visual stimulus resulted in significantly decreased sympathetic nervous activity compared to the control condition (control, -0.26 $\pm$ 0.17; visual, -0.67 $\pm$ 0.17; p < 0.05;), which indicates a decrease in stress. When comparing the four conditions (control, visual, olfactory, and visual-olfactory), there was no significant difference in heart rate.

2.6.4.5 Electrodermal activity

Three studies reported changes in electrodermal activity (EDA) when including multisensory experiences. In Zhang et al. (2023), in the visual condition, the amplitudes of skin conductance (SC) (ΔSC = 0.19 $\pm$ 0.01 $\mu\Omega$, p < 0.05) increased significantly relative to the control group. In addition, SC values significantly increased under the olfactory–visual stimulus method (ΔSC = 0.45 $\pm$ 0.34 $\mu\Omega$, p < 0.05), and this increase was significantly higher than that of the olfactory-only condition. These findings can indicate that the effect of smelling and seeing garden plants gives more excitement than just smelling or seeing. On the other hand, the work in Qi et al. (2022) showed that in terms of the physiological restoration, the skin conductance level (SCL) value revealed a negative effect in the audio-olfactory stimulation, only the audio stimulus resulted in higher levels of restoration than the control group, illustrated by the SCL (p = 0.04).

In the study by Hedblom et al. (2019), a greater decrease in EDA was observed in natural (park) environments compared to urban environments, with a significant difference (β=2.02, (t(2471)=2.45; p < 0.02)). A similar trend, though not statistically significant, was also noted between park and forest environments (β=0.56, (t(2471)=0.67, p$=$0.25)). The study used a regression model to explore the relationship between perceived environmental pleasantness and SCL values during stress and recovery periods. It was found that only odor pleasantness significantly predicted SCL during both periods (stress period : β=-0.164; p=0.04; recovery period : β=-0.188; p=0.03), with auditory pleasantness showing marginal significance in the recovery period (β=-0.45; p=0.05).

2.6.4.6 Electroencephalography

Most studies measuring electroencephalograms focused on alpha waves, which represent a state of calm and feelings of quietness and relaxation. Two studies, in addition to alpha waves, also showed results related to beta waves, which are related to effortful thinking and active attention. In Zhang et al. (2023), there was a significant increase in alpha and beta wave power during visual and combined olfactory-visual stimulation compared to before the stimulation. Specifically, alpha

waves increased from 13.90 $\pm$ 7.19 μV to 20.10 $\pm$ 9.45 μV ($p < 0.001$) in the visual condition and from 16.03 $\pm$ 5.03 μV to 18.31 $\pm$ 6.77 μV ($p < 0.05$) in the olfactory-visual condition. Beta waves also rose from 8.27 $\pm$ 5.09 μV to 13.78 $\pm$ 6.79 μV ($p < 0.001$) in the visual condition and from 10.12 $\pm$ 4.35 μV to 11.52 $\pm$ 4.87 μV ($p < 0.05$) in the olfactory-visual condition. No significant changes were noted with olfactory stimulation alone. However, when compared to a control group, all three conditions showed a significant increase in both alpha and beta wave powers.

In Qi et al. (2022), audio-visual-olfactory stimuli led to greater restoration and changes in beta wave power (compared with the only-audio condition). As for the alpha wave power, correlations were seen with a lifting effect in the audio-visual condition and a negative effect in the audio-olfactory condition ($p = 0.00$), with a relatively equal mean difference when compared to the audio-only condition. Combining audio (birdsong) with olfactory stimuli from environments such as rose gardens and pine forests led to a significant decrease in α power ($p \leq 0.01$). An osmanthus garden also notably lowered α power ($p = 0.00$), indicating that certain plant landscapes may induce negative physical arousal. Regarding β band power, adding visual and visual-olfactory stimuli to audio-only (birdsong) scenarios generally improved restoration ($p = 0.00$). However, in lawn settings, the addition of visual-olfactory stimuli had a variable impact on β values ($p = 0.00$). The work in Amores et al. (2018) also investigated changes in theta wave, which can be observed during meditation and drowsiness. A relaxation metric based on the Renyi entropy of different EEG frequency bands was proposed, and showed that the relaxation score increased significantly ($p < 0.05$) between the audio-visual-olfactory experience and the control condition (no stimulus).

2.7 Conclusion

In this chapter, we have provided some theoretical background describing the main population studied in this doctoral research, as well as some important concepts to understand the metrics used in the following works. Finally, we summarized the main findings from related work identified in our literature review (Lopes et al., 2024a).

3 IMPACT OF SENSORY MODALITIES ON RELAXATION STATES : A USE-CASE WITH UNIVERSITY STUDENTS

3.1 Preamble

This chapter is compiled from material published in IEEE International Conference on Metrology for Extended Reality, Artificial Intelligence and Neural Engineering (Lopes et al., 2022).

3.2 Introduction

More recently, incorporation of smells into virtual experiences has been shown to improve the level of relaxation and reduce stress (Amores et al., 2018; Aiken et al., 2015; Pizzoli et al., 2021; Baus et al., 2010). Moreover, incorporating the sense of touch has also been shown to improve the sense of presence and immersion of virtual experiences (Serrano et al., 2016), thus incorporating haptic feedback into the experience could be beneficial. In this study, we aim to explore this hypothesis.

In particular, we propose Nat(UR)e, a multisensory reality nature walk experience in which a digital shinrin-yoku environment is enhanced with olfactory, vibroacoustic, and somatosensory stimuli, in addition to the usual 360-degree audio and visual stimuli. Experiments with 16 participants were conducted, where each participant experienced a video-only (VO), audio-visual (AV), audio-visual-olfactory (AVO), and audio-visual-olfactory-haptic, referred to here as “ultra-reality” (UR) version while using two wearable devices to track several physiological signals.

3.3 Materials and methods

In this section, we describe the data collection, experimental setup, and physiological features extracted for analysis.

3.3.1 Participants

Sixteen participants from an academic environment (6 females, 27 ± 7.46 years) consented to participate in this experiment, which was approved by the INRS Ethics Committee. In particular, special COVID-19 safety measures were followed, including social distancing, masking, sanitizing the VR headset and wearable devices with alcohol wipes, and placing the VR headset into a UV-C chamber custom-built for VR headsets (Cleanbox Technology, USA).

3.3.2 Experiment setup

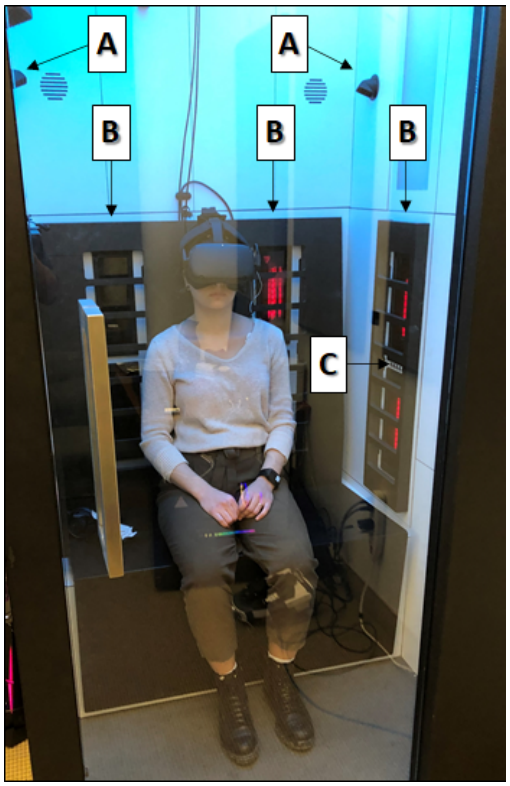
The experiment was conducted inside a SENSIKS (SENSIKS, Netherlands) multisensory booth (see Fig. 3.1a), where four fans surround the participants (shown as 'A' in the figure), heating elements surround the sides, back and front of the users ('B'), high definition speakers provide immersive audio, a subwoofer under the seat provides vibroacoustic feedback, and a scent device diffuses up to six different aromas ('C'). All of these stimuli were time-synchronized with the 360-degree video, which was presented via an Oculus Quest VR headset (Fig. 3.1b). The multisensory nature walk synchronized i) fans to coincide to parts of the video in which leaves were blowing and wind noise could be heard, ii) the heaters with the sun shining through the trees, iii) vibroacoustic feedback as the user walked through nature and stepped on crackling leaves, and iv) smells comprised of dirt, forest, grass, and mist freshness, which were presented subtly in the background.

Moreover, to measure physiological information, participants wore a BioHarness3 (Zephyr, USA) chest-strap (Fig. 3.1c), which measured ECG at a 250 Hz sample rate, breathing signals at 18 Hz sample rate, as well as an E4 (Empatica, USA) wristband (Fig. 3.1d) to measure skin temperature, electrodermal activity, and blood volume pulse.

3.3.3 Experiment description

The experiment itself comprised four sessions/conditions : video only (VO), audio-visual (AV), audio-visual-olfactory (AVO), and "ultra-reality" (UR), where audio, visual, olfactory, somatosensory, and vibroacoustic feedback was enabled. The ordering of the conditions was counterbalanced across participants to avoid any ordering biases. At the end of each session, a modified RRS questionnaire was used (Labbé et al., 2007b) where each participant rated their current level of relaxation state from 1 ("Not relaxed at all") to 5 ("Very much relaxed"). Here, we will focus only on comparisons between the AV and UR conditions to test the benefits of the proposed 'Nat(UR)e' framework with conventional digital nature systems.

The experience comprised participants immersed in a forest environment for roughly one minute (see Fig. 3.2). In the AV session, in addition to the main surround sound track, participants could hear the voice of a young woman whispering in the background, encouraging self-reflection on existence and awareness throughout the video experience. Participants could see and hear the leaves blowing and see sunshine passing through the trees. In the UR session, the same female background voice was present, but additionally, participants could smell different aromas in the background, such as the scent of dirt, forest, and grass. When the sound of wind appeared, and leaves blew, airflow would be produced by built-in fans to simulate the wind. As the person moved and stepped on leaves, crackles were translated into vibrations in the seat. Lastly, as sun rays emerged from the trees, various heating elements around the sides, back, and front of the parti-



(a)



(b)



(c)



(d)

FIGURE 3.1 : (a) Multisensory pod showing A-fans, B-heating elements, and C-scent diffuser, (b) Oculus Quest VR headset, (c) Zephyr BioHarness3 chest-strap and (d) Empatica E4 wristband.



(a)



(b)

FIGURE 3.2 : Nat(UR)e scenes (left) and view inside the booth (right) as (a) sunlight was blocked by the trees (heating elements in low settings) and (b) sunlight appearing and heating elements were on high settings.

cipant would come on at varying intensities to match the intensity of light observed. Figure 3.2a, for example, shows the heating elements at low intensity when the sun was hidden by the leaves, whereas Fig. 3.2b shows the increased heating intensity as light intensity increased.

3.3.4 Feature extraction

From the physiological signals, several features were extracted from each modality, namely skin temperature, BVP, and EDA from the Empatica E4 wristband, and ECG and breathing curves from the Bioharness 3 cheststrap. Table 3.1 summarizes all of the extracted features per signal modality.

3.4 Results and discussion

Figure 3.3 shows the average relaxation ratings reported for all participants across the four conditions. As can be seen, participants significantly rated the AVO and UR conditions as more relaxing than the traditional audio-visual condition with p-value < 0.05, and p-value < 0.01, respectively. These findings are consistent with shinrin-yoku principles, suggesting that multisensory experiences may enhance the perceived benefits of nature exposure.

TABLE 3.1 : List of extracted features for each signal modality.

Modality	Features
Skin temperature	mean, standard deviation, range, mean of 1° difference, minimum, maximum, skewness, kurtosis, delta temperature, spectral energy from 0-0.01 Hz, and 0.1-0.2 Hz.
BVP	maximum, minimum, spectral energy from 0-0.5 Hz, 0.5-1.0 Hz, 1.0-1.5 Hz, 1.5-2.0 Hz, and 2.0-2.5 Hz, spectral energy ratio between 0.04-0.15 Hz and 0.15-0.5 Hz.
EDA	mean, standard deviation, mean of 1st difference, mean of negative 1st difference, spectral energy from 0-0.2 Hz, 0.2-0.4 Hz, 0.4-0.6 Hz, 0.6-0.8 Hz, and 0.8-1.0 Hz from the phasic component of EDA signal.
ECG	mean RR, standard deviation RR, coefficient of variation, RMSDD, pNN50, mean of 1st diff, mean of absolute 1st diff normalized, standard deviation of absolute 1st diff, low-frequency power (0.04-0.15 Hz), high-frequency power (0.15-0.4 Hz), very-low-frequency power (0-0.04 Hz), normalized low-frequency power, normalized high-frequency power, the ratio of low-frequency power and high-frequency power, total power.
Breathing	mean, standard deviation, range, skewness, kurtosis, mean of 1st diff, spectral energy from 0-0.2 Hz, 0.2-0.4 Hz, 0.4-0.6 Hz, 0.6-0.8 Hz, and 0.8-1.0 Hz, spectral energy ratio between 0.05 - 0.25 Hz and 0.25-0.5 Hz, the frequency with maximum spectral energy, centroids

Regarding the impact of the multisensory VR experiment on the user experience parameters, Figure 3.4 depicts the average ratings obtained across all participants for their sense of realism, presence, immersion, engagement, flow, emotion, and cybersickness for each of the four conditions. As can be seen, except for cybersickness, stimulating additional senses (conditions AVO and UR) showed significant improvements. The introduction of smells seemed to improve the most the sense of realism, presence, immersion, and emotion. Adding haptics to smells seemed to improve further (though not significantly) the sense of realism, presence, and flow.

From the analysis of the physiological signals, we compared two conditions : the conventional AV experience with the multisensory UR. Data from three participants had to be removed from the Bioharness 3 chest strap due to the low quality of the recordings. Additionally, data from the Empatica E4 wristband of one participant had to be deleted due to device battery issues that resulted

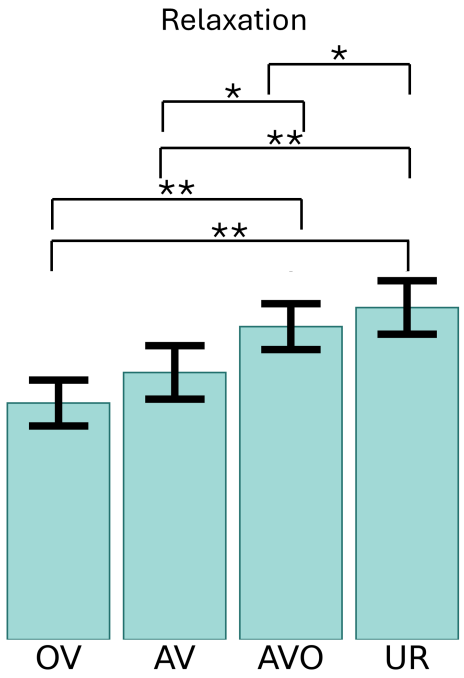


FIGURE 3.3 : Average relaxation rating across the four conditions.

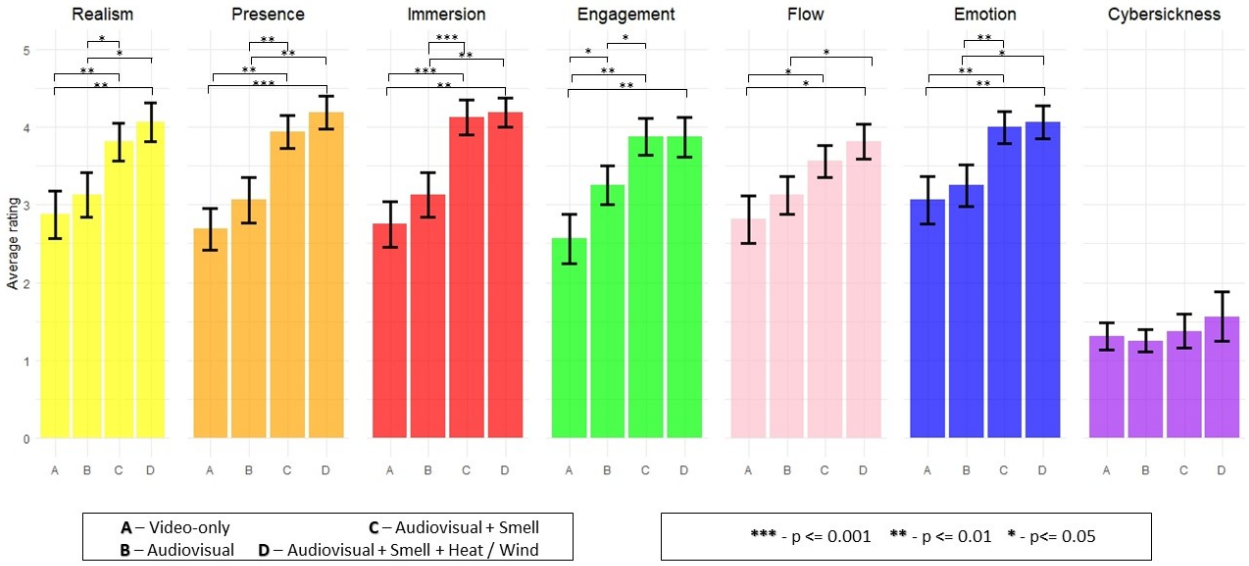


FIGURE 3.4 : Average rating for each experience factor across the four different conditions.

in an incomplete recording of the session. For these analyses, we observed biological signatures associated with stress and anxiety reduction previously reported in the literature. For example, Fig. 3.5 shows the difference in the average (across all participants) high-frequency (HF) component of the ECG signal between the UR and AV conditions. These findings align with previous

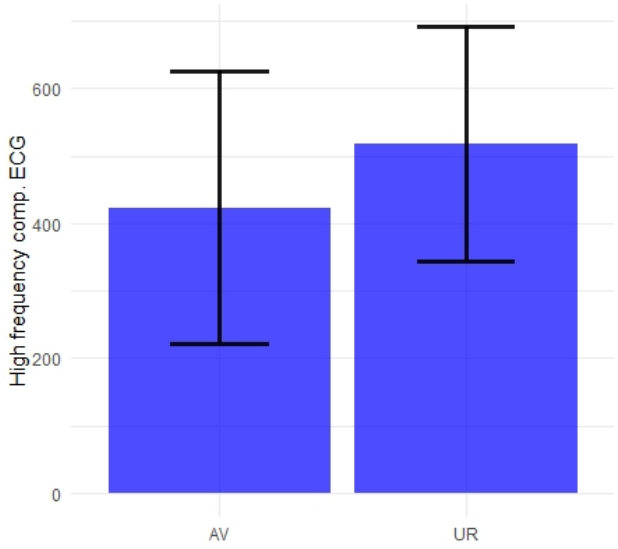


FIGURE 3.5 : Comparison of the ECG HF component.

studies(Castaldo et al., 2015; Anderson et al., 2017; Murata et al., 2004), which showed increases in HF during deep relaxation situations such as meditation, or decreases in HF during stressful situations.

