Une forêt de réalité virtuelle pour la réduction du stress physiologique chez les personnes sans troubles neurodégénératifs

Mémoire

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Résumé

Ce travail de recherche pour la réduction du stress physiologique a été effectué initialement auprès de personnes n’ayant pas de troubles neurodégénératifs en vue de soutenir le projet visant à résorber l’anxiété des personnes atteintes de la maladie d’Alzheimer, qui se trouvent à un stade avancé, qui ont perdu leur motricité et qui ne peuvent donc plus se promener dans la nature, ou en forêt.

L'exposition à la nature permet non seulement de se sentir mieux émotionnellement, mais elle contribue également au bien-être physique, en réduisant la tension artérielle, la fréquence cardiaque, la tension musculaire et la production d'hormones de stress. L'exposition à la nature à l'aide de technologies de réalité virtuelle pourrait donc apporter des avantages en termes de bien-être émotionnel aux personnes qui ne peuvent pas accéder à l'extérieur.

L’article 1 présente une revue de la littérature, qui montre que bien qu'il existe un corpus comparant les effets entre la nature réelle et la nature virtuelle, il n'y a pas beaucoup d'études qui ont comparé l'effet relatif entre la nature reproduite avec différentes techniques de développement en réalité virtuelle. Plus précisément, si les différences en termes d'exploration active ou passive, la richesse de la scène ou son dynamisme, pourraient affecter le potentiel thérapeutique de ces environnements simulés, n'apparaît pas encore clairement.

L'article 2 présente une étude auprès des adultes en bonne santé a été réalisée pour tester les effets de 10 min d'exposition à la nature virtuelle dans une forêt. L'objectif était d'évaluer si l'exploration d'une forêt virtuelle pouvait induire un état de connexion avec la nature, améliorer le confort des utilisateurs et réduire leur stress. Il a été émis l'hypothèse que l'exploration d'un environnement forestier virtuel à travers un visiocasque aurait un effet thérapeutique sur les manifestations de stress physiologique, dans un premier temps, chez l'adulte sans troubles neurodégénératifs.

Abstract

This research work for the reduction of physiological stress was initially carried out with people without neurodegenerative disorders in order to support the project aimed at reducing the anxiety of people with Alzheimer's disease, who are located at an advanced stage, who have lost their motor skills and who can no longer walk in nature, or in the forest.

Exposure to nature not only makes you feel better emotionally, but it also contributes to physical well-being, by reducing blood pressure, heart rate, muscle tension and the production of stress hormones. Exposure to nature using virtual reality technologies could therefore bring emotional well-being benefits to people who cannot access the outdoors.

Article 1 presents a review of the literature, which shows that although there is a body of work comparing the effects between real and virtual nature, there are not many studies that have compared the relative effect between nature reproduced with different development techniques in virtual reality. More precisely, whether the differences in terms of active or passive exploration, the richness of the scene or its dynamism, could affect the therapeutic potential of these simulated environments, is not yet clear.

Article 2 presents a study in healthy adults was performed to test the effects of 10 min of exposure to virtual nature in a forest. The objective was to assess whether exploring a virtual forest could induce a state of connection with nature, improve user comfort and reduce stress. It was hypothesized that the exploration of a virtual forest environment through a head-mounted display would have a therapeutic effect on the manifestations of physiological stress, initially in adults without neurodegenerative disorders.

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MA - Maladie d'Alzheimer

QdV - Qualité de vie

RV - Réalité virtuelle

IRDPQ - Institut de réadaptation en déficience physique de Québec

CIRRIS - Centre interdisciplinaire de recherche en réadaptation et intégration sociale

HMD – Head-mounted display (ou visiocasque)

ECG - Electrocardiogram

EEG - Electroencephalogram

EDA – Electrodermal activity (ou conductance cutanée)

ART – Attention restoration theory

SRT – Stress reduction theory

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Enfin, je tiens à remercier mon épouse Yesica, toute ma famille et mes amis qui m'ont accompagné tout au long de mon parcours académique.

Avant-propos

Ce mémoire est présenté sous forme de deux articles qui ont été rédigés par l'étudiant lors de son cursus à la maîtrise.