Moreover, Fig. 3.6 shows a lower average across participants of the low frequency component of the electrodermal activity signal for the condition UR when compared to AV. An increase in the low-frequency component of EDA has been associated with stress (Posada-Quintero et al., 2016), which supports the view that the Nat(UR)e framework may promote greater relaxation. Similarly, Fig. 3.7 shows a decrease in the average maximum BVP signal for the UR condition relative to AV, in line with prior work linking this pattern to relaxation (Kreibig et al., 2007). It is important to mention, however, that despite these observed behaviours, the observed differences did not show a statistically significant difference between the two conditions based on the paired t-test analysis. On the contrary, the mean of the negative 1^{st} difference and the standard deviation of the electrodermal activity signal presented a significant difference between the two conditions (t(14) = -2.2, p-value $<$ 0.05 and t(14) = 2.52, p-value $<$ 0.05, respectively). These features have been used in the past to classify stressful versus non-stressful situations, thus corroborating previous findings (Hasanbasic et al., 2019; Pakarinen et al., 2019; Hsieh et al., 2019).

Moreover, we have explored the correlation between the extracted biosignal features and the subjects' relaxation ratings. Figure 3.8, for example, depicts the scatter plot of the standard deviation of the absolute 1st difference of the ECG feature along with the respective correlations obtained with the relaxation rating for the four conditions. While this feature did not show a significant correlation with relaxation in the OV and AV conditions, it showed a negative correlation in the AVO and UR conditions, reaching statistical significance in the UR condition. This feature has been linked to stress and anxiety in the past (e.g., (Tiwari et al., 2019, 2020; Rainville et al., 2006; Hsieh

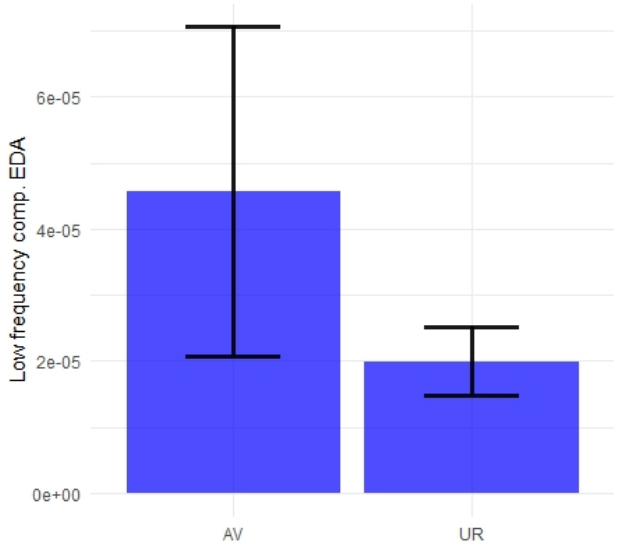


FIGURE 3.6 : Comparison of the EDA low frequency component.

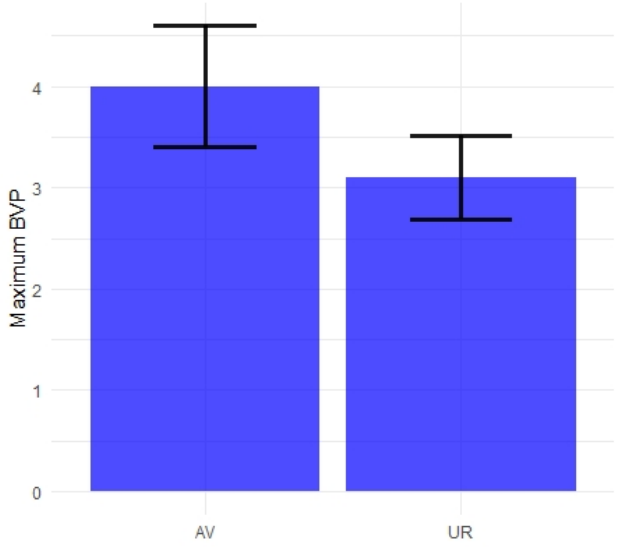


FIGURE 3.7 : Comparison of the maximum BVP value.

et al., 2019; Hasanbasic et al., 2019; Pakarinen et al., 2019)), thus further validating the benefits of multisensory exposure to virtual nature to reduce stress.

3.5 Conclusion

This study explored the effects of multisensory digital nature walks on user (from academic settings) relaxation and compared subjective and objective findings relative to a conventional VR experience. Significant improvement in relaxation was found, and several biometric features indicative of stress/anxiety/relaxation showed significant changes and correlations with the reported relaxation ratings. Results are promising as (1) they suggest multisensory VR experience could be

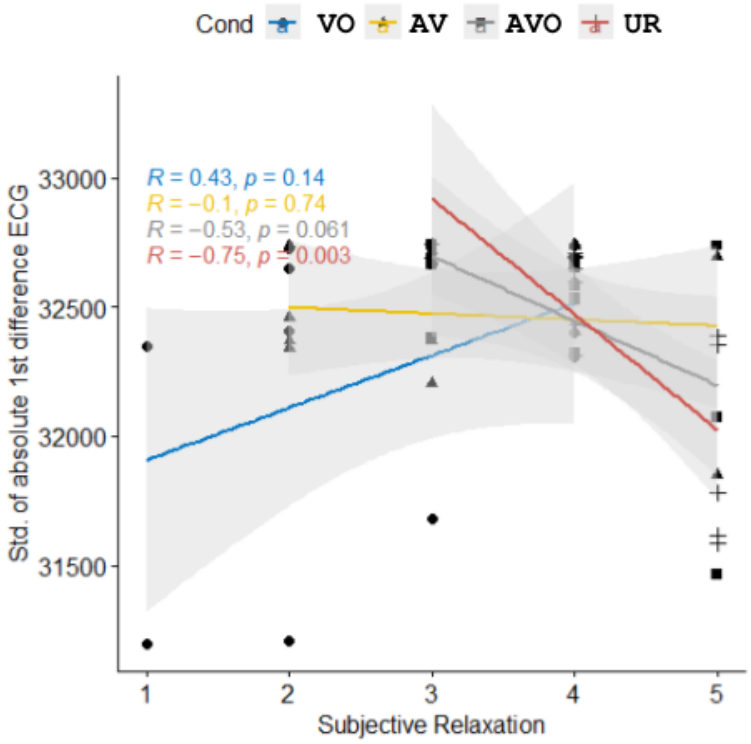


FIGURE 3.8 : Scatter plot for standard deviation of the absolute 1st difference of the ECG and the correlation achieved with the subjective relaxation rating for each condition.

used as an alternative to nature walks for those with, e.g., mobility issues, and (2) that wearables could potentially be used to monitor, in real-time, stress states and allow for biofeedback to change the multisensory scene to customize the experience per user.

4 MULTISENSORY VR EXPERIENCES IN REALISTIC ENVIRONMENTS : A USE CASE WITH NURSES IN A MENTAL HEALTH INPATIENT WARD

4.1 Preamble

This chapter contains material extracted from the manuscript published in the journal Frontiers in Virtual Reality (Lopes et al., 2024b) and in the 16th International Conference on Applied Human Factors and Ergonomics (AHFE 2025) (Lopes et al., 2025a).

4.2 Introduction

Here, we conduct a study in which we monitor both EEG and HRV responses while participants are immersed in a VR nature scene under two conditions : audio-visual only (AV) and audio-visual-olfactory (AVO). Participants are comprised of nurses from a mental health in-patient ward. Nurses have been notably challenged by high-stress levels and demanding environments during the pandemic (Riedel et al., 2021; Spoorthy et al., 2020), demands which have persisted post-pandemic. The protocol consists of brief immersive exposures to 360-degree natural scenes with counterbalanced conditions. Alongside subjective relaxation restoration and quality of experience (QoE) ratings, we compute EEG-derived biomarkers (e.g., valence, arousal, attention, engagement, mental workload, and subband powers) and HRV metrics (time-domain, frequency-domain, and non-linear). This combined view allows the chapter to report not only whether multisensory cues improve perceived relaxation, but also whether they produce measurable physiological shifts and whether these shifts track participants' reported experience.

4.3 Materials and methods

4.3.1 Participants

Twenty-seven nurses (16 females, mean age 40.5 ± 10.4 years old) from the mental health in-patient ward at Michael Garron Hospital (MGH) participated in a one-on-one study session (lasting approximately 30 minutes) during their work shifts from September 23rd to September 28th, 2022. All participants agreed to participate in this experiment, which was approved by the MGH and INRS Ethics Committees. As an exclusion criterion, after a preliminary interview, data were not collected from participants who had a pacemaker or a history of epilepsy or seizures to avoid

contraindications with VR device manufacturers. In addition, participants who had lost their sense of smell (as a result of COVID-19, for example) were screened out. For those who wore prescription glasses during the experiment, we adjusted the focus of the VR glasses to ensure that the scene seen through their glasses was clear. In particular, as the experiments were done at MGH, special COVID-19 safety measures were followed, including social distancing, sanitizing the VR headset and wearable devices with alcohol wipes, and placing the VR headset into a UV-C box custom-built for VR headsets (Cleanbox Technology, USA).

4.3.1.1 Modality-specific analytic samples

Twenty-seven nurses completed the protocol. Due to signal-quality constraints, analyses are reported on modality-specific samples. EEG analyses use 22 participants' data after excluding five participants (three acquisition issues; two early terminations due to odor sensitivity). PPG-derived HRV analyses use 14 participants' data due to PPG signal loss affecting thirteen participants (notably headset–forehead contact issues, especially for participants wearing glasses). Accordingly, all EEG and HRV results are interpreted within their respective analytic samples and are not assumed to reflect identical participant sets.

4.3.2 Experimental design

The study took place in a nursing break room, where only two evaluators who conducted the experiment and the participant were present in the room. Figure 4.1 outlines the flow diagram of the experimental process, which alternated between questionnaires and VR exposure sessions. Participants selected one of three 360-degree natural scenes (i.e., beach, lake, or forest) to experience twice : once with only AV elements, and again with an added olfactory component (AVO condition). Given the limited availability of nurses during their work shifts, it was necessary to optimize the duration of the experiment. Including setup, administration of questionnaires, and interviews, this constraint allowed for only one scenario per participant. To ensure that most of the fragrance was dispersed, a window was opened before and between conditions and then closed. To reduce biases, the ordering of the AV and AVO conditions was randomized among participants. Each VR session/condition lasted 2 minutes and 30 seconds, totaling 5 minutes of VR interaction. The primary objective was to assess the effect of VR on relaxation, as well as to contrast the results between the two conditions. After concluding the VR exposure and removing the HMD, participants completed a concluding questionnaire. This feedback is invaluable to refine the protocol for future applications targeting patients.

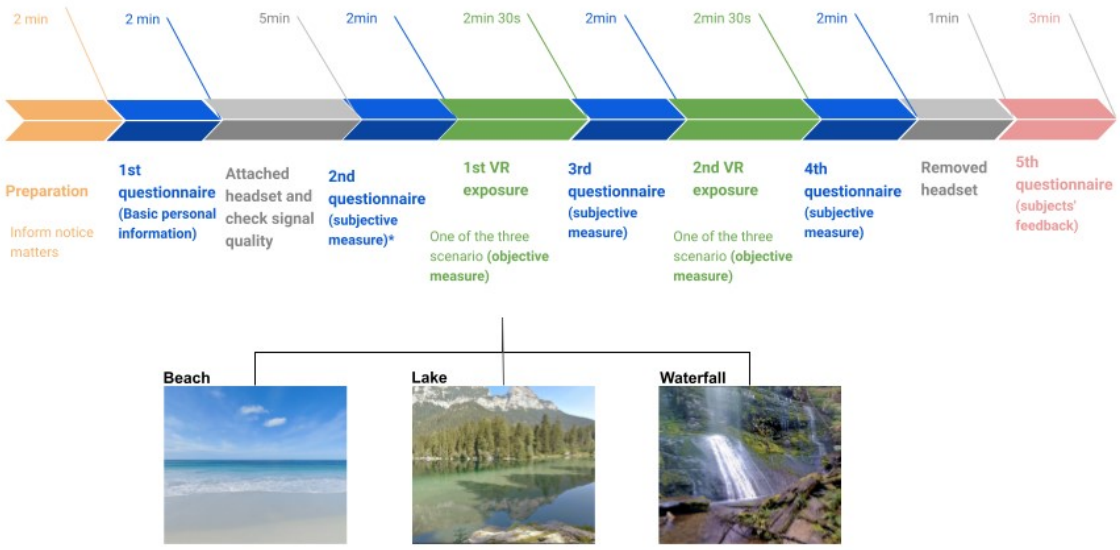


FIGURE 4.1 : Flow diagram of experiment. The $*$ in the figure means the question was just about the relaxation level.

4.3.3 Hardware

The experiment used an in-house instrumented Meta Oculus Quest 2 HMD. The headset comprises a single Fast-Switch LCD panel, providing a resolution of 1832×1920 pixels per eye with a default refresh rate of 72Hz, which can be adjusted to 60Hz when needed. The HMD was instrumented with electroencephalogram (EEG), electrooculogram (EOG), and photoplethysmogram (PPG) sensors, following advice from Cassani et al. (2020), as depicted by Figure 4.2a.

OpenBCI Cyton and Daisy bioamplifiers (OpenBCI, USA) were used to acquire 16 ExG signals. The board was placed inside a 3D-printed case attached to the top of the HMD (see Figure 4.2c). The instrumented headset allowed for the measurement of EEG data in real-time at a sample rate of 125Hz. A total of 11 EEG channels were collected from the sensors placed on the foam and straps of the headset at the 10-20 locations Fp1, Fpz, Fp2, F3, F4, C3, C4, P3, P4, O1, and O2, as shown in Figure 4.2b. These locations have been shown in the literature to be related to stress/anxiety or relaxation (Ganguly et al., 2019; Davidson et al., 2003; Field et al., 1998; Kosunen et al., 2016; Parent et al., 2020).

To diffuse smells, an OVR ION2 scent diffusion device (OVR Technologies, USA) was attached to the HMD to provide an olfactory stimulus by dispersing aromas close to the user's nose (see Figures 4.3, 4.4, and 4.6). The employed scent kit contains a predefined cartridge with nine different scents. In this study, we used the Nature cartridge, which has scents : flowers, earth dirt, forest, ocean breeze, grass, wood, beach, lavender, and citrus.

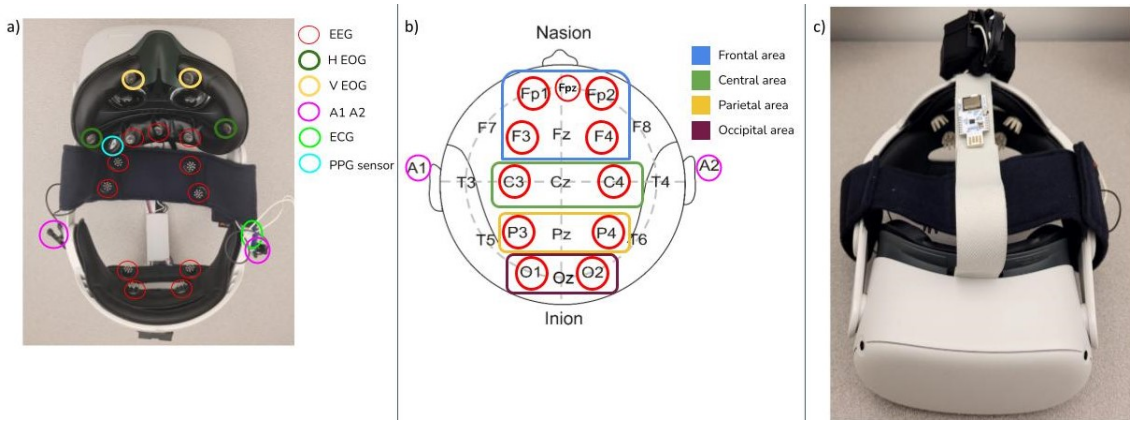


FIGURE 4.2 : a) Electrodes from the instrumented HMD and their respective modalities. b) EEG electrode positions and associated scalp areas. c) In-house developed instrumented head-mounted display.

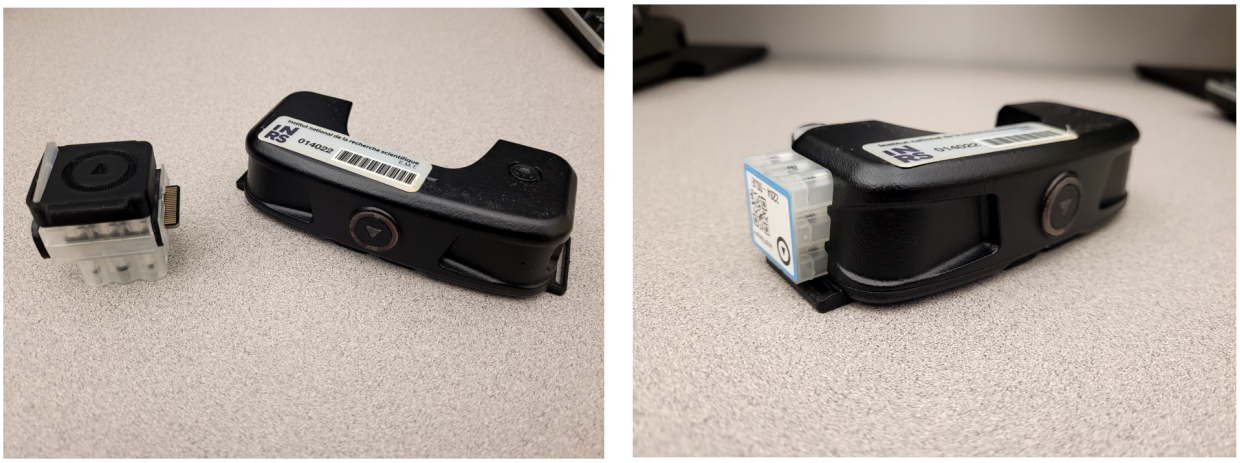


FIGURE 4.3 : OVR ION 2 scent diffusion device.

4.3.4 Virtual environments

An application was developed, as depicted in Figure 4.5, where participants were offered a choice among three 360-degree nature videos. The first scene transports the viewer to the Alpine Lake-wide in Bavaria, Germany, where they find themselves in front of a serene lake with distant mountains and cabins. Trees and rocks complete the surrounding landscape. The second scene places the participant on the Arctic Beach in the Lofoten Islands, Norway, with fine white sand underfoot and a view of a turquoise sea, distant mountains, and a blue sky with few clouds. The third video immerses the viewer in a forest setting in Tasmania, Australia, with a prominent waterfall cascading over rocks and logs, surrounded by moss-covered rocks and trees whose leaves sway with the breeze. Accompanying these visuals, for the audio stimuli, original audio from the videos delivered authentic nature sounds such as waves, birdsong, and rustling leaves. All videos were sourced and licensed from the Atmosphaeres Library [1].

1. https://www.atmosphaeres.com/

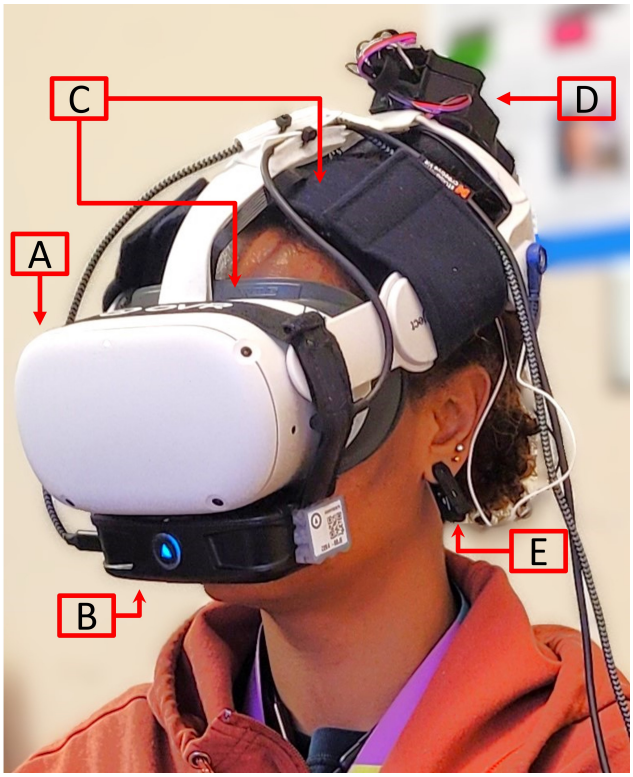


FIGURE 4.4 : Equipment used including (A) VR headset,(B) ION 2 device, (C) ExG electrodes (not shown), (D) bioamplifier, and (E) reference electrodes.

Using the ION2 scent diffuser, different aromas were used for each scene. For the lake scene, smells of flowers, earth dirt, forest, and grass were diffused. This combination was also utilized for the waterfall scene, but complemented by the scent of wood. For the beach scene, scents called beach and ocean breezes were used. Intensities were kept at a level of 1 out of 5, as this was a hospital setting. The timing of the scent dispersion was the same across the three videos to avoid any biases.

4.3.5 Questionnaires

Questionnaires were used to explore participants' psychological state and their general experience and observations throughout the procedure. Questionnaires were presented five times, as shown in Figure 4.1. The first was to collect demographic data, including gender and age. The second asked participants to rate their current relaxation level on an eleven-point Likert scale, where scores ranged from 0 (very low) to 10 (very high). This was filled out once the participant chose their preferred VR environment. The third questionnaire was after the first VR exposure and had users rate not only their relaxation level, but also other so-called quality of experience (QoE), such as their sense of engagement and sense of immersion, if they had forgotten everyday concerns, lost track of time, and felt any motion sickness. These all relied on the 11-point Likert scale.



FIGURE 4.5 : The developed application's main scene, where participants could choose the three nature scenes.

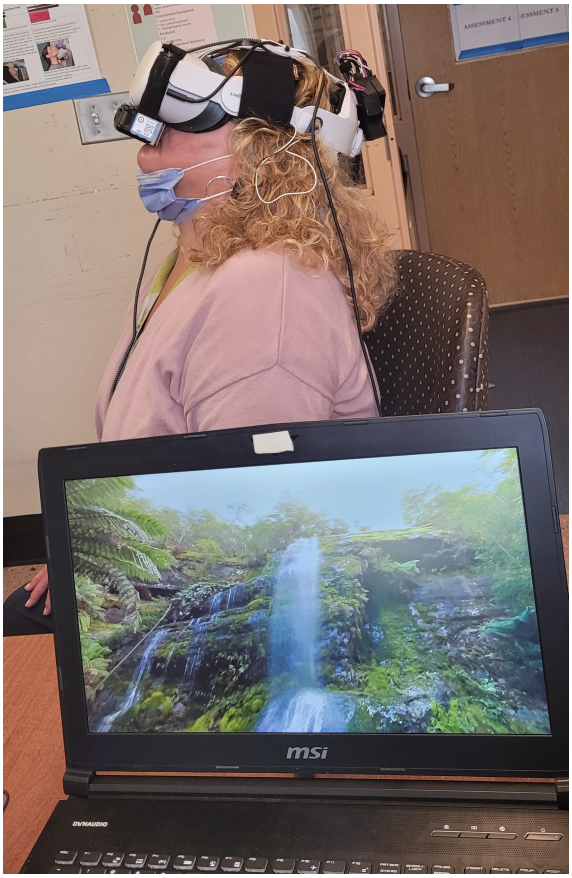


FIGURE 4.6 : The experiment in progress with one nurse who chose the waterfall scene.

TABLE 4.1 : Questions asked at the end of the experiment

Feedback questions
How long would you say you were in the VR?
Did you realize that in one exposure you had smells, and in the other there was no smell?
Did you prefer the experience with or without smell? Why or why not?
Did the smell mimic the environment realistically? Was it appropriate?
How would you describe the overall experience? - difference senses - the strength - volume - realism
Consistency with the real world experience (from 1 to 10).
Did you feel the experience met the general aim (providing relaxation)?
Do you think that you would like to use VR with your patients?
What challenges do you see with administering VR with your patients?
What might you suggest to make the session more effective?
What are some measurable outcomes we could evaluate that would indicate success of VR in your patient population?
Is there anything else you would like to share about your experience?

Before starting the second VR exposure, participants reassessed their new pre-exposure relaxation levels. After the second exposure, the same battery of questions was then asked about their experience. Upon completion of these questionnaires within the virtual environment, the HMD was removed, and a final questionnaire was presented to the participants asking about their overall experience. Here, participants were asked for insights and suggestions to refine the protocol, especially for its potential application in future experiments involving individuals with mental health disorders. The specific questions asked are shown in Table 4.1.

4.3.6 PPG pre-processing and feature extraction

For the HRV metrics calculation, the PPG signals were first pre-processed using a singular value decomposition (SVD) technique for motion artifact removal. First, a bandpass filter from 0.5 Hz to 4.0 Hz was applied, then the Short-Time Fourier Transform (STFT) was computed as a complex matrix, which was then decomposed via SVD. SVD components deemed as outliers are discarded prior to an inverse STFT being performed. More details about this pre-processing step can be found in Rojano et al. (2016). Next, several time, frequency, and non-linear HRV measures were computed from the PPG signals. Table 4.2 summarizes all the extracted features per domain. HRV measures were computed over the entire 2.5-minute session, as well as during the first and last minute of each session, to gauge the temporal changes that occurred during each condition.

4.3.7 EEG pre-processing and feature extraction

All neurophysiological data were synchronized with application events using the Lab Stream Layer (LSL). To prepare the EEG signals for feature extraction, a 'minimal' pre-processing pipeline was used, inspired by recent findings from (Delorme, 2023) suggesting that discriminative information may be removed from the EEG data via certain pre-processing algorithms. As this is the first experimentation with EEG and multisensory experiences with the instrumented headset, we chose

TABLE 4.2 : List of extracted HRV for each domain

Domain	Features
Time-Domain	Heart rate (HR), Interbeat interval (IBI), Standard deviation of RR intervals (SDNN), Standard deviation of successive differences (SDSD), Root mean square of successive differences (RMSSD), Successive differences above 50ms (NN50), Proportion of successive differences above 50ms (pNN50)
Frequency Domain	Low-frequency spectrum between 0.05-0.15Hz (LF), High-frequency spectrum between 0.15-0.5Hz (HF), High frequency / low frequency ratio (HF_LF), Normalized LF (nLF), Normalized HF (nHF)
Non-linear Domain	Standard deviation perpendicular to identity line (SD1), Standard deviation along identity line (SD2), SD1/SD2 ratio (SD1_SD2)

TABLE 4.3 : List of six metrics used as proxies for different mental/cognitive/affective states

Engagement score	$ES = \frac{2*\beta_{mean}}{\alpha_{mean}+\theta_{mean}}$
Valence index	$VI = \frac{\alpha_{F4}}{\beta_{F4}} - \frac{\alpha_{F3}}{\beta_{F3}}$
Attention	$Attention = \frac{2}{\alpha_{F3}+\alpha_{F4}}$
Arousal index	$AI = \frac{\beta_{F3}+\beta_{F4}}{\alpha_{F3}+\alpha_{F4}}$
Frontal alpha asymmetry	$FAA = ln(\alpha_{F4}) - ln(\alpha_{F3})$
Mental workload	$MW = \frac{\alpha_{P3}+\alpha_{P4}}{\theta_{F3}+\theta_{F4}}$

to modify the signals the least possible. Thus, a notch filter was applied to remove the 60 Hz power line noise. Next, high-pass filtering with a zero-phase Butterworth filter set to a cutoff frequency of 0.25 Hz was used to eliminate low-frequency drifts. Finally, signals were segmented into 2-second epochs without overlap for feature extraction. It is important to emphasize that by using this minimal pre-processing pipeline, data from Fp1, Fp2, and Fpz remained very noisy. In our analyses, these electrodes are hence discarded, resulting in only eight EEG channels for analysis.

For features, normalized power spectral measures were computed for the five conventional EEG subbands, namely : delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–45 Hz), thus resulting on 40 power measures (8 channels $\times$ 5 bands). Normalization was achieved with the total EEG power. These features have been widely used in the literature for human emotional state monitoring (Saidatul et al., 2011; AlShorman et al., 2022; Sulaiman et al., 2011; Wen et al., 2020; Ko et al., 2009; Mahajan, 2018). In addition to the subband power features, six other metrics that measure different affective, cognitive, and mental states were computed, as highlighted in Table 4.3. These included metrics of engagement, valence, arousal, attention, mental workload, and withdrawal (given by the frontal alpha asymmetry metric, FAA) (Pope et al., 1995; McMahan et al., 2015; Myrden et al., 2017; Holm et al., 2009; Zhang et al., 2018).

4.3.8 Regression

In this study, linear regression analysis was used to assess changes in the above-listed markers throughout the AV and AVO sessions to check if positive, negative, or null trends could be observed. The analysis was done using MATLAB's (R2021A, MathWorks, Natick, Massachusetts, USA) fitlm function. The goal of this analysis is to explore the impact of the AV and AVO experiences on the measured neuromarkers, compare the differences seen between the two conditions, and potentially find the optimal markers to automatically track relaxation states during VR immersion. To test the significance of the trends, a Wald test was performed.

4.4 Results and discussion

For the EEG analysis of the results, data from five participants had to be removed; three of them due to problems with the signal acquisition, and two of them asked to stop the experiment due to sensitivity to the smells. Due to connectivity issues and signal loss, the PPG analyses are based on data from only fourteen participants; data from thirteen participants were excluded, particularly those who wore glasses, since this often prevented proper headset contact with the forehead.

4.4.1 Subjective results

Figure 4.7 depicts the average ratings reported for the relaxation level. Figure 4.7a shows the rating before (called baseline in the figure) and after the VR interventions for the AV and AVO conditions. In this graph, all participants were grouped without distinguishing the scenarios. In Figure 4.7b, we separate the participants by scenario, so we can see the influence of different environments and odors. After performing a Shapiro-Wilk test to check the normality of the distributions, the Wilcoxon signed-rank test was used to compare the significance of the differences. As can be seen, using all participants, we have a significant difference between baseline and post-intervention, with $p \leq 0.01$. The comparison between exposure did not show a significant difference.

For the separate scenarios analysis, the baseline and AV condition shows significant difference ($p \leq 0.01$) for the Lake scenario. For the Waterfall scenario, the baseline and AVO also show a significant difference ($p \leq 0.001$). For both scenarios combined (Lake and Waterfall), the AVO average relaxation value is greater than in the AV condition. On the other hand, for the Beach scenario, none of the conditions show significant differences with the baseline. The AV condition showed a higher average relaxation value compared to the AVO condition.

Furthermore, the Wilcoxon signed-rank test was performed to investigate the significance of the differences reported in the QoE ratings. The following values were found :

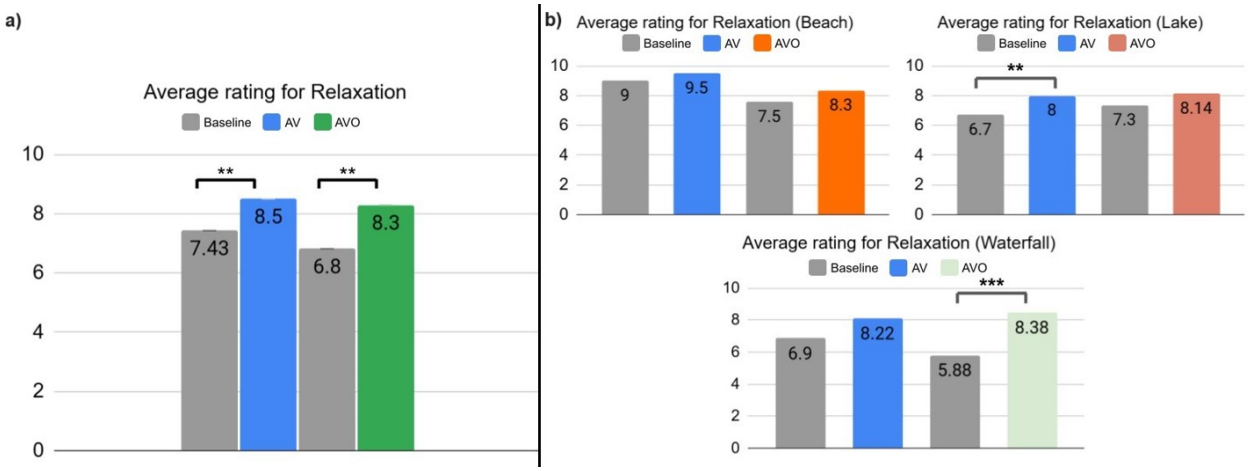


FIGURE 4.7 : Results average of relaxation ratings. a) Average rating of all subjects. b) Average rating per scenario. Beach scenario : 6 participants. Lake scenario : 7 participants. Waterfall scenario : 9. ** - p $\leq$ 0.01, * - p $\leq$ 0.001**

TABLE 4.4 : Results of comparative analysis for the AV and AVO conditions. The reported p-values are from a Kruskal-Wallis test to measure significance between the three different scenarios for each AV and AVO condition.

QoEs	Beach AV	Lake AV	Waterfall AV	Beach AVO	Lake AVO	Waterfall AVO	AV p-value	AVO p-value
Senses Engagement	9.67 $\pm$ 0.82	8.00 $\pm$ 1.91	7.50 $\pm$ 1.37	8.33 $\pm$ 1.86	8.50 $\pm$ 1.44	8.17 $\pm$ 1.37	0.031*	0.941
Sense of Immersion	9.00 $\pm$ 1.55	7.14 $\pm$ 2.34	8.22 $\pm$ 1.39	8.17 $\pm$ 1.60	7.50 $\pm$ 1.76	8.22 $\pm$ 1.20	0.243	0.536
Forgot Everyday Concerns	8.00 $\pm$ 4.00	7.86 $\pm$ 1.68	8.78 $\pm$ 1.30	7.33 $\pm$ 2.42	7.14 $\pm$ 3.39	8.67 $\pm$ 1.00	0.398	0.455
Lost Track of Time	7.83 $\pm$ 4.02	7.71 $\pm$ 2.43	7.33 $\pm$ 2.92	6.33 $\pm$ 3.72	7.79 $\pm$ 2.38	7.78 $\pm$ 1.20	0.57	0.733
Motion Sickness	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.00 $\pm$ 0.00	0.33 $\pm$ 0.82	0.57 $\pm$ 1.51	0.11 $\pm$ 0.33	N/A	0.925

— Senses engagement : AV (M = 8.25 SD = 1.66); AVO (M = 8.32 SD = 1.47),
— Sense of immersion : AV (M = 8 SD = 1.85); AVO (M = 8 SD = 1.47),
— Forgot everyday concerns : AV (M = 8.27 SD = 2.33); AVO (M = 7.82 SD = 2.36),
— Lost track of time : AV (M = 7.6 SD = 2.9); AVO (M = 7.4 SD = 2.4), and
— Motion sickness : AV (M = 0 SD = 0); AVO (M = 0.32 SD = 0.95).

None of these differences were found to be significant.

Table 4.4 further lists the reported QoE ratings separated by the scenarios for each condition. Using a Kruskal-Wallis test, we can see in that only the senses engagement for the AV condition shows a significant difference between scenarios ($p \leq 0.05$).

In both conditions, all participants felt significantly more relaxed after the AV and AVO exposures, despite the differences between the AV and AVO conditions not being significant. Similar results were observed with the QoE ratings. Notwithstanding, when analyzing the results per scenario, some interesting differences could be observed. For example, most participants who experienced the beach scenario reported lower relaxation ratings in the AVO condition, while those who experienced the other two scenarios reported higher relaxation ratings in the AVO condition. These results show the power of multisensory experiences in influencing our levels of relaxation and other experiential factors, as further discussed next.

As mentioned above, the beach scene was the only one in which the AVO condition resulted in poorer relaxation levels compared to the AV setting. Similarly, for the QoE ratings in the lake and waterfall scenarios, the AVO condition resulted in a greater sense of engagement, sense of immersion, and participants losing track of time, as compared to the AV condition.

Further investigation into the unexpected behavior seen in the beach scene suggests this could be related to the idiosyncratic interpretation of smells and non-congruence with expectations. For example, participants mentioned they were expecting a tropical beach and related smells (one mentioned the smell of sunblock lotion), while the actual presented video and smells represented that of a more Arctic beach. Candid feedback from the participants included : *"The smell did not agree with the reality of their beach scene. It should be more salty and sandy, not very sweet as this one was"*.

In turn, for the waterfall and lake scenarios, the smells more closely matched what was expected. Candid feedback from some of the users in these two scenarios included : (1) *"In the first section (without the smell) it was pretty. I could only hear the waterfall. However, in the second one, the smell made the experience more real. It took me back to when I was there (in a waterfall). All my senses were engaged."*, (2) *"I know it is virtual, but I did feel I was sitting in front of the waterfall"*, and (3) *"smells were a good addition to the virtual experience"*.

4.4.2 Objective results

Table 4.5 shows the result of a linear regression analysis for the conditions AV and AVO for the five different EEG subbands, per electrode. In this analysis, the slope direction is reported to show if EEG subband powers are increasing or decreasing (significantly) during the exposure. One, two, or three asterisks are used to indicate the significance levels, i.e., 95%, 99%, and 99.9%, respectively. As we used a minimal pre-processing pipeline, we had to discard three electrodes (Fp1, Fpz, and Fp2) due to the large amounts of artifacts. As can be seen from the Table 4.5, most electrodes presented statistically significant drops over the exposure for both AV and AVO conditions. This can be interpreted differently for each band and brain area.

In particular, the delta band presented significant negative slopes across both conditions, except for the central left region in the AVO condition. Overall, more significant drops were observed in the AVO condition. In turn, an increase in frontal (F3) theta power was only seen in the AV condition, while most other regions showed a significant decrease. The beta band shows decreased activity in many channels across both conditions, while alpha power showed decreasing trends for most electrodes in the AVO condition, but only on half of the channels in the AV condition. Lastly, although most of the slopes presented in the gamma band were negative, for some regions, such as the left parietal and central regions, a strong positive significance was seen for the AV condition, while a negative slope was seen with the AVO condition.