Le premier article intitulé « Scoping review on virtual reality environments for physiological stress reduction », a été écrit en 2020 et sera soumis à la revue : The International Journal of Design in Society. Cette revue décrit la littérature étudiant les effets de l'immersion dans des plateformes de nature virtuelle sur le stress mesuré par des signaux physiologiques. L'étudiant a voulu que cette revue soit utile à la communauté des chercheurs travaillant sur le développement de plateformes virtuelles pour restaurer le stress physiologique et induire un état affectif positif.

Le deuxième article intitulé « EEG-based affective responses to immersion in a virtual forest », a été écrit en 2021 et sera soumis à la revue : The International Journal of Design in Society. Cet article porte sur une étude qui a été menée pour étudier les effets de l'exploration de trois forêts de réalité virtuelle (RV) sur la réduction du stress physiologique et le changement d'état affectif chez des adultes sans troubles neurodégénératifs. L’article décrit trois méthodologies différentes qui ont été utilisées pour reproduire un environnement forestier : (1) à partir de la technologie lidar, (2) des modèles tridimensionnels et (3) une vidéo immersive à 360 degrés. L'expérience principale de cette étude a consisté en des sujets exposés à un environnement différent pendant dix minutes. Au cours de l'expérience, des données sur les états affectifs du participant ont été collectées à l'aide d'un nouvel outil numérique basé sur l'EEG.

L'étudiant a participé à la rédaction en tant que premier auteur de ces articles sous la supervision de la directrice de recherche, la professeure Jocelyne Kiss et des codirecteurs de recherche, les professeurs Martin Béland et Geoffrey Edwards.

Introduction

La maladie d'Alzheimer (MA) est une forme majeure de démence sénile [1]. La MA résulte du dysfonctionnement et de la mort de neurones dans des régions et des circuits spécifiques du cerveau qui sont généralement activés dans le processus de la mémoire et de la cognition [2, 3].

Cette maladie se caractérise par des déficits progressifs de la mémoire, des troubles cognitifs et comportementaux. Elle touche plus de 5,4 millions de personnes aux États-Unis. Sa prévalence, son coût des soins, son impact sur les patients et leurs soignants et le manque de traitements font de la MA l'une des maladies les plus accablantes [4].

Les symptômes neuropsychiatriques couramment observés dans la MA sont le syndrome apathique, le syndrome affectif (qui comprend l'anxiété et la dépression), ainsi que le syndrome psychomoteur (y compris l'agitation, l'irritabilité et le comportement moteur aberrant), le syndrome psychotique (tel que les délires et les hallucinations) et le syndrome maniaque (incluant la désinhibition et l'euphorie) [5].

La dépression et l'anxiété sont alors courantes; surtout pendant les phases initiales lorsque les patients sont encore conscients de leurs déficits de mémoire [6]. De plus, l'anxiété et l'agitation peuvent être causées par un certain nombre de facteurs différents tels que les médicaments, l'interaction avec les gens ou par toute circonstance qui aggrave la capacité de penser du patient. La personne atteinte de démence subit une perte profonde de sa capacité à gérer l'information et les stimuli. C'est donc une conséquence directe de la maladie.

L'anxiété est courante dans la population MA avec des estimations de prévalence allant de 5 % à 21 % pour les troubles anxieux [7] et de 8 % à 71 % pour les symptômes d'anxiété [8]. L'anxiété est associée à une mauvaise qualité de vie (QdV), à des problèmes de comportement et à des limitations dans les activités de la vie quotidienne, même après contrôle de la dépression.

Étant donné les preuves croissantes que le stress peut aggraver la progression de la MA, la question demeure de savoir si le soulagement des symptômes de stress contribuera au traitement de la MA [9]. Il est alors tentant de spéculer que si les patients atteints de MA qui souffrent de dépression, d'anxiété excessive ou d'épisodes d'agression reçoivent une attention neuropsychiatrique supplémentaire, une éventuelle intervention pharmacologique et, alternativement, des traitements non pharmacologiques, leur qualité de vie pourrait être améliorée.

Par exemple, le toucher thérapeutique, dont il a été démontré qu'il réduit les niveaux de stress, a été testé dans des essais cliniques avec des patients atteints de démence et les résultats ont indiqué une réduction des épisodes liés à l'anxiété et une légère diminution du cortisol salivaire [10].