TABLE 4.5 : Linear regression slope direction and significance. * - p $\leq$ 0.05, ** - p $\leq$ 0.01, * - p $\leq$ 0.001**

Electrode	delta		theta		alpha		beta		gamma	
	AV	AVO	AV	AVO	AV	AVO	AV	AVO	AV	AVO
F3	$\uparrow$	$\uparrow$	$\uparrow^{*}$	$\downarrow$	$\uparrow$	-	$\uparrow$	$\downarrow^{***}$	-	$\uparrow^{***}$
F4	$\downarrow^{**}$	$\downarrow$	-	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{**}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$
P3	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{**}$	$\downarrow^{**}$	$\uparrow^{**}$	$\downarrow^{***}$	$\uparrow$	-	$\uparrow^{***}$	$\downarrow^{***}$
P4	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow$	$\uparrow$	$\uparrow$	-	$\uparrow$	$\downarrow^{*}$	$\uparrow$	$\downarrow^{***}$
C3	$\downarrow^{*}$	$\uparrow^{***}$	$\uparrow$	$\downarrow^{***}$	$\uparrow$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$	$\uparrow^{***}$	$\downarrow$
C4	$\downarrow^{**}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{*}$	$\downarrow^{*}$	$\downarrow^{**}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{**}$	$\downarrow^{***}$
O1	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$
O2	$\downarrow^{***}$	-	$\downarrow^{***}$	$\downarrow$	$\downarrow^{*}$	$\uparrow$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{***}$	$\downarrow^{*}$

A Mann-Whitney U test with Holm-Bonferroni correction was performed between the AV and AVO conditions across each EEG channel. Significant differences were observed in channels F3, C3, P4, and O1 for delta; F4 and P4 for theta; C4 and F4 for alpha; C4, F4, C3, and O2 for beta; and F3, F4, C3, C4, and O2 for gamma.

A Kruskal-Wallis test with Holm-Bonferroni correction was employed to observe differences across EEG channels under the three scenarios within the AV and AVO conditions. In the AV condition, statistically significant differences were noted across the following channels : C4, F4, O2, P3, and P4 for delta; C4, F3, O2, P3, and P4 for theta; C3, C4, and P4 for alpha; C4, F4, O2, and P4 for beta; and C4, F3, F4, O1, O2, P4 for gamma. In the AVO condition, significant differences were detected in channels C3, C4, F3, F4, and O2 for delta; C4, O2, and P4 for theta; C3, C4, F3, and O2 for alpha; C4, O1, P3, and P4 for beta; and C3, C4, F3, F4, O1, and P4 for gamma.

Next, we explore the changes seen with the six metrics tested as proxies for mental/ cognitive/ affective states, as listed in Table 4.3. Mann-Whitney U test analysis between the AV and AVO was performed. The attention feature shows a significant difference ($p \leq 0.001$) between the AV (M = 0.25, SD = 1.44) and AVO (M = -0.055, SD = 1.60) conditions. The FAA metric presented a significant difference ($p \leq 0.001$) between both conditions, with a negative mean (M = -0.16, SD = 1.48) in the AV session and a positive mean (M = 0.47, SD = 2.74) in the AVO session. The engagement index also showed a significant difference ($p \leq 0.003$) between the two conditions, with (M = -0.03, SD = 1.58) for AV and (M = 0.27, SD = 1.93) for AVO. The valence, arousal, and mental workload metrics did not demonstrate significant differences between AV and AVO conditions.

As reported in Table 4.5, the delta band presented a negative slope in most electrodes. Typically, the delta band is associated with meditation or sleep in resting states. In fact, Teplan et al. (2014) demonstrated that a reduction in delta power correlated with successful relaxation. Other studies have also shown that a decrease in delta could be related to increased motivation (Cowley et al., 2014).

Moreover, changes in theta band powers have been associated with attention or cognitive load, with a reduction in theta power indicating a reduced level of attention (Sowndhararajan et al., 2016). The work by (Cahn et al., 2010) showed an increase in frontal theta power during meditation, as well as a significant increase in parieto-occipital gamma power. In the present study, only frontal (F3) theta power showed an increase, and for most other regions, results showed a significant decrease. Decreases in theta powers have also been linked with positive valence or pleasantness (Reuderink et al., 2013); this could explain the changes observed herein.

The fact that we are relying on VR in our study could also have an impact on EEG beta band activity. In (Tarrant et al., 2018), for example, a VR natural environment was used for mindfulness practice, and decreased beta activity was observed. Beta activity is linked to active thinking and alertness. In our obtained results, the decreases in beta activity across many channels in both sessions suggest a general decrease in active cognitive processing or a shift towards a more relaxed state. On the other hand, increases in alpha powers have been linked to increasing emotional arousal (Reuderink et al., 2013). Comparing the results from the alpha and theta changes, one can observe a decrease in arousal and an increase in pleasantness, thus moving towards a calmer and more relaxed emotional state.

Gamma activity has been associated with high-level cognitive (Fitzgibbon et al., 2004) processing and sensory integration, thus corroborating the fact that the majority of the channels showed significant changes. In fact, the work in (Zhang et al., 2019) showed the importance of gamma activity for odor recognition, indicating a strong relationship between olfactory processing and gamma band activity in the brain. This may explain the more significant changes seen in gamma band activity with the AVO condition relative to the AV one.

Moreover, the attention feature showed a significant difference between the AV and AVO conditions, suggesting changes in visual attention once additional sensory cues were provided. The FAA metric also had a significant difference between the two conditions. The negative mean in the AV session and positive mean in the AVO session indicate a shift from a withdrawal tendency to a greater approach tendency (Goodman et al., 2013) with the AVO experience.

The engagement index also showed a significant difference between the two conditions, with a negative mean for AV and a positive mean for AVO, which is consistent with the higher immersion and sense engagement reported by the participants. The participants' feedback included : (1) *"More senses were activated making the experience more engaging and increasing the sense of presence"*, (2) *"I preferred the multisensory experience because I could engage with the environment better. I think the smell is a smooth smell and it makes me relax better".* and (3) *" It is great. I have not tried VR before, with smells being more engaging and more relaxing. I wanted to stay there longer".*

To better visualize the changes in neural patterns, a topographical plot visualization is used. In this analysis, we group the subjects into two groups : those who reported improvements in relaxation with VR exposure and those who did not. Figure 4.8 shows the alpha band topoplots for

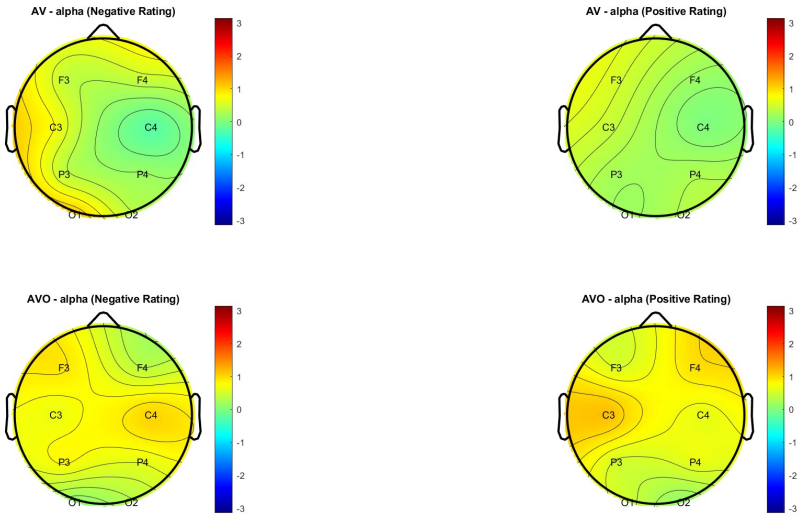


FIGURE 4.8 : Topoplot of alpha band distribution. Positive and negative relaxation ratings for AV and AVO sessions.

the “negative” group (i.e., did not show improvements in relaxation) on the left and the “positive” group (i.e., those that showed increased relaxation) on the right. The top plots are for the AV condition, and the bottom plots are for the AVO. As can be seen, for the AVO conditions, the asymmetry in alpha bands inverts from left to right hemispheric dominance. This is corroborated by the FAA metric, which showed a significant difference with (M = -0.125, SD = 1.62) for the ‘negative’ group and (M = 0.24, SD = 1.77) for the ‘positive’ group.

When analyzing the results shown in Figure 4.8, it can be observed for the AVO condition that the shift in the alpha band asymmetry occurred between the negative and positive groups, which is suggestive of the withdrawal and approach patterns reported in the literature (more on this below). This interhemispheric asymmetry is not as pronounced in the AV-only condition, suggesting some differences in neural patterns between AV and AVO conditions.

As mentioned previously, the withdrawal behavior is likely due to the non-congruence of the expected smells, especially with the beach scenario. This highlights the importance of customizing experiences on a per-user basis to minimize such issues. In addition, our results corroborate those by (Park et al., 2011), where positive emotional information was reflected in a decrease in alpha power of the left frontal hemisphere, while the processing of negative emotional information was reflected by the decrease of alpha power over the right frontal hemisphere (Reuderink et al., 2013).

Overall, these findings suggest that indeed there are neural differences between the AV and AVO conditions, and several traditional metrics are sensitive enough to detect these changes. It is hoped that these insights can lead to improved interventions, such as neurofeedback nature immersion tools, that can help patients and nurses better manage their stress levels.

Next, we examine the changes observed in the objective HRV metrics, beginning with a comparison of the first and last minutes of the experiences, as outlined in Table 4.6. Time-domain metrics consistently showed reductions in HRV over time in both AV and AVO conditions, suggesting increased physiological arousal as the experiment progressed. Notably, RMSSD and NN50, both markers of parasympathetic activity, showed pronounced declines in both conditions. This trend was particularly marked in the AVO condition, where reductions were associated with large effect sizes. Such findings suggest that the addition of olfactory stimuli in the AVO condition may amplify physiological arousal compared to the AV condition.

Frequency-domain metrics displayed greater variability compared to time-domain measures. LF Power and HF Power exhibited opposite trends in AV and AVO conditions. Specifically, AV showed slight increases in both LF and HF power, whereas AVO displayed decreases in these measures. The LF/HF ratio showed minimal changes in both conditions, with slightly higher values in AVO. This observation suggests that the addition of olfactory stimuli may cause participants to experience greater arousal or engagement compared to the AV condition, although the short time windows used for frequency-domain analysis may limit the reliability of these measures.

The SD1 and SD2 showed a consistent decline in both conditions, reflecting reduced variability and short-term parasympathetic activity. The decline in SD1 was more pronounced in the AVO condition, suggesting a more substantial impact on parasympathetic withdrawal when adding olfactory stimuli. This may result from increased engagement due to added sensory input or from stimulus incongruence, as some participants reported a mismatch between smell and the beach scenario.

The Spearman correlation analysis revealed significant relationships between objective physiological metrics and subjective ratings for both the AV and AVO conditions over the full 2.5-minute signal duration. In the AV condition, the significant correlations are listed in Table 4.7, while the significant correlations for the AVO condition are shown in Table 4.8. Notably, the LF_HF ratio was positively correlated with “Relaxation (post minus pre)”; however, this correlation was not statistically significant.

Significant changes in HRV metrics were observed between the first and last minutes of both conditions. AV and AVO conditions exhibited reductions in Mean_IBI, SDNN, RMSSD, SDSD, NN50, pNN50, and SD1, coupled with an increase in HR. The AVO condition also demonstrated significant reductions in the SD1_SD2. These changes indicate a consistent decline in short-term HRV and parasympathetic activity over time, which may reflect increased engagement and attentional focus as the VR session progresses. The substantial effect sizes (e.g., Cohen’s d values ranging from 0.60 to 0.76) further emphasize the physiological significance of these changes.

The reduction in variability measures, such as RMSSD and SDSD, alongside decreases in NN50, pNN50, and SD1, reflect decreased parasympathetic activity and increased sympathetic dominance. Despite the VR experience involving nature VR experiences with the goal to promote relaxation, participants also reported high levels of engagement, presence, and immersion. This

TABLE 4.6 : Slope direction and significance for HRV metrics. *p $\leq$ 0.05, **p $\leq$ 10-2, ***p $\leq$ 10-3

Metric/ Units	AV slope (Cohen's d value)	AV First Minute	AV Last Minute	AVO slope (Cohen's d value)	AVO First Minute	AVO Last Minute
HR (bpm)	$\uparrow^{**}$ (-1.09)	74.43 $\pm$ 5.7	76.7 $\pm$ 5.66	$\uparrow^{*}$ (-0.67)	74.03 $\pm$ 5.11	75.78$\pm$ 5.75
Mean_IBI (ms)	$\downarrow^{**}$ (1.04)	810.65 $\pm$ 63.5	786.45 $\pm$ 59	$\downarrow^{*}$ (0.64)	806.34 $\pm$ 61.57	789.2 $\pm$ 63.13
SDNN (ms)	$\downarrow^{*}$ (0.76)	87.87 $\pm$ 40.6	65 $\pm$ 25.08	$\downarrow^{*}$ (0.8)	76.49 $\pm$ 30.1	52.83 $\pm$ 19.8
RMSSD (ms)	$\downarrow^{**}$ (0.93)	129.52 $\pm$ 62	88.6 $\pm$ 45.6	$\downarrow^{**}$ (1.02)	116.98 $\pm$ 51.7	68.12 $\pm$ 30.9
SDSD (ms)	$\downarrow^{**}$ (0.93)	129.51 $\pm$ 61	88.6 $\pm$ 45.6	$\downarrow^{**}$ (1.02)	116.97 $\pm$ 51.7	68.09 $\pm$ 30.96
NN50	$\downarrow^{**}$ (0.85)	39.38 $\pm$ 12.69	28.1 $\pm$ 12.8	$\downarrow^{*}$ (0.85)	35.0 $\pm$ 7.69	26.1 $\pm$ 11.45
pNN50 (%)	$\downarrow^{**}$ (1.05)	52.9 $\pm$ 14.8	35.6 $\pm$ 16.8	$\downarrow^{**}$ (0.94)	49.25 $\pm$ 11.94	36.39 $\pm$ 16.99
LF_Power (ms2)	$\downarrow$ (-.027)	188 $\pm$ 139.8	225 $\pm$196	$\downarrow$ (0.55)	259.6 $\pm$ 215.9	167 $\pm$ 143.7
HF_Power (ms2)	$\downarrow$ (-0.007)	235 $\pm$ 184	236.5 $\pm$ 162	$\downarrow$ (0.45)	401.6 $\pm$ 304.3	226.2 $\pm$ 190
LF_HF	$\uparrow$ (-0.13)	0.75 $\pm$ 0.51	0.86 $\pm$ 0.72	$\uparrow$ (-0.14)	0.85 $\pm$ 0.78	1.07 $\pm$ 1.09
nLF	$\uparrow^{*}$ (-0.66)	1.7e-3 $\pm$ 1e-3	3e-3 $\pm$ 3e-3	$\uparrow$ (-0.4)	2e-3 $\pm$ 2e-3	4e-3 $\pm$ 3e-3
nHF	$\uparrow$ (-0.36)	2e-3 $\pm$ 1e-3	3e-3 $\pm$ 2e-3	$\uparrow$ (-0.21)	4e-3 $\pm$ 2e-3	1e-2 $\pm$ 4e-3
SD1 (ms)	$\downarrow^{**}$ (0.93)	91.6 $\pm$ 43.5	62.6 $\pm$ 32.3	$\downarrow^{**}$ (1.02)	82.7 $\pm$ 36.6	48.15 $\pm$ 21.9
SD2 (ms)	$\downarrow$ (0.4)	79.6 $\pm$ 32	67.6 $\pm$ 18.4	$\downarrow$ (0.43)	75.9 $\pm$ 27.3	61.8 $\pm$ 31.05
SD1_SD2	$\downarrow$ (0.5)	1.12 $\pm$ 0.17	1.02 $\pm$ 0.2	$\downarrow^{*}$ (0.66)	1.0 $\pm$ 0.17	0.81 $\pm$ 0.27

TABLE 4.7 : Spearman correlation results for AV condition

Physio Metric	Rating Metric	Correlation Coefficient	P-value	Duration
nHF	Forgot everyday concerns	-0.613	0.02	Full
Mean_IBI	Post-relaxation	0.586	0.028	Full
SD1_SD2	Presence	0.642	0.033	Full
HR	Post-relaxation	-0.583	0.037	Full
Mean_IBI	Presence	0.542	0.045	Full
LF_Power	Pre-relaxation	-0.605	0.029	First minute
HR	Post-relaxation	-0.583	0.037	Last minute
Mean_IBI	Post-relaxation	0.586	0.028	Last minute
HF_Power	Relaxation (post minus pre)	0.905	0.3-3	Last minute
LF_HF_Ratio	Lost track of time	0.556	0.039	Last minute
nHF	Senses engagement	-0.666	0.018	Last minute

likely explains the observed reduction in HRV metrics (e.g., SDNN, RMSSD, SD1) and increased HR, particularly in the AVO condition. The multisensory nature of AVO may have intensified cognitive and emotional engagement, leading to greater sympathetic activation and further reductions in HRV compared to AV.

TABLE 4.8 : Spearman correlation results for AVO condition

Physio Metric	Rating Metric	Correlation Coefficient	P-value	Duration
LF_HF_Ratio	Lost track of time	0.6	0.023	Full
pNN50	Forgot everyday concerns	-0.636	0.048	Full
HR	Pre-relaxation	-0.601	0.03	First minute
SDNN	Presence	0.663	0.013	Last minute
RMSSD	Presence	0.57	0.042	Last minute
SDSD	Presence	0.57	0.042	Last minute
LF_HF_Ratio	Relaxation (post minus pre)	0.519	0.069	Last minute
SD1	Presence	0.57	0.042	Last minute

The AV condition showed increases in LF and HF power, indicating balanced autonomic activity, while AVO exhibited decreases, suggesting reduced parasympathetic modulation and a shift toward sympathetic dominance. The higher LF/HF ratio in AVO supports the idea that olfactory stimuli enhance arousal and engagement, consistent with research linking olfactory inputs to emotional and attentional responses (Herz, 2004).

Lastly, although the short duration (2.5 minutes) of the videos may have limited the potential for relaxation, the subjective responses indicate high levels of relaxation, presence, and engagement, emphasizing the immersive potential of the stimuli. Additionally, the participants' background as mental health nurses may have heightened their physiological responses, given their elevated baseline arousal and sensitivity.

It is worth noting that when comparing the HRV measures computed during the first minute of the experiments between the AV and AVO conditions, none of the features showed significant differences. This suggests that participants may still be in an initial adjustment phase, during which they regulate their heart rate. This early regulation period likely represents the transition from baseline to immersive engagement, during which autonomic responses stabilize.