De plus, il a été démontré que la musicothérapie soulage le stress et ralentit la perte cognitive chez les patients atteints de démence [11]. Bien que ces études suggèrent que la réduction du stress est bénéfique pour les patients atteints de MA, il reste à déterminer si cela ralentit également la progression de la maladie.

Par ailleurs, il est largement reconnu que le contact avec la nature favorise la santé et le bien-être [12]. Le potentiel réparateur de la nature a souvent été utilisé comme cadre théorique expliquant ces effets bénéfiques [13].

Selon la théorie de la restauration de l'attention [14] et la théorie de la réduction du stress [15], la restauration psychophysiologique fait référence à la capacité des environnements naturels à reconstituer les ressources cognitives épuisées par les activités quotidiennes et à réduire les niveaux de stress. Ces deux théories partagent une approche évolutionniste basée sur l'hypothèse de la biophilie [16] qui postule que les êtres humains ont développé une tendance innée à répondre positivement aux environnements naturels à des fins d'adaptation.

Il existe un grand nombre de preuves empiriques soutenant les avantages cognitifs, affectifs et physiologiques du contact avec la nature [12, 15, 17-19]. D’un autre côté, plusieurs études ont examiné l'effet thérapeutique potentiel de l'observation de la nature pour les personnes âgées [20, 21], ce qui incite à considérer que la nature pourrait avoir un effet thérapeutique similaire sur la population atteinte d'Alzheimer. Cela soutient également l'hypothèse selon laquelle une expérience virtuelle de la nature peut réduire les émotions stressantes et les comportements associés chez ces patients.

Problématique

Les personnes atteintes de la maladie d'Alzheimer souffrent d'épisodes aigus de stress et d'anxiété en raison de leur état. En plus des médicaments prescrits pour traiter ces symptômes, il existe des traitements alternatifs qui peuvent aider à réduire leur anxiété. L'une de ces alternatives pourrait être de permettre à ces patients de faire l'expérience de la nature à l'aide de technologies de réalité virtuelle. Cependant, les études qui existent sont majoritairement focalisées sur l'effet absolu entre le milieu naturel et un milieu urbain, donc un effet relatif entre différentes manières d'expérimenter la nature simulée n'a pas été étudié afin de connaître l'approche la plus appropriée pour que cette population puisse bénéficier de cet outil. Dans quelle mesure, un environnement immersif reproduisant le contexte naturel forestier permettait-il de réduire le stress physiologique ? Comment des différentes formes d'environnements immersifs qui reproduisent la forêt naturelle diffèrent-elles en termes d'effets sur la réduction du stress ?

Objectif de la maîtrise

Les objectifs de ces travaux à la maîtrise sont de participer au processus de conception d'un outil de réalité virtuelle simulant une promenade en forêt et, par des mesures expérimentales, de déterminer si cet outil aurait un effet réparateur chez l'utilisateur sur des états affectifs négatifs et des marqueurs physiologiques reliés au stress.

Plus précisément, cette maîtrise se veut une étape préliminaire à une étude destinée aux participants atteints de la maladie d'Alzheimer. Une application simulant une visite virtuelle sera développée avec un réalisme et une esthétique élevés, cependant, l'évaluation de son effet thérapeutique sera réalisée avec des adultes sans conditions neurodégénératives dans un premier temps.

Ce travail de maîtrise a permis le développement de trois scènes immersives virtuelles dans le but de créer une sensation de connexion authentique entre l'utilisateur et un environnement naturel. De plus, ce projet a permis de mieux comprendre les mécanismes sous-jacents qui influencent la façon dont l'exposition à des environnements virtuels contribue à promouvoir un état affectif positif.

Méthodologie

Le premier travail réalisé dans le cadre de cette maîtrise est une revue de la littérature sur des milieux naturels simulés en réalité virtuelle pour la réduction du stress physiologique, avec un focus comparatif sur les méthodes de mesure des fluctuations des marqueurs liés au stress. Cette revue a suivi les normes PRISMA-ScR (preferred reporting for items for systematic reviews and meta-analyses, http://www.prismastatement.org/), mais n'a pas été enregistrée. Dans les résultats de cette revue, nous comparons de manière succincte les résultats d'études sur l'exposition à la nature virtuelle pour la réduction du stress. Nous décrivons également les protocoles expérimentaux, les types de paysages naturels simulés pour produire des bénéfices thérapeutiques, et les mesures du stress physiologique les plus couramment utilisées pendant ces expériences.