While no significant differences were found between AV and AVO conditions during the first minute, the last-minute comparisons revealed that the AVO condition induced greater reductions in HRV metrics, such as SDNN, RMSSD, SDSD, SD1, and the SD1_SD2 ratio. This suggests that the inclusion of olfactory stimuli may lead to a more pronounced decrease in parasympathetic activity over time. Although the changes in HRV may be linked to stress (Kim et al., 2018a; Boyett et al., 2019), participants also reported an increase in the sense of engagement, presence, and relaxation, which is consistent with previous findings (Kim et al., 2021). Participants also reported that while they felt relaxed during the immersive experience, spending more time in the virtual environment would have been ideal to deepen their relaxation.

Significant correlations were found between HRV metrics and subjective ratings. Considering the overall 2.5 minutes in the AV condition, positive correlations of Mean IBI and SD1_SD2 with "Post-relaxation" and "Presence" highlight the role of parasympathetic activity in fostering these subjective experiences. Conversely, the negative correlation between HR and "Post-relaxation"

reinforces that lower HR, indicative of parasympathetic dominance, could be indicative of a relaxed state (Rudics et al., 2025; Osborne et al., 2020; Immanuel et al., 2023). During the initial phase, “Pre-relaxation” feelings were negatively linked to LF_power in the AV condition and HR in the AVO condition, suggesting that initial parasympathetic activity plays a crucial role in shaping baseline relaxation. The strong positive correlation between HF_power and the change in relaxation from start to finish “Relaxation (post minus pre)” in the AV condition underscores the relationship between parasympathetic activity and self-reported relaxation. These findings align with the literature, which links parasympathetic increases to enhanced relaxation (Lehrer et al., 2014).

The positive correlation between “Presence” and HRV features (SDNN, RMSSD, SDSD, and SD1) in the AVO condition suggests that greater immersion in audiovisual-olfactory environments improves autonomic regulation. These HRV measures reflect parasympathetic activity, indicating relaxation and better physiological balance. The findings highlight how the addition of olfactory stimuli enhances the sense of presence, which may promote relaxation and emotional engagement (De Jesus Jr et al., 2022) and also showed in Chapter 3.

4.5 Conclusions

This study explored the impact of multisensory nature immersion as a tool to improve the relaxation of nurses in an in-patient hospital in Canada. Via an instrumented VR headset, we tracked the EEG and PPG signals of nurses while they were immersed in one of the natural scenes (beach, waterfall, and lake), chosen by them, under two conditions, namely audio-visual (AV) and audio-visual-olfactory (AVO). Comparing the two conditions, without distinguishing between scenes, the AV condition resulted in higher levels of relaxation. In turn, when considering specific scenarios (i.e., lake and waterfall), the AVO condition showed greater improvements in relaxation levels, as well as improvements across several other user experience ratings, such as sense of immersion and engagement levels. These findings suggest that sensory congruence may play a role in enhancing the user experience when the olfactory sense is stimulated.

Moreover, using the instrumented headset, significant changes were seen in the neural patterns between the two conditions, with the AVO condition showing increased behavioral approach (via a frontal alpha asymmetry measure), increased engagement, as well as several changes in EEG subband powers, suggesting greater relaxation levels, increased valence, and decreased arousal, just to name a few. The importance of smell congruence became very clear from both the subjective and objective analyses, suggesting that customization may be crucial for multisensory immersive experiences.

Significant differences in several HRV metrics were also identified between the initial and final segments for both AV and AVO conditions. Correlation analysis showed stronger links between HRV metrics, relaxation levels, and QoE ratings in the AVO condition, particularly in the final seg-

ments. These results indicate that both AV and AVO conditions enhanced relaxation and QoE while inducing measurable HRV changes.

Overall, despite some limitations of the study (i.e., limited number of subjects, limited experiment duration, limited customization of smells), the in-house instrumented headset provided invaluable insights that were not available with just the questionnaires. The potential to monitor, in real-time, participant mental, affective, and cognitive states, as well as relaxation and user experience levels, may allow for next-generation multisensory, adaptive immersive biofeedback applications that are optimized to each user's experience. Given that olfaction is a very subjective sensory input, such monitoring may allow for real-time detection of scent incongruence, which we have seen here can substantially (negatively) effect the overall experience. This study underscores the importance of customizing multisensory virtual reality stimuli to achieve specific outcomes, such as relaxation, engagement, or a balance of both.

5 MULTISENSORY NATURE IMMERSION : A NEW INTERVENTION FOR PTSD PATIENTS

5.1 Preamble

This chapter contains material extracted from the conference proceedings papers in 17th International Conference on Quality of Multimedia Experience (QoMEX) (Lopes et al., 2025c), IEEE International Conference on Acoustics, Speech, and Signal Processing (Lopes et al., 2026b), and the 48th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC 2026) (Lopes et al., 2026a).

5.2 Introduction

Conventional post traumatic stress disorder (PTSD) treatments include trauma-focused therapies such as exposure therapy, where patients gradually face trauma memories or reminders in a safe setting (Rauch et al., 2012; McLean et al., 2022). These approaches can work well, but they can be hard to access and are emotionally difficult, resulting in high drop-out rates (Benbow et al., 2019). As such, virtual reality has emerged as an alternative to support PTSD treatment by making exposure therapy easier to deliver in a safe, controlled way. With VR exposure therapy, the patient is gradually exposed to trauma-related cues inside a virtual scene that can be repeated and adjusted, which may reduce the need to rely on imagination and can help when real-life exposure is not practical (Gonçalves et al., 2012; Rizzo et al., 2009). Multisensory VR exposure therapy, where extra sensory cues (for example, vibration and/or smell) are also included, has also emerged and shown to improve treatment outcomes (Freedman et al., 2024; Im Kim et al., 2019). Multisensory VR exposure therapy, however, requires extensive customization for each patient and can be overwhelming for some patients. To this end, more recent research has explored the use of multisensory nature immersion as an alternative tool to help individuals better manage their mental health during exposure to virtual nature immersion (Sasu et al., 2024).

In this study, we evaluate the effectiveness of two types of multisensory immersion systems for patients diagnosed with PTSD : (1) a portable system, which delivers olfactory stimulation directly through a head-mounted display (HMD), and (2) a pod system, in which participants are seated in a multisensory pod that augments HMD audio-visual content with synchronized olfactory cues and haptic feedback (wind and vibration). Beyond comparing the two modalities, this work focuses on how neural activity changes throughout the experience. Specifically, we analyze electroencephalography (EEG) responses in relation to participants' subjective affective ratings, clinical questionnaires, and cognitive faculties.

TABLE 5.1 : Demographics of study participants

Variable	Categories	n	%
Sex	Female	3	37.5
	Male	5	62.5
Marital Status	Single	2	25.0
	Common-law	2	25.0
	Married	4	50.0
Parental Status	No children	1	12.5
	At least 1 child	7	87.5
Educational Level	High school	2	25.0
	Professional Diploma	1	12.5
	CEGEP	2	25.0
	Bachelor's degree	3	37.5
Professional Status	Full/Part time job	3	37.5
	Invalid	3	37.5
	Retired	2	25.0

5.3 Materials and methods

5.3.1 Participants

The data used here were collected at a PTSD psychotherapy clinic in Sept-Îles, QC, Canada. While ten adults with PTSD (diagnosed by their family physicians) participated in both experiments, here data from only eight are used, as two participants had missing EEG data that prohibited some of our analyses. All participants gave informed consent, and the study was approved by the Ethics Committee of Research with Human Beings (CER-22-669) from INRS. Table 5.1 presents the demographics information for the eight participants. Given the limited sample size, the results reported here should be considered preliminary and should be confirmed in a larger cohort.

5.3.2 Experimental design

The experiments followed the multi-week protocols depicted by Fig. 5.1. The first study relied on a portable scent diffusion device (henceforth referred to as 'PORTABLE'; more details in Section 5.3.3), while the second on a multisensory pod (termed 'POD'; see Section 3.3.2). Both protocols started with a pre-test period, termed Pre-test 1, which included a brief exposure to a short multisensory VR scene with olfactory stimulation to screen for cybersickness or other exclusion criteria. This was followed by a 30–45 minute neurocognitive assessment (see Section 2.4.1.1), collection of demographic information, standardized questionnaires assessing PTSD symptoms and psychological distress, and a semi-structured clinical interview. After three weeks without VR ex-

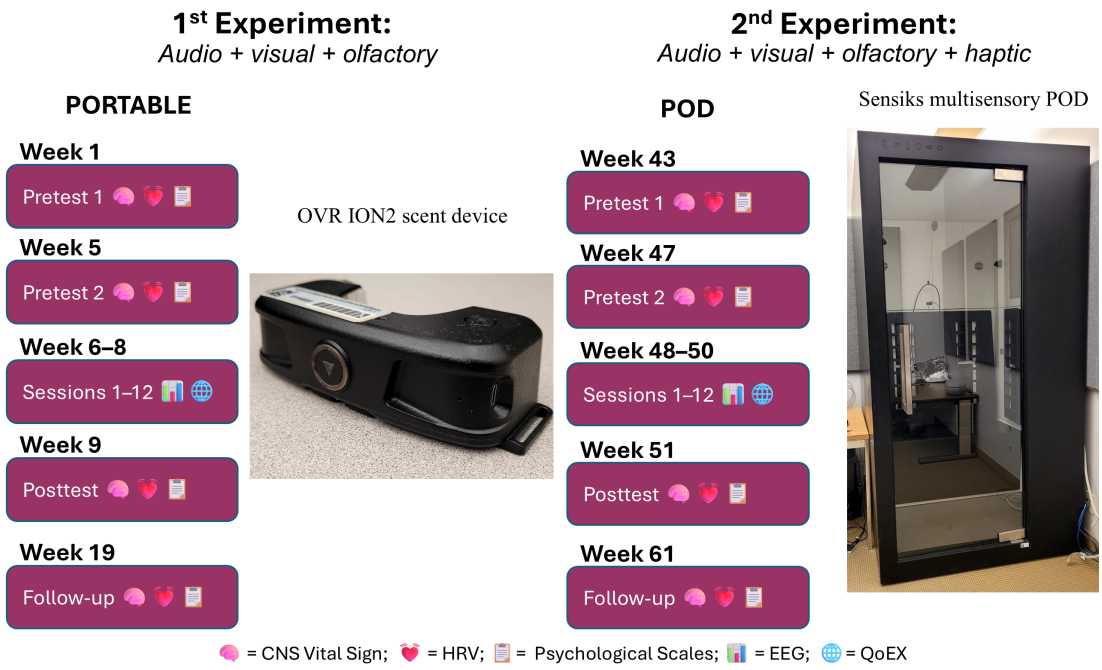


FIGURE 5.1 : Flow diagram for the two experiments.

posure (psychotherapy continued as usual), participants completed a second pre-test, now termed Pre-test 2, one day before the multisensory intervention. Pre-test 2 repeated the same measures as Pre-test 1, except for the demographic information.

The intervention itself then consisted of 12 multisensory VR sessions over three weeks (four sessions per week). Each session lasted 15 minutes and involved viewing different immersive natural environments (e.g., beach, forest/lake, park; more details in Section 5.3.4) paired with either synchronized olfactory stimulation (in the experiment termed 'PORTABLE') or with olfactory, directional airflow, and vibroacoustic feedback in the so-called POD experiment. The order of the presentation of the virtual environments was randomized to avoid ordering effects. Immediately after the 12th session, participants completed a Post-test, which was identical to the Pre-test 2. A follow-up assessment was conducted three months later to evaluate longer-term effects. A break of 23 weeks was given between experiments.

5.3.3 Hardware

In the first study, olfactory stimulation was delivered using the portable OVR setup, which is presented in Chapter 4. In the second experiment, a multisensory POD setup was used, as presented in Chapter 3. In both cases, nature-related sensory stimuli were time-synchronized with the 360-degree VR video displayed in the same HMD.

5.3.4 Virtual environments

Each of the 12 sessions included three nature scenes chosen to support relaxation. The scenes were calm, visually stable, and showed natural environments with slow movement and familiar elements. In the first experiment (PORTABLE), the first scene placed participants by a mountain lake from the Atmosphaeres Library [1]. The second scene showed a local beach familiar to participants in Sept-Îles, QC, Canada, with the viewpoint close to the water. The third scene depicted a rocky seaside area in the same city, surrounded by forest, combining coastal and natural elements.

In the second experiment (POD), the first scene was the same mountain lake used in the PORTABLE study. The second scene showed a Thailand beach with clear turquoise water and slow wave movement. The third scene was a mountain timelapse, showing gradual changes in light and clouds over a fixed landscape, designed to remain calming while maintaining visual interest.

5.3.5 Subjective measures

To evaluate the effects of the two interventions, participants completed a set of standardized clinical questionnaires and semi-structured interviews. PTSD symptom severity was assessed using the PDEQ (Marmar et al., 2004), PCL-5 (Weathers et al., 1993), CAPS-5 (Weathers et al., 2018), DES-II (Carlson et al., 1993), and PHQ-9 (Kroenke et al., 2001) questionnaires. Cognitive functioning was also evaluated across several domains, including verbal and visual memory, complex attention, working memory, and sustained attention. The CNS Vital Signs cognitive functioning software was used for this (see Section 2.4.1 for more details).

In addition to these clinical and cognitive measures, participants completed session-level questionnaires related to their VR experience after each session, including their perceived sense of presence and cybersickness (e.g., (Kim et al., 2018b; Jennett et al., 2008; Witmer et al., 1998)). In the second study, participants also provided pre- and post-session ratings of their perceived stress, as well as post-session relaxation and immersion ratings.

5.3.6 EEG signal processing

EEG recordings were analyzed using the EEGLAB toolbox (Delorme et al., 2004). The data were first filtered between 0.5 and 50 Hz using a zero-phase FIR filter to remove slow signal drifts and high-frequency noise. Motion-related artifacts were then attenuated using artifact subspace reconstruction (ASR). We used a burst criterion of 20 to avoid over-cleaning the EEG. Independent Component Analysis (ICA) was subsequently applied, and components were automatically classified with ICLabel (Pion-Tonachini et al., 2019) to distinguish neural activity from non-neural sources

1. https://www.atmosphaeres.com/

such as eye or muscle artifacts. Components classified as muscle or eye activity with a probability of 0.9 or higher were rejected.

For feature extraction, the cleaned EEG signals were divided into 2-second epochs without overlap. Spectral features were computed as normalized power within seven conventional frequency ranges : delta (delta, 1-4 Hz), theta (theta, 4-8 Hz), alpha (alpha, 8-12 Hz), beta (beta, 12–30 Hz), beta1 (beta_1, 12-21 Hz), beta2 (beta_2, 21-30 Hz), and gamma (gamma, 30–45 Hz). In addition to spectral power, several derived neurophysiological metrics associated with affective and cognitive processing were calculated, including engagement, valence, arousal, attention, and frontal alpha asymmetry (FAA) metrics(Pope et al., 1995; McMahan et al., 2015; Myrden et al., 2017; Zhang et al., 2018).

5.3.7 Data/statistical analyses

The subjective responses were first tested for normality using Shapiro-Wilk test. Following this, repeated measures ANOVA and a post-hoc paired t-test were used to compare the significance of the differences in measurements over time. The p-values were also corrected using the Benjamini–Hochberg false discovery rate (FDR) method for the post-hoc tests.

To examine within-participant associations between neural activity and VR experience across sessions, we first used repeated-measures correlation (rmcorr) to assess whether fluctuations in EEG features tracked corresponding fluctuations in post-VR self-report measures across the intervention. For each EEG feature and subjective rating, we evaluated whether session-to-session variation in the feature covaried with variation in the rating within the same individual. This analysis was performed on cumulative session means to characterize how the measures changed together over time. Multiple comparisons were controlled using FDR.

To further characterize these relationships, we fitted mixed-effects models to test whether EEG feature values predicted subjective ratings across sessions while accounting for repeated measures. For each EEG feature–rating pair, the model estimated the within-subject association between the feature and rating, included a random intercept to allow each participant to have their own baseline, and included session number as a covariate to account for progression through the intervention.

In addition, to examine how changes in EEG features across the VR intervention related to improvements in PTSD symptoms and cognitive performance pre- and post-intervention, we first quantified behavioral improvement as the difference between the post-test score and the second pre-test score (Post minus Pre-test 2), yielding a single change score per participant for both clinical and cognitive measures. For each EEG feature, participant-specific linear regression models were then fitted across sessions (feature value$\sim$session number feature value$\sim$session number). The resulting slope parameter served as an index of the magnitude and direction of longitudi-

nal neurophysiological change (positive slopes indicating increases over sessions and negative slopes indicating decreases). Finally, Spearman correlations were computed between EEG slopes and behavioral change scores across participants, and p-values were corrected for multiple comparisons.

To examine longitudinal changes in neural activity, we applied linear mixed-effects models to the EEG features. For each feature, models were fitted to assess differences between the first and last sessions, while accounting for repeated measurements within participants and controlling for scenario effects. This analysis specifically evaluates whether EEG activity shows a statistically robust change across the full intervention period, independent of inter-individual baseline differences.

In addition, we investigated the relationship between changes in subjective experience and neural activity using Spearman correlation analyses. For this purpose, both subjective measures and EEG features were summarized as difference scores between the last and first sessions, and correlations were computed between these change values. This approach allows us to assess whether participants who showed larger subjective changes over the intervention also exhibited corresponding changes in specific EEG features. Given the exploratory nature of this analysis, results were interpreted with caution and corrected for multiple comparisons using the FDR method.

Finally, to complement the statistical analyses, we examined session-by-session trends in neural activity using descriptive visualizations. Mean EEG feature values were plotted across sessions to illustrate the changes in neural activity patterns throughout the intervention period. These plots provide an intuitive view of gradual adaptations, stability, or variability across sessions and help contextualize the results obtained from the first-to-last session analyses.

5.4 Results and discussion

5.4.1 Subjective PTSD and cognitive assessments

Figures 5.2-5.9 show the graphs for PTSD clinical assessments and cognitive tests across the protocol, respectively. The results for the two experimental setups (PORTABLE in green and POD in orange) are shown separately. As can be seen, in the PORTABLE experiment, DES-II decreased over time. A repeated-measures ANOVA across all DES-II assessments was significant ($F \approx 5.32$, $p = 0.024$), indicating that it changed consistently throughout the intervention timeline. Post-hoc paired comparisons showed that scores dropped significantly from the first pre-intervention assessment (Pre-test 1) to the long-term follow-up (paired $t = 5.05$, $p = 0.01$), with a very large within-person effect size ($d \approx 1.79$). Follow-up scores were also lower than those at the immediate post-test (paired $t = 2.69$, $p = 0.031$ (before correction), $d \approx 0.95$), and the later pre-test baseline (Pre-test 2; paired $t = 2.58$, $p = 0.036$ (before correction), $d \approx 0.91$). These post-hoc comparisons

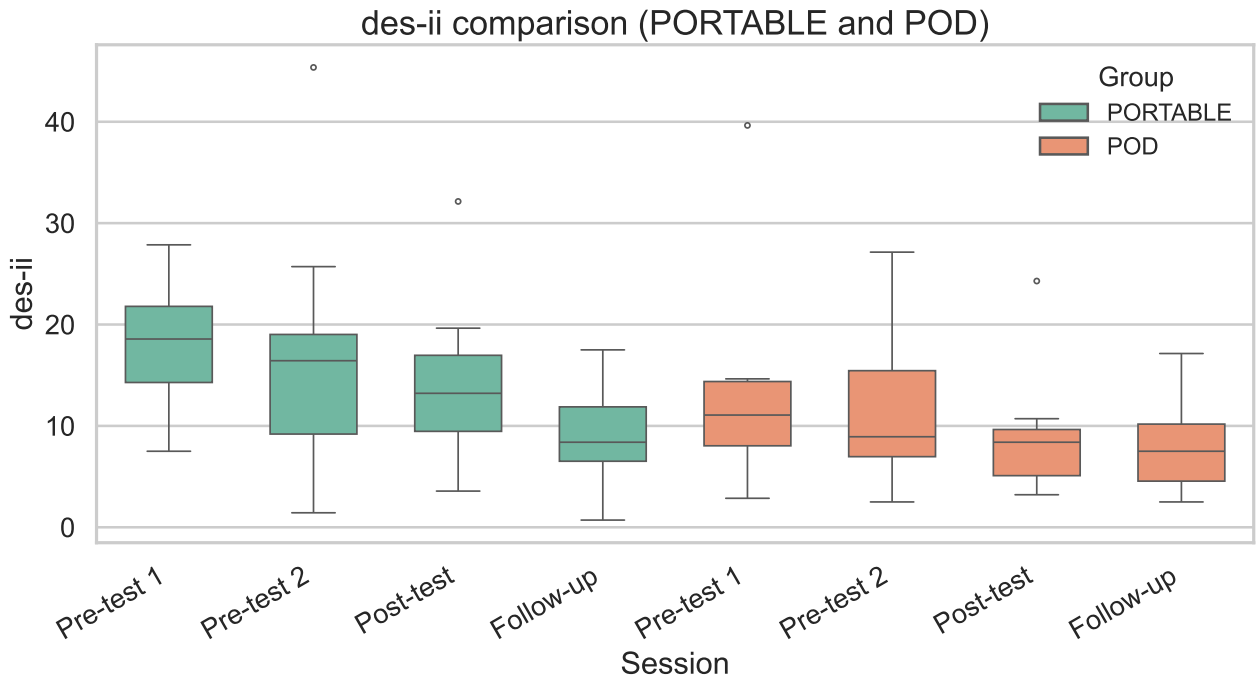


FIGURE 5.2 : Changes in DES-II clinical assessment scores across the intervention

did not remain significant after FDR correction (p = 0.064 for both), but the effect sizes are still in the "large" range (d $\approx$ 0.9).

In the POD experiment, the PHQ-9 were significantly lower at follow-up than at immediate post-test (paired t = 2.61, p = 0.035 (before correction), d $\approx$ 0.92), with a similarly sized trend when comparing follow-up to the later pre-test baseline ("Pre-test 2 vs Follow-up" : t = 2.31, p = 0.054 (before correction), d $\approx$ 0.82). After FDR correction, these comparisons do not reach the adjusted threshold. For the DES-II, there was a trend toward reduction from the earliest pre-test to the post-test (t = 2.24, p = 0.060, d $\approx$ 0.79), indicating a large effect size, even though the p-value is not significant. Overall, in POD, we observe medium-to-large within-person drops in depressive symptoms and, to a lesser extent, dissociation by the final follow-up; however, these changes are statistically weaker than those observed in PORTABLE.

For the PORTABLE experiment, we noted a strong improvement in cognitive processing speed/efficiency. The score increased over time : there was a significant gain from Pre-test 1 to Post-test (paired t = –3.92, p = 0.028), with a very large effect size (d $\approx$ –1.38), and the repeated-measures ANOVA across all sessions was also significant (F = 5.16, p = 0.028). This indicates that, on average, participants in the PORTABLE experiment showed an improvement in processing abilities across the intervention period. We also saw an increase from Pre-test 1 to Pre-test 2 (paired t = –3.24, p = 0.033), suggesting that some cognitive improvement may be attributable to psychotherapy received by the participants, rather than solely to the VR intervention. In contrast, complex reasoning / complex problem-solving showed a weaker pattern; the improvement from Pre-test 1 to Follow-up

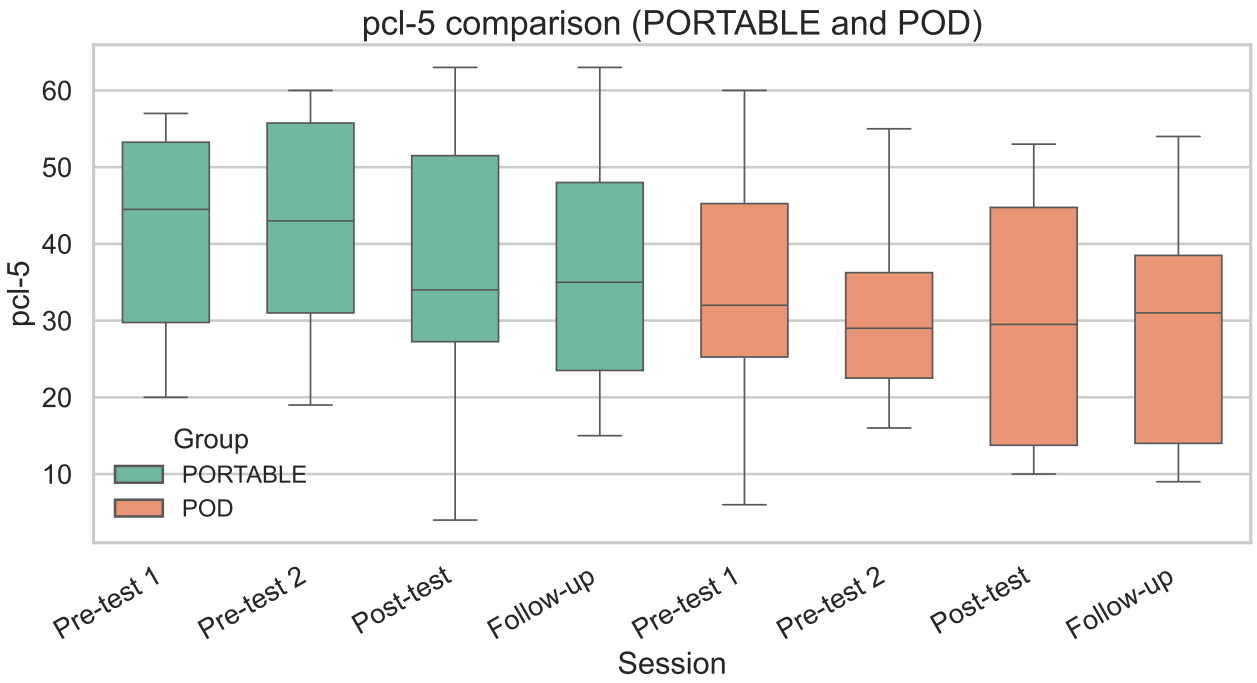


FIGURE 5.3 : Changes in PCL-5 clinical assessment scores across the intervention

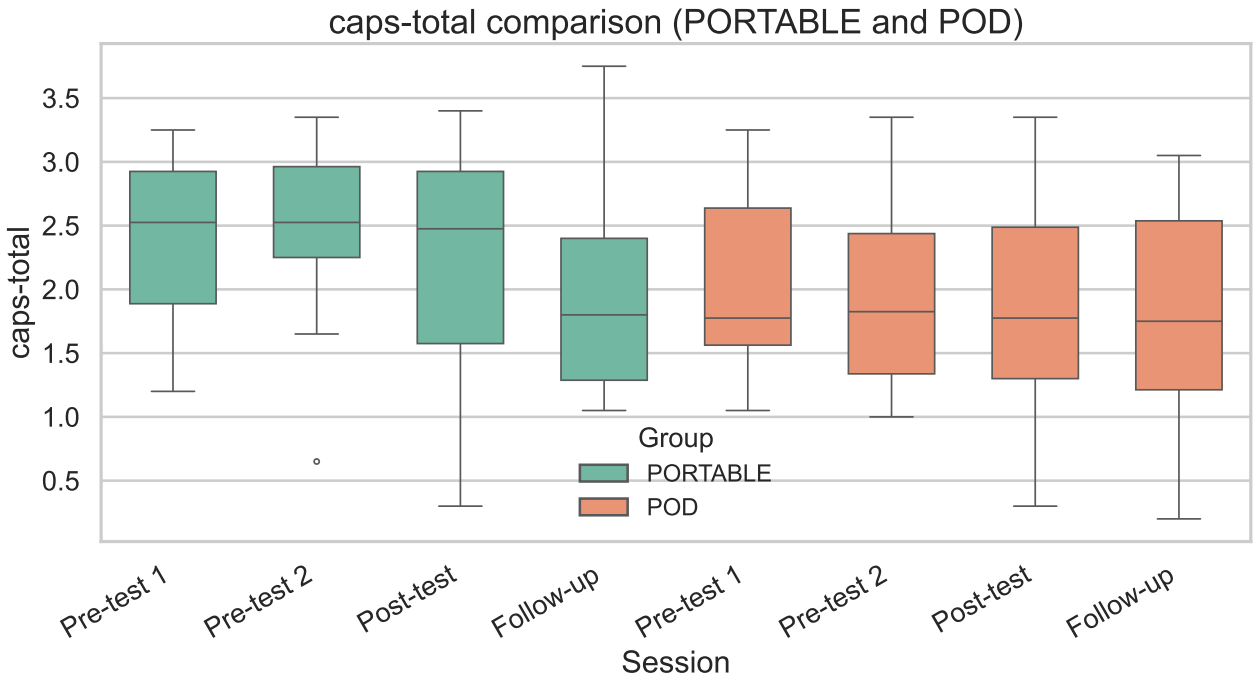


FIGURE 5.4 : Changes in CAPS-5 clinical assessment scores across the intervention

reached significance before p-value correction (paired t = –2.48, p = 0.042, d ≈ –0.88), but not after correction (p ≈ 0.28).

In the POD experiment, we did not see the same consistent results, but there are hints of improvement in specific domains. Working memory/working efficiency increased from Pre-test 1 to Post-test (paired t = –2.44, p = 0.045 (before correction), d ≈ –0.86), and sustained atten-

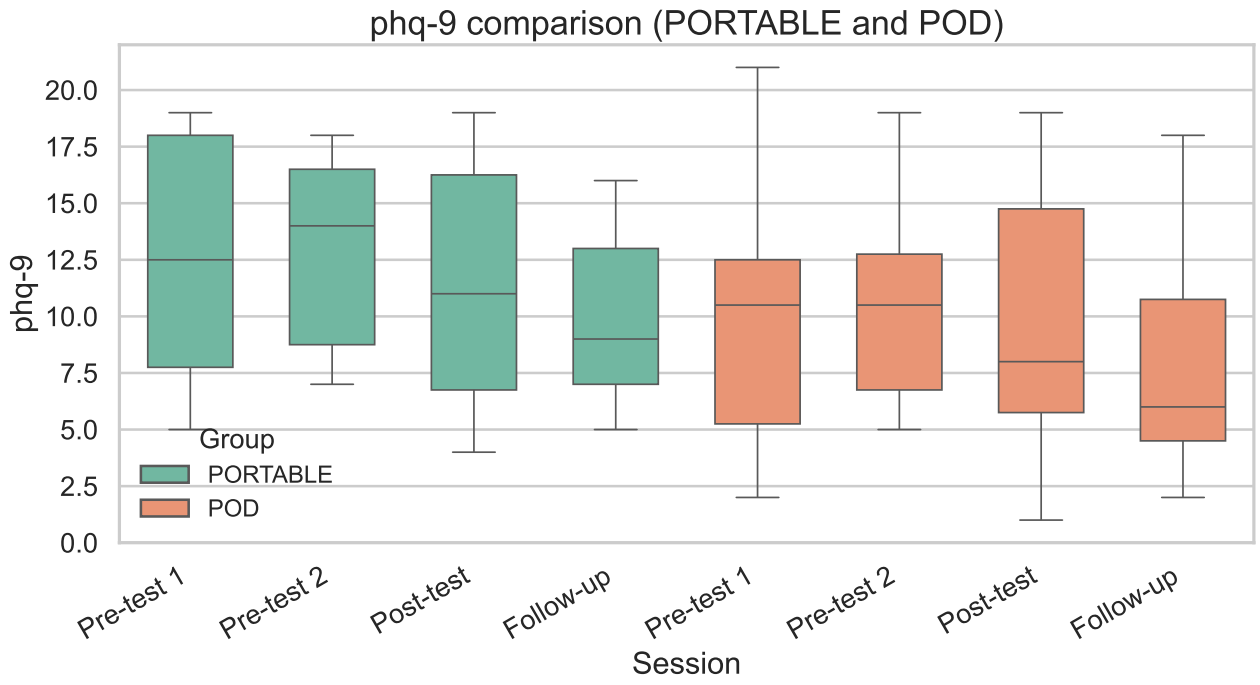


FIGURE 5.5 : Changes in PHQ-9 clinical assessment scores across the intervention

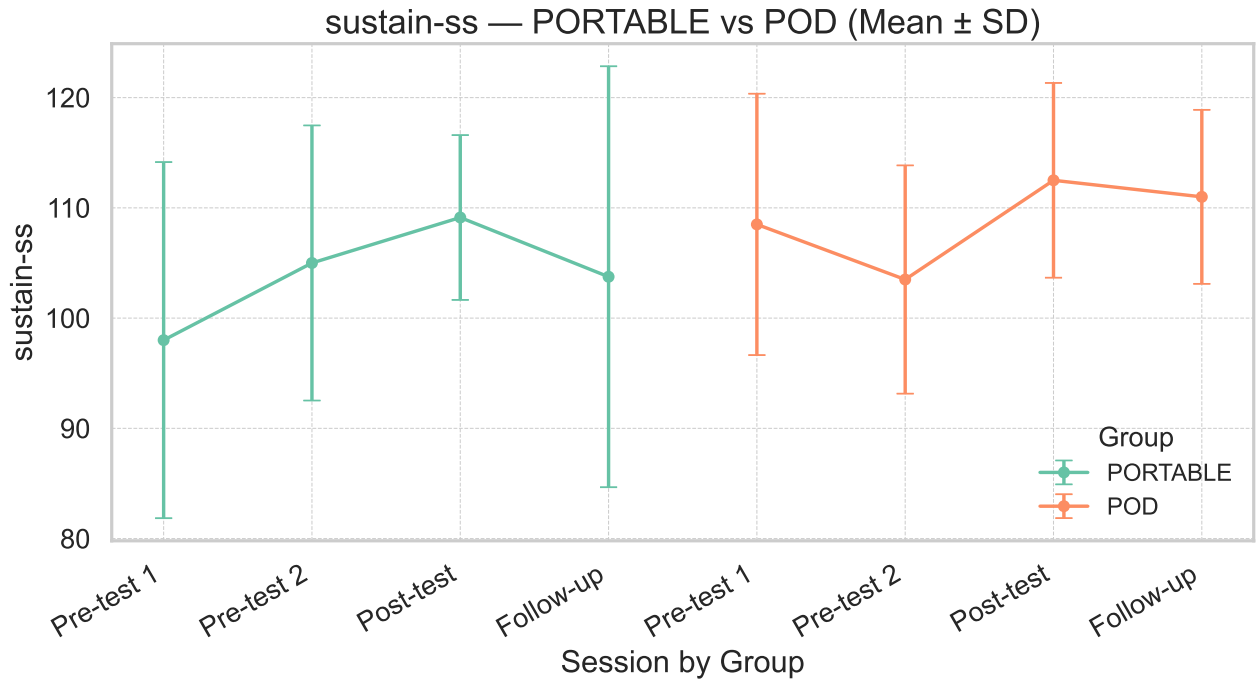


FIGURE 5.6 : Changes in Sustained attention scores across the intervention

tion/vigilance ("sustain-ss") improved between Pre-test 2 and both Post-test and Follow-up (paired $t \approx -2.38$ to -2.44, $p \approx 0.045$–0.049 (before correction), $d \approx -0.84$ to -0.86). These effect sizes are in the "large" range, which suggests meaningful individual-level change. However, none of these comparisons were significant after FDR correction ($p \sim 0.17$–0.25).