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Le deuxième travail est une expérience, en tant qu'étude préliminaire à celle à mener auprès de patients atteints de la maladie d'Alzheimer, qui nous a permis d'examiner comment la nature peut améliorer le bien-être d'une personne en utilisant un casque de réalité virtuelle comme nouvelle approche pour renforcer un état affectif positif. Dans cette expérience, les participants ont exploré une forêt virtuelle. La forêt virtuelle a été reproduite de trois manières différentes. Les états affectifs des participants ont été mesurés à l'aide d'un outil basé sur l'EEG tout au long de l'exposition à la nature virtuelle. Nous avons émis l'hypothèse que les différences de réalisme, de dynamisme, de contenu des scènes et de mode d'exploration des différents environnements de nature virtuelle auraient un impact différent sur leurs états affectifs et donc sur la réduction du stress physiologique. Les résultats de ces travaux sont mixtes, cependant, ils s'inscrivent dans le cadre de la littérature qui décrit les avantages sur des états affectifs de l'expérience de la nature par le biais de la réalité virtuelle.

Structure du mémoire

Le premier chapitre de ce mémoire porte sur la revue de la littérature. Le chapitre 2 présente et discute les résultats expérimentaux et évalue les effets thérapeutiques des trois environnements forestiers simulés.

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Chapitre 1 Scoping review on virtual reality environments for physiological stress reduction

1.1 Résumé

Le but de cette étude était d'explorer les preuves de l'exposition à la nature virtuelle pour la restauration du stress physiologique. Cette revue a été réalisée selon la méthodologie PRISMA-ScR. Sept bases de données bibliographiques ont été consultées. Des critères d'inclusion ont été établis et tous les résultats ont été examinés en fonction de ces critères. 88 titres ont été initialement identifiés, dont 16 études ont été incluses dans cette revue. La moitié des articles ont comparé un groupe conditionnel versus témoin (milieu urbain versus milieu naturel). Les chercheurs ont utilisé des films bidimensionnels (n = 4) et des vidéos immersives à 360 degrés (n = 3) pour afficher les environnements virtuels. La moitié des études ont reproduit des scènes forestières. 11 mesures différentes utilisées pour évaluer les effets des doses naturelles sur la restauration du stress physiologique ont été identifiées parmi ces études.

1.2 Abstract

The aim of this study is to explore the evidence of virtual nature exposure for physiological stress restoration. This review was carried out using the PRISMA-ScR methodology. Seven bibliographic databases were consulted. Inclusion criteria were established, and all results were examined against these criteria. 88 titles were initially identified, of which 16 studies were included in this review. Half of the articles compared a conditional versus control group (urban environment versus natural environment). The researchers used two-dimensional films (n = 4) and immersive 360-degree videos (n = 3) to display the virtual environments. Half of the studies reproduced forest scenes. 11 different measures used to assess the effects of natural doses on physiological stress restoration were identified among these studies.

Introduction

Rationale

As both practitioners and researchers are interested in using virtual reality tools to support mental health and well-being, we investigated the available evidence to support making informed decisions regarding the development of immersive restorative environments. This involved finding which instruments have produced a positive impact on individuals' mental health and well-being and describing what kinds of engagement with virtual nature (equipment used, type of environment presented, time dose experienced, etc.) provide said impacts.

Theoretical basis

Green environments and stress recovery

Exposure to nature has been found to help recover from physiological stress and mental fatigue [1]. Also, a close positive association between exposure to green environment and human health supports that visiting natural habitats is an efficient approach for stress-caused ailments prevention [2].

Two theoretical frameworks explain the reduction of physiological and mental stress when experiencing nature. The Attention restoration theory [3] suggests that the cognitive and affective benefits of exposure to nature are caused by the recovery of the cognitive resources necessary to direct and maintain attention. Kaplan proposes that such recovery occurs through the use of effortless attention which is facilitated by stimuli that a person would perceive as fascinating. However, fascination may be necessary but not sufficient for complete restoration: the fascinating stimuli must be part of an environment that creates a sense of being away from directed attention demands.