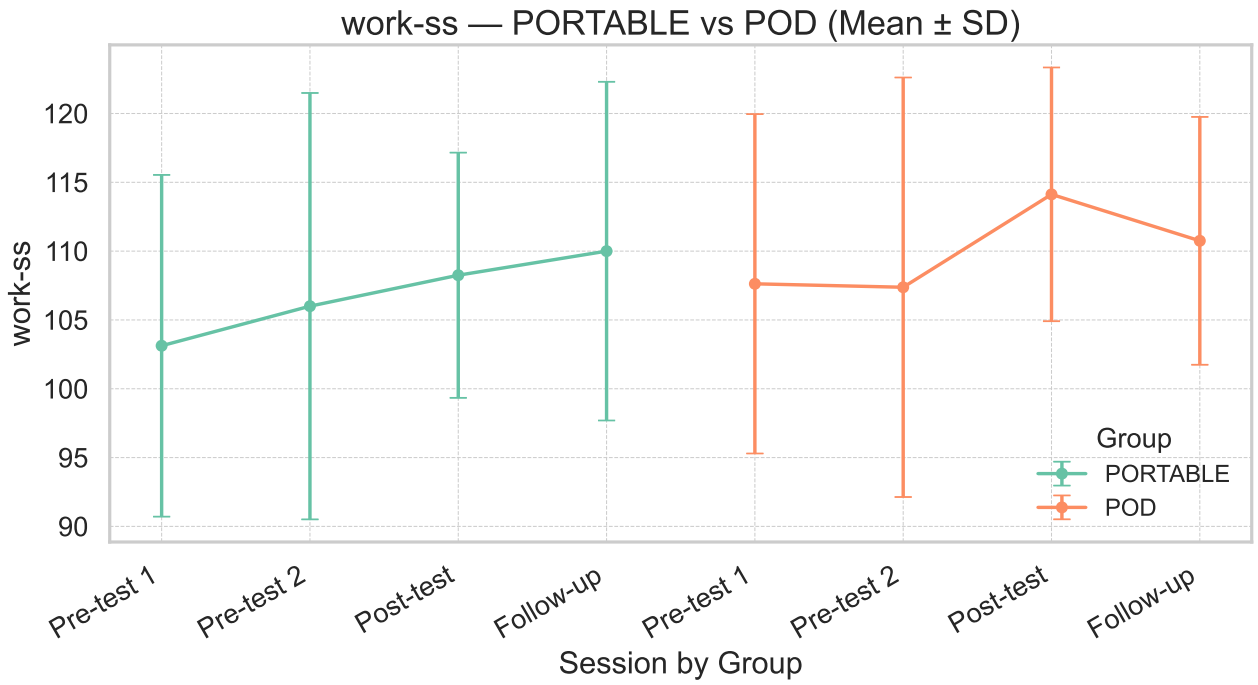


FIGURE 5.7 : Changes in Working Memory scores across the intervention

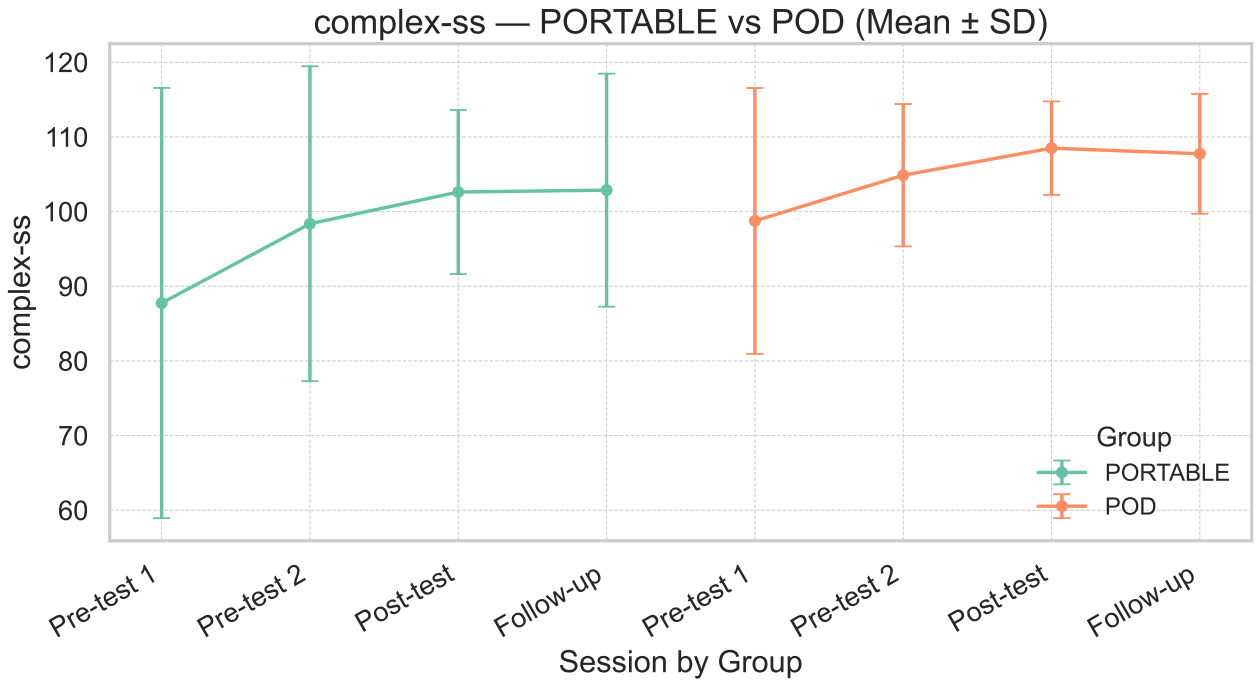


FIGURE 5.8 : Changes in Complex Attention scores across the intervention

5.4.2 Subjective response across sessions

Figure 5.10 depicts the changes in user experience responses for the PORTABLE experiment. As can be seen, cybersickness remained low and stable across all participants and sessions, with only minor fluctuations and no evidence of cumulative discomfort over time. The user's sense

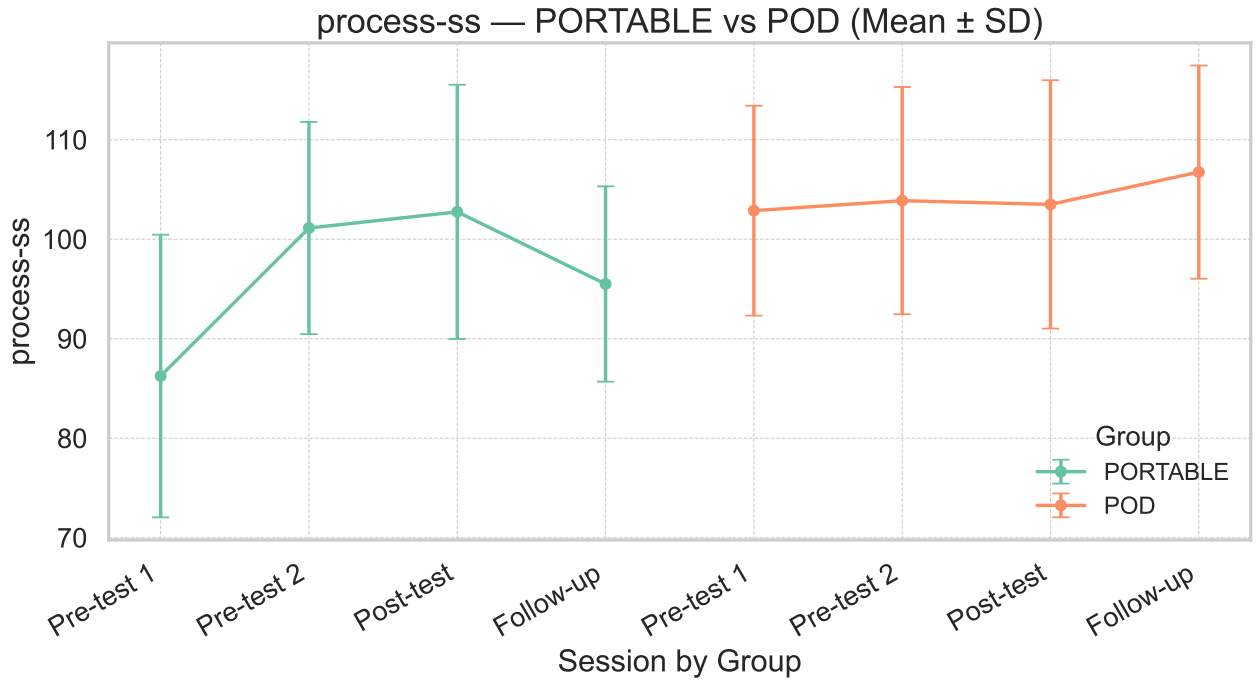


FIGURE 5.9 : Changes in Processing Speed scores across the intervention

of presence, in turn, stayed consistently high throughout the protocol, indicating that repeated exposure did not degrade the perceived immersive quality of the experience. The variability across participants was higher, but remained consistent across the 12 sessions.

Figure 5.11 shows the responses for the POD experiment. As seen, the perceived sense of immersion and relaxation showed some session-to-session variability, but remained globally stable. The reported post-session stress levels were consistently lower than those reported pre-session, highlighting the relaxing effect of the nature immersion protocol. No statistically significant changes across sessions were observed after p-value correction.

Fig. 5.12 depicts the average level of appreciation reported across participants for each sensory modality. As observed, audio, visual, and haptic senses were deemed the most appreciated, with olfaction showing the lowest appreciation rating.

5.4.3 VR experience and neural activity - repeated measures correlation

In the PORTABLE experiment, we observed the strongest effects in the cumulative series. Here, higher Cybersickness scores covaried with higher frontal delta power (e.g. F4_delta, F3_delta; $r \approx 0.5$, $p < 0.001$) (Lee et al., 2025; Jang et al., 2022) and with lower frontal and occipital beta_1 power (e.g. F4_beta_1, O2_beta_1; $r \approx$ -0.5, $p < 0.001$) (Kim et al., 2005). Cybersickness also co-occurred with lower arousal scores. In contrast, higher Presence showed the opposite behavior; Presence increased alongside higher frontal and occipital alpha and theta power (e.g. F4_alpha,

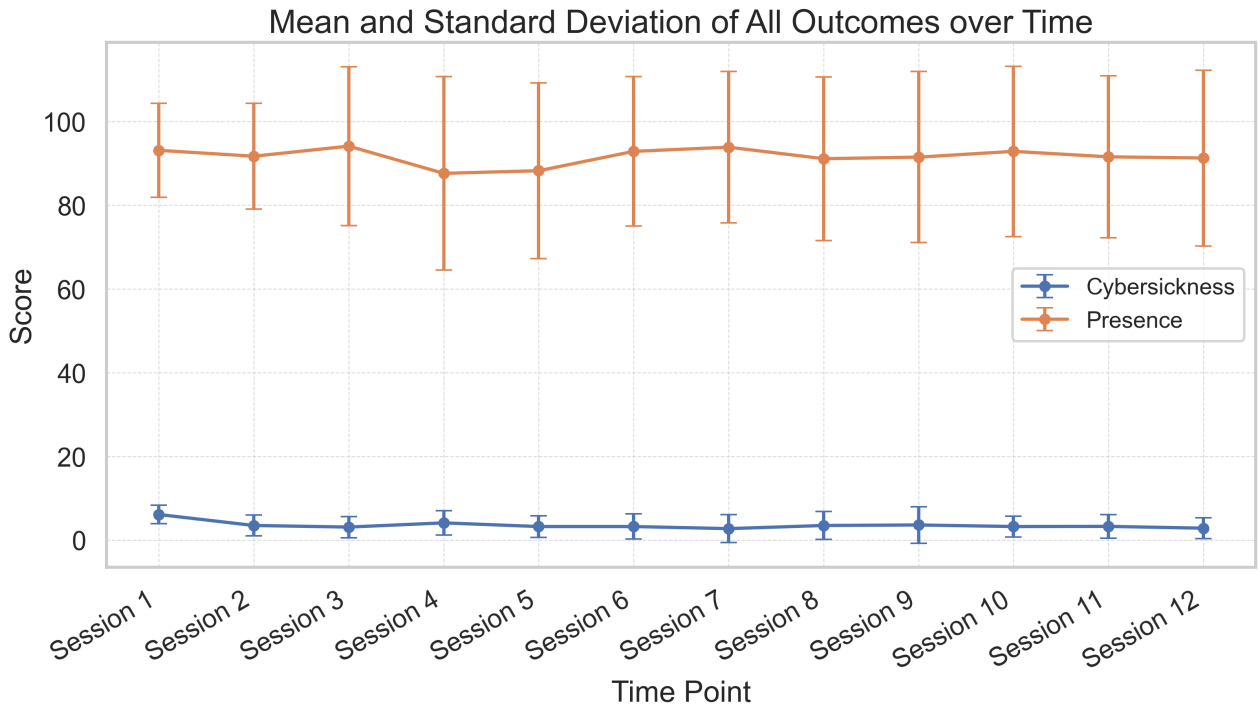


FIGURE 5.10 : Change in ratings per session (PORTABLE).

O1_theta, P4_theta; $r \approx 0.5$, $p < 0.01$) (Kober et al., 2012) and a reduction in central area in beta_1 power (C3_beta_1; -0.36, $p < 0.01$).

Within the POD experiment, the strongest and most reliable effects also appeared in the cumulative series; higher Relaxation scores over time were associated with higher alpha-band power across broad frontal, central, parietal, and occipital areas ($r \approx 0.4$-0.5, $p < 0.05$). This corresponds to a shift in participants' EEG toward increased alpha, a spectral pattern commonly linked to lower cortical activation (Zhang et al., 2021) alongside a reported feeling of increased relaxation across the interventions. In addition, higher Immersion scores were related to lower engagement ($r = -0.37$, $p < 0.05$), meaning that as participants reported being more present in the VR experience, their engagement biomarker tended to decrease within that same person across sessions. Finally, we observed that larger reductions in stress from pre- to post-session tracked with higher right frontal theta power (F4_theta; $r = -0.38$, $p < 0.05$). This could also be attributed to higher relaxation scores across the VR sessions. (Lagopoulos et al., 2009).

5.4.4 VR experience and neural activity - linear mixed-effects model

In the PORTABLE experiment, for Presence, many EEG features showed significant positive relationships. The strongest and most consistent effects were in the lower-frequency bands (theta and alpha), especially over central, parietal, and occipital areas. For Cybersickness, many beta and alpha band features had negative coefficients (Kim et al., 2005).

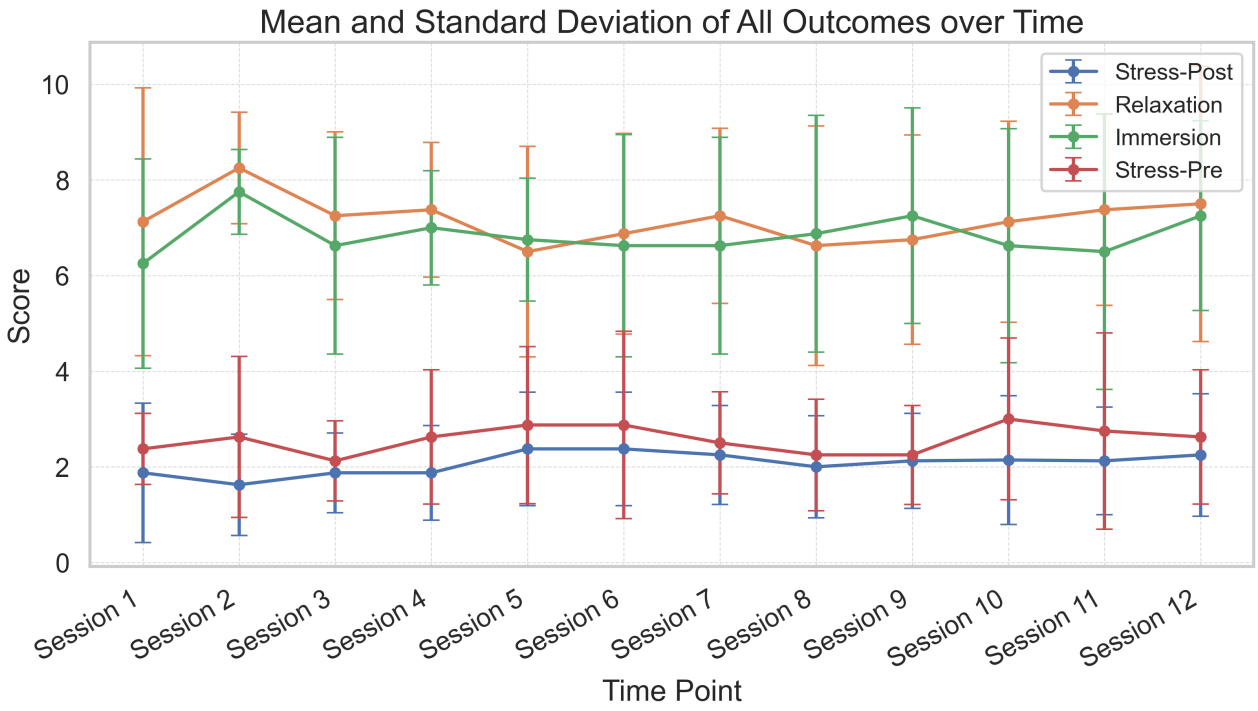


FIGURE 5.11 : Change in ratings per session (POD).



FIGURE 5.12 : Change in appreciation per session (POD).



FIGURE 5.13 : Change in appreciation per session (POD).

For the POD experiment, we see that higher beta and beta_1 power at the frontal area is strongly associated with lower Immersion scores across sessions; the same behavior was noted with the engagement biomarker. The increase in FAA was associated with a higher Immersion. For the Relaxation rating, a higher alpha power at the frontal and central areas was associated with higher Relaxation (Zhang et al., 2021). For Stress post- minus pre-, results show a positive association with gamma over the central, parietal, and occipital areas in the left hemisphere and a negative association with the arousal index (Wriessnegger et al., 2025).

5.4.5 Correlation of symptom improvement with EEG

In the PORTABLE experiment, for depression (PHQ-9), we had a very strong positive association with frontal and central theta and alpha power slopes. Specifically, the slope of F4-theta power was strongly correlated with improvement in depression scores (ρ = 0.99, p $\approx$ 0.0003). Similar effects appear for C3-theta, F4-alpha, Cz-alpha, and Cz-theta (all $\rho \geq 0.93$, all p < 0.02) (Jokić-begić et al., 2003).

For PTSD symptoms (PCL-5), we observed the opposite pattern, but in higher-frequency bands. The slope of Cz_beta and beta_1 is strongly negatively correlated with improvement in PTSD scores (ρ = –0.99, p $\approx$ 0.009). This could indicate that participants who saw a greater decrease in central beta power over time showed the greatest PTSD symptom relief (Jokić-begić et al., 2003). We also see a similar negative association for the attention index (ρ = -0.95, p $\approx$ 0.009).

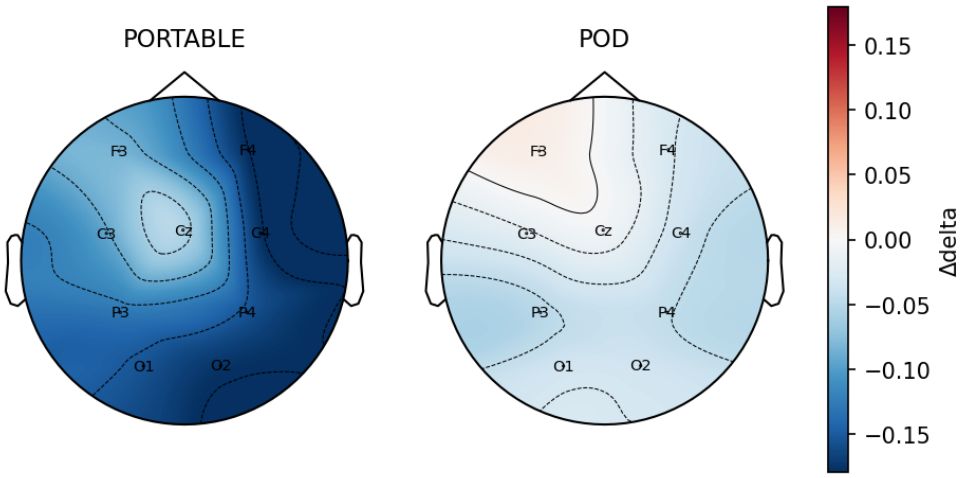


FIGURE 5.14 : Topoplot of delta band changes for (left) PORTABLE and (right) POD.

In the POD experiment, we found a consistent pattern of strong correlations between improvement in dissociative symptoms (DES-II) and the slope of occipital and parietal EEG power; however, after correcting the p-value, the correlations were not significant.

5.4.6 First-to-Last session : EEG changes assessed with linear mixed-effects models

In this analysis, the environment presented was included as a fixed-effect covariate to account for differences related to the visual content, since all participants were exposed to the same set of scenarios across sessions. For the PORTABLE experiment, the linear mixed-effects analysis showed clear neurophysiological changes from the first to the last session. The main result is a strong increase in higher-frequency activity, especially in the beta bands (beta_1 and beta_2), most notably over right frontal (F4), parietal (P4), and occipital (O2) regions. At the same time, delta power decreases across frontal, central, parietal, and occipital sites, indicating a gradual reduction in low-frequency activity. These effects remain statistically significant after FDR correction. This pattern (less slow activity and more fast activity) matches what has been reported during short rest/relaxation periods : delta tends to decrease while beta can increase, especially over frontal/central areas (Teplan et al., 2014). An increase in beta power has also been reported in PTSD patients (Jokić-begić et al., 2003). However, in the present study, the self-reported increase in relaxation supports interpreting the beta increase as part of the overall relaxation-related change rather than a stress-related effect. Figure 5.14 presents a topographical plot of the change in delta-band power between the last and first sessions for the PORTABLE (left) and POD experiments (right).