Ulrich's Stress restoration theory [4] is also based on evidence of the benefits of natural environments and how they can reduce physiological arousal after stress. These benefits, and the associated improvements in positive affect and attention, are argued to arise as a function of interest and positive affective evaluations of natural environments that possess certain adaptive qualities. These qualities can be aesthetic, such as levels of complexity, pattern, depth, surface texture, and mystery within an environment, or semantic, such as the absence of threat and the presence of resources. These positive appraisals of such settings and subsequent reductions in arousal and negative affect lead to recovery from physiological stress and exhausted attention.

Nature and virtual reality

A virtual environment is an artificial world, created by computers, that induce a sense of presence to the experiencer [5]. Their use has been applied in areas such as entertainment, simulation, industrial and architectural design, training and medicine [6]. Restorative environments appear to be and additional area of application of virtual reality technology for relaxation and restoration purposes [7]. Virtual reality technology facilitates the manipulation of an environment allowing the designer to disentangle, prioritize and emphasize the various characteristics of an original environment. The versatility of using virtual reality to replicate nature allows the content of a computer-generated environment to be based on its creator's sense of natural objects and phenomena, even when this number is finite, as opposed to the number of variables that can be found in real nature. Given this dissimilarity, it has been determined that virtual nature is more an interpretation of what nature is, than the result of a replication process, such as that found in a photograph or video [8].

This review aims to fill the gap in the literature on experimental protocols used in studies of restorative virtual environments and different measures of stress restoration, focusing on physiological markers.

The present research asked: (1) What physiological methods have been jointly used to assess fluctuations in stress restoration? (2) How do experimental protocols for assessing the efficacy of restorative environments differ in the identified literature? It is hoped that answers to these questions will further the development of the field of restorative environments, as well as the development of a unified theoretical research framework for the study of their potential effects on physiological stress reduction.

Terminology

Physiological stress

According to Selye [9], indicators of stress are indicative of the over-stimulation of the adrenal and autonomic systems of the body. Adrenal outputs (i.e. epinephrine and norepinephrine) and autonomic outputs such as blood pressure (with its systolic and diastolic components), respiratory rate, pulse rate, galvanic skin response, focal activity, electrical brain activity, and glucose and cortisol levels appear on Selye's list of stress indicators. Although both adrenal and autonomic responses are essential, autonomic responses are generally easier to measure [10, 11].

Measures of physiological stress

Several types of measuring physiological stress through autonomic responses of the body have been identified.

EEG

Electroencephalography is one of the most widely used brain-related measures in the field of cognitive science. The EEG measures the electrical potential of the activity of neurons located perpendicularly to the scalp in a passive and non-invasive way [12]. EEG signals present amplitudes between 2-100uV, a dynamic range between 0.5-60Hz and can be analyzed in different ways. Continuous EEG signals are generally divided into frequency bands: delta, theta, alpha, beta, and gamma, and interpreted in relation to human behavior and cognitive processes [13]. The power spectrum of frequency bands has been extensively explored to describe intra-individual changes associated with the stress response [14]. The predominance of alpha waves is observed during states of relaxation or under conditions of minimal cognitive demand or emotional tension. In contrast, conditions with significant processing demands or high levels of alertness are associated with the occurrence of higher frequency rhythmic activity, such as beta waves [15].

The EEG asymmetry index is defined as the natural algorithm for subtracting the alpha power from the right to the left hemisphere and is another indicator of stress that reveals emotional arousal [16]. Studies support the idea that during stress states there is generally greater right frontal alpha activity relative to left alpha activity [17]. The decrease in alpha waves and the increase in beta activity, as well as the decrease in the alpha asymmetry index, can provide reliable estimates of stress [18].

GSR

The galvanic response of the skin, also known as electrodermal activity (EDA), conductive skin responses (SCRs) or skin conductance level (SCL) measures how electrical variations in the skin activate the eccrine sweat glands. Skin conductance level has been associated with emotional states such as stress, excitement, engagement, frustration and arousal [19]. The EDA signal is characterized by a baseline, from which phasic disturbances arise in response to certain events. An EDA signal can be decomposed into two main components: a low-bandwidth reference tonic component (3Hz) that expresses the thermal regulation activities denoted as electrodermal level (EDL), and an electrodermal response phase component (EDR) that expresses responses related to psychology when a regulatory activity of the sympathetic nervous system occurs. The mean value of the EDA signal allows us to infer the level of excitation and activation of the sympathetic nervous system since the EDA response is usually observable in a stressful or surprise event when an increase in perspiration decreases the resistance of the skin [20]. Ionic sweat is more conductive than dry skin; therefore, it causes an increase in conductivity proportional to the amount of filling of the glands coordinated by sympathetic activation due to external sensory or cognitive stimuli [21].