For the POD experiment, results showed a consistent and robust increase in gamma activity across frontal, central, parietal, and occipital regions, with all gamma coefficients positive and

significant after FDR correction (q $<$ 0.01). This indicates that gamma power is higher at the end of the protocol than at the beginning, independent of the virtual environment and individual baseline differences. In contrast, theta power decreases mainly over occipital and parietal regions, while beta_2 activity shows smaller but still significant increases. Overall, although the sample size is limited, these results may suggest the presence of a neuromarker associated with multisensory VR exposure in patients with PTSD.

5.4.7 First-to-Last session : Correlation between subjective responses and EEG

For this experiment, results indicated that higher Presence scores were linked to lower beta_2 and gamma activity over central, parietal, and occipital areas, while increases were observed in lower-frequency activity, such as theta at C3 and O2. A similar pattern was found for Cybersickness, where larger changes were associated with lower theta power at P4 and higher attention-related measures. However, after correcting for multiple comparisons using FDR, none of these relationships remained statistically significant (q $>$ 0.2). These findings should therefore be viewed as exploratory.

In the POD experiment, strong negative relationships were observed between changes in Immersion and higher-frequency EEG activity, especially for beta_2 power over right frontal and parietal regions, with correlation values close to -0.9. This pattern was consistent across beta and gamma frequencies and across frontal, central, parietal, and occipital areas, showing that higher Immersion was linked to lower high-frequency activity. In contrast, higher Immersion was associated with increased delta activity over parietal and occipital regions. This negative beta_2, gamma pattern is different from some haptic VR studies done in threatening or demanding tasks, where higher immersion is often linked to higher beta, gamma activity (more effort and alertness) (Cong et al., 2025; Ping et al., 2025). In our calming nature-therapy setting, higher immersion may instead mean less effort and less alertness, which fits with the increase in low-frequency delta activity. Many of these relationships remained significant after correction for multiple comparisons (q $<$ 0.05), despite the small number of participants.

5.4.8 First-to-Last session : Correlation between PTSD symptom change and EEG

In the PORTABLE condition, larger symptom improvements were mainly linked to reductions in frontal high-frequency activity. In particular, larger PHQ-9 improvements tended to occur in participants showing stronger decreases in beta/beta_1/beta_2 power at F3 and F4 ($\rho \approx -0.81$ to -0.86), and this pattern also aligned with a higher engagement score being associated with lower PHQ-9 improvement. For dissociation (DES-II), larger improvements were also related to decreases in parietal beta_2 and gamma at P3 ($\rho \approx -0.81$). For CAPS-5 total, improvements were instead associated with increases in frontal delta power at F3/F4 ($\rho \approx +0.80$). Overall, these exploratory results

suggest that larger symptom improvements were linked to lower frontal/parietal high-frequency activity and relatively higher low-frequency activity, which may reflect a calmer, lower-effort state. A similar decrease in beta activity has been reported during relaxing VR mindfulness (Tarrant et al., 2018).

In the POD condition, greater symptom improvement was mostly linked to lower high-frequency EEG activity and lower arousal index. Larger PTSD improvements (PCL-5) were associated with larger decreases in left-frontal beta_2 (and beta) ($\rho \approx -0.83$ to -0.86) and with decreases in the arousal index ($\rho \approx -0.86$). CAPS-5 improvements showed the same direction with the arousal index ($\rho \approx -0.83$). For dissociation (DES-II), larger improvements were linked to decreases in beta_2 and gamma over central, parietal, and occipital sites ($\rho \approx -0.73$ to -0.83), together with increases in occipital delta ($\rho \approx +0.71$). Taken together, these correlations suggest lower beta and gamma activity and more delta activity, which matches EEG reports in calmer, more absorbed states (DeLosAngeles et al., 2016). This is also consistent with stress studies showing that beta power often increases under stress (Vanhollebeke et al., 2022). However, after global FDR correction, for both experiments, none of the correlations remained significant, so the results should be interpreted with caution.

5.4.9 Changes in neural activity during sessions

Figures 5.15 and 5.16 show how brain activity at the right frontal site (F4) changes across the 12 sessions for both the PORTABLE and POD experiments for the delta and gamma bands, respectively. As can be seen, the delta power decreases over time in both experiments, with a stronger drop in the PORTABLE condition. Frontal delta activity is often linked to lower alertness or higher effort, so this decrease suggests that participants gradually become more comfortable and efficient during the sessions. This pattern matches the mixed-effects results, which also showed lower low-frequency activity at the end of the protocol compared to the beginning.

In contrast, gamma power at F4 increases gradually across sessions for both conditions, with slightly larger changes in the PORTABLE experiment. Frontal gamma activity is commonly linked to active processing and engagement. The increase over time, therefore, suggests that participants remained engaged and could process the experience more effectively as sessions progress. Together, the decrease in delta and increase in gamma power provide a clear visual summary of the neural changes observed in the statistical analyses.

5.5 Conclusions

This study explored two multisensory VR nature immersion interventions over a period of 12 weeks for patients diagnosed with PTSD. The first relied on a PORTABLE scent diffusion device for

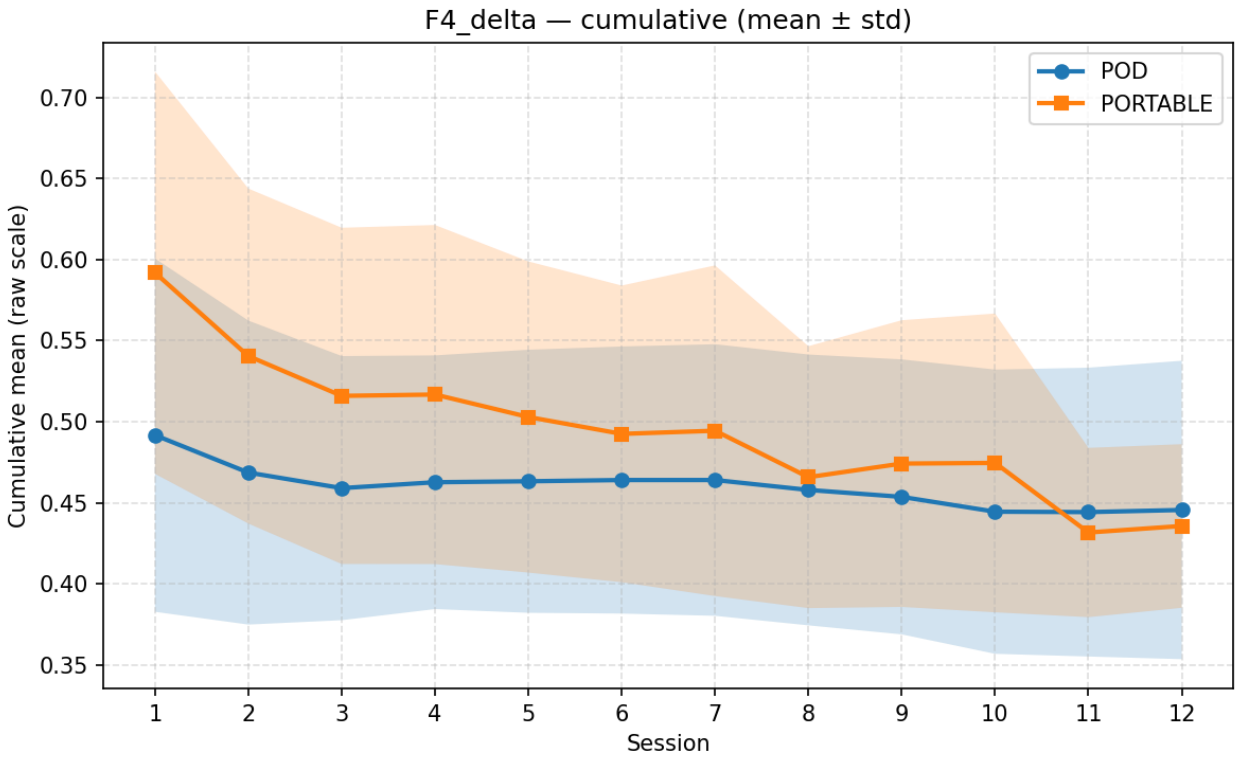


FIGURE 5.15 : Change in delta power at electrode F4 across the 12 sessions for the PORTABLE and POD experiment.

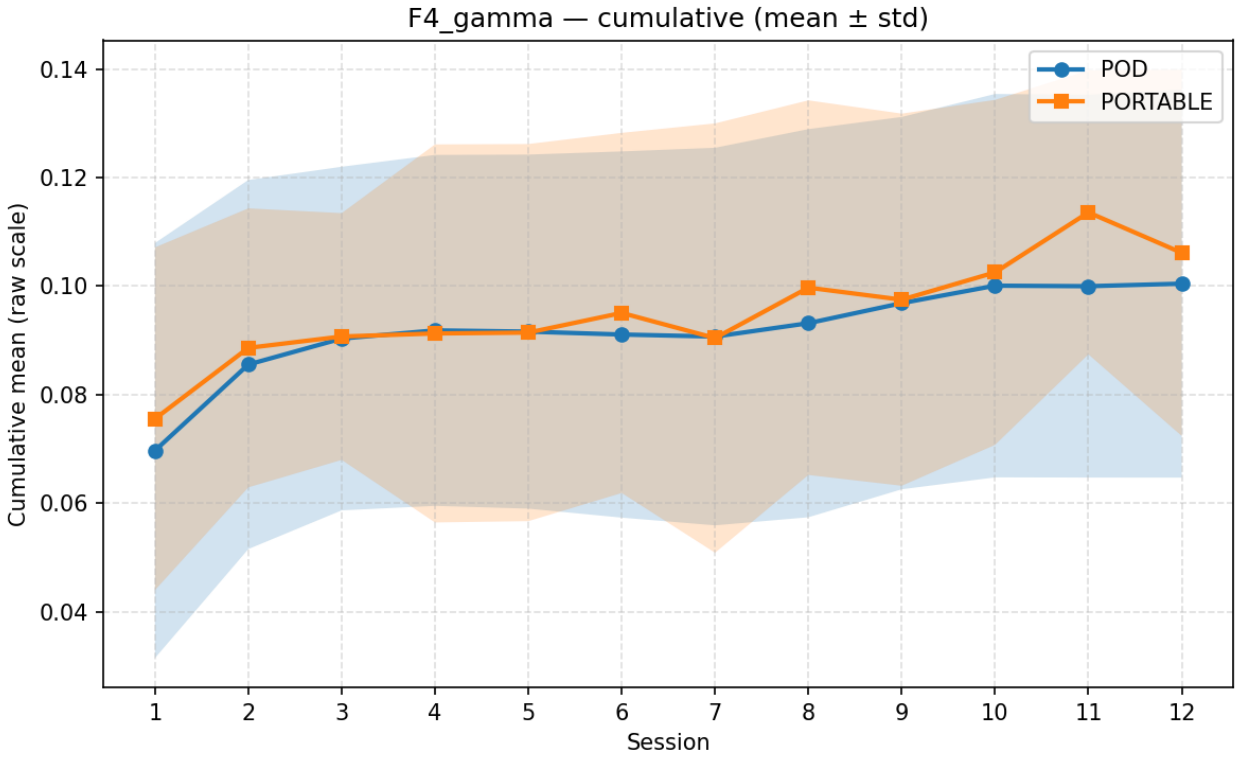


FIGURE 5.16 : Change in gamma power at electrode F4 across the 12 sessions for the PORTABLE and POD experiment.

audio-visual-olfactory stimuli, and the second on a multisensory POD with audio-visual-olfactory-haptic stimuli. We examined the impact of the two interventions across subjective responses and EEG activity across the duration of the protocol. We found that subjective measures of user experience remained stable across sessions, with no significant changes after correction for multiple comparisons. These results indicate that repeated exposure to multisensory VR was well tolerated and did not lead to increased discomfort or loss of immersive quality over time.

In contrast, EEG analyses showed clear changes in brain activity across sessions. Over time, low-frequency activity (delta and theta) decreased, while higher-frequency activity (beta and gamma) increased across several brain regions. These patterns were seen in the statistical analyses and in the session-by-session plots, and were also linked to changes in the perceived sense of Immersion in the POD experiment. Together, these results suggest that repeated multisensory VR sessions lead to gradual brain adaptation rather than fatigue. Although the number of participants was small, the findings motivate further studies with a larger sample population to confirm and extend these observations.

6 CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

6.1 Summary of contributions

Stress and trauma-related conditions are becoming more common and have increasing impacts on individuals, workplaces, and healthcare systems. From everyday stress to occupational burnout and clinical post-traumatic stress disorder (PTSD), there is a need for interventions that are accessible, tolerable over repeated exposure, and measurable using objective indicators that can complement self-reports. While nature exposure (e.g., shinrin-yoku) has emerged as a promising non-pharmacological intervention to reduce stress and anxiety, access to restorative natural environments remains limited for many people due to different factors, including geography, time, mobility, and/or clinical constraints.

In this thesis, we explored multisensory virtual nature immersion as an accessible and potentially therapeutic tool to promote relaxation and improve stress regulation. A central premise is that conventional audio-visual (AV) virtual nature may not fully reproduce the restorative quality of real-world nature, and that augmenting immersion by stimulating additional senses (i.e., via olfaction and somatosensory cues such as wind, heat, and vibroacoustics) would enhance both user experience and physiological engagement. In parallel, as multisensory interventions move closer to real-world and clinical settings, clinicians and researchers require practical ways to quantify outcomes and track progress; therefore, this thesis also demonstrates the importance of objective monitoring through neuro-physiological sensing, including via wearable sensors and by sensors directly integrated into the VR HMD.

A key contribution of this doctoral work is its step-by-step evaluation across three distinct populations in highly ecological settings. First, we tested the main hypotheses in a predominantly academic population under controlled pilot conditions. Second, we applied the approach to a demanding work environment by studying nurses in an in-patient hospital context, where time constraints, fatigue, and ecological validity are central. Lastly, we extended to a clinical population, conducting repeated multisensory VR nature exposure studies with participants diagnosed with PTSD in a psychotherapy clinic.

Chapter 1 introduced the motivation and thesis objectives. Chapter 2 then presented the background and related works. Chapter 3 presented the first experiment, where we tested the multisensory virtual nature experience by synchronizing additional sensory stimuli, such as olfaction, wind, heat, and vibroacoustics with a 360-degree nature video. This study provided initial evidence that increasing sensory stimulation can meaningfully improve perceived relaxation states relative to a conventional AV condition, and that physiological responses consistent with relaxed states could be observed.

Chapter 4 then investigated whether these effects also appear in a demanding occupational context by focusing on nurses in a stressful inpatient mental health ward. The work investigated how multisensory stimulation interacts with context and content (e.g., specific nature scenes) and highlighted that olfactory augmentation is not uniformly beneficial : sensory congruence and user-specific expectations can shape both subjective experience and neural patterns. Complementary analyses using heart rate variability (HRV) further provided an objective view of short-term regulation dynamics and reinforced the importance of robust sensing when deploying VR interventions in the field.

Lastly, Chapter 5 extended multisensory virtual nature exposure to PTSD populations through repeated-session protocols and multiple delivery formats (i.e., portable, with scent diffusion embedded into the HMD, and via a multisensory pod). This chapter evaluated whether participants could use the interventions repeatedly and comfortably, whether they were associated with changes in clinical symptoms and cognitive measures, and how the delivery format affected intervention outcomes. The study also assessed the neurophysiological changes associated with the repeated exposures. It was shown that multisensory VR nature-based interventions can be used repeatedly in a clinical workflow, while producing measurable changes in symptoms and/or objective markers.

Overall, the results presented in this thesis support three overarching conclusions. First, multisensory virtual nature immersion can be considered to be a feasible intervention across controlled, occupational, and clinical environments, but its effectiveness depends on content quality and sensory congruence rather than sensory addition alone. Second, adding synchronized smell and haptic sensations (such as wind or vibration) to an audio-visual nature VR experience can increase self-reported levels of relaxation and cause measurable changes in neurophysiological signals linked to arousal, engagement, and emotions. Third, integrating objective measurements into these types of interventions is not only feasible but can also provide important added value by enabling richer evaluation, highlighting individual differences, and supporting the development of adaptive interventions tailored to the user and their context.

6.2 Limitations and future work

Despite promising results, the studies in this thesis are not exempt from limitations. The first study, for example, was affected by the COVID-19 pandemic. Data collection took place in 2021, during lockdowns and at a period when recruitment and experimental access were strongly restricted. Due to these time restrictions, important details, such as the participant relaxation levels at the beginning of the experience, were not collected. The second study was conducted in a hospital setting with nurses. Because of their demanding schedules and the short period during which we had access to the premises, we could recruit only a limited number of participants. The same constraints also limited the duration of the protocol, so we tested only two conditions (AV and AVO), with exposures of 2.5 minutes each. These short sessions also reduce the sensitivity

of subjective and objective measures, especially for physiological metrics that benefit from longer windows, such as HRV. In addition, the need to keep the protocol brief led to simplified self-report measures, which are less reliable than standardized multi-item questionnaires.

The third study was also influenced by COVID-19 and by practical recruitment limits. Our clinical partner is located in Sept-Îles, QC, where the pool of eligible PTSD participants is smaller. In addition, because we compared two experimental formats, the analyses relied on a subset of participants, namely those who completed both formats. This further reduced the sample size for direct comparisons. Future work should focus on an increased number of participants to ensure greater statistical power. As well as the use of a baseline to register participants' state, both subjectively and objectively. All three studies also had as limitation the lack of a control condition (e.g., meditation and/or breathing exercises), which should be addressed in future studies.

Another limitation was the use of pre-selected smell intensity and types. This lack of customization meant that some subjects dropped out of the experiments because of sensitivity to the smells, while others did not appreciate the non-congruence of the presented smell with what was expected. A clear example of this was the beach smell in the study with the nurses. This caused biases in both the subjective and objective ratings. Future work should explore scent-enabling customization to reduce these unwanted effects.

In fact, congruence was shown to be important not only with smell-scene matching, but also with the congruence of pre-conceived expectations. The beach scene is another good example of this. Several nurses reported that they were expecting to see tropical beaches, which is what they thought of initially when imagining a relaxing environment. It is not feasible, however, to have a collection of videos for all possible beach types for an intervention. As such, a promising approach could be to leverage generative artificial intelligence (AI) tools that are emerging to personalize the immersive environment "on the fly" based on a text prompt generated by the user. While current generative AI tools still face limitations for producing long, high-quality 360-degree content that is fully consistent and suitable for extended VR sessions, technology is advancing at high speeds, and such tools may be made available in a very near future. We have already started looking into existing possibilities and described the potential and challenges of personalized AI-based immersive nature interventions in Lopes et al. (2025b). Future work should explore the use of generative AI models for real-time rendering of 360-degree videos, allowing for personalized virtual nature experiences that can improve both the user experience, as well as enhance intervention outcomes across users.

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