ECG

Heart rate (HR) is the calculation of the average heartbeat per period of time, usually 1 minute. Instead, heart rate variability (HRV) is the measure in milliseconds of the changes between successive beats called the R-R interval. Heart rate variability comprises high-frequency bands (0.15-0.40 Hz) and low-frequency bands (0.04 - 0.15 Hz). The high-frequency band reflects the parasympathetic nervous system's activity, and the LF / HF ratio is an indicator of the sympathetic nerve's activity.

The most common experimental methodology for measuring heart rate is electrocardiography (ECG or EKG). The ECG records changes in electrical potential associated with the heartbeat. Photoplethysmography (PPG) is also popular due to its affordability. PPG uses a pulse oximeter that illuminates the skin and detects changes in light absorption to detect blood volume changes in microvascular tissue, thus indirectly measuring heart rate.

Although physiological measures are objective indices of the level of stress experienced by a subject, there is no consensus on which measure is the best to use. In addition, many of these measures have practical limitations, such as requiring the subject to be still, requiring a long preparation time or being expensive, so they cannot be applied to all types of interventions.

Objectives

Research question

This study looked to describe the body of evidence of virtual nature exposure for physiological stress restoration in terms of implemented experimental protocols, technology used for immersion, natural scenery reproduced, exposure time and physiological methods utilized to measure a potential restorative effect.

Methods

Study design

Over the years, three types of literature surveys have been proposed: exploratory surveys, scoping surveys, and systematic surveys [1]. The methodology used here was a scoping review of the literature of published research articles that involves examining the available state-of-the-art evidence that provides information on the volume of literature and an overview of its approach [2]. This type of review has been chosen as it is currently difficult to know the amount of evidence available or its significance. The first step was to define the research questions and establish the study protocol. Second, relevant research manuscripts were identified, considering articles written during the last three decades. These articles were then reviewed at different stages, based on their titles, abstracts, and keywords. Subsequently, a sub-sample of articles was evaluated. Finally, the reviewed research information was summarized and classified into the current review as a step forward to surface and describe themes and gaps and a more focused research.

Scoping review protocol

Following PRISMA-ScR standards for scoping reviews, we carried out this review (preferred reporting for items for systematic reviews and meta-analyses, http://www.prisma-statement.org/). The review protocol can be accessed upon request, but it was not registered.

Data sources

The search for relevant articles was carried out using some of the most popular and interdisciplinary databases of scholarly articles: SpringerLink, ScienceDirect, MDPI, Taylor & Francis Online, Mary Ann Liebert Inc., Frontiers and NCBI. Keywords used for the search included "virtual environments" or "virtual nature", and "physiological stress" or "physiological effects". These words were searched as keywords, title, and subject terms in the abstract. We also use the "cited by" search tools, and findings were cross-checked with references from review articles.

Study selection, data extraction

Studies were eligible for inclusion in this scoping review if they met the following criteria: (1) study protocols included physiological – objective measures to asses stress restoration and/or relaxation effects such as EKG, EDA, EEG, etc. (excluding studies that only used semi-structured interviews or other qualitative approaches); (2) studies compared participants across at least two virtual environments; (3) scenery visualization formats were distinct from two-dimensional static images, that is, researchers incorporated high-definition videos, immersive 360-degree formats or virtual environments; researchers used virtual reality technology to perform immersion such as head-mounted displays (HMDs), high definition screens or monitors, or wall projectors (4); and (5) the study was published in English or French. Studies that did not meet these criteria were excluded.

After deduplicating potential articles, all titles and abstracts were screened for relevance based on our inclusion criteria by a reviewer. Manuscripts not excluded based on titles and abstracts, were reviewed and for each included study, study characteristics, sample characteristics, and results were extracted to thematic tables.

Data analysis

Given the multidisciplinarity of the subject matter of this review and that many of the included studies relied on small sample sizes, this scoping review used a thematic analysis to look across studies and pulled out themes for future consideration.

Results

Included studies and characteristics

In sum, 88 resources were identified and once de-duplicated, 69 titles and abstracts were screened for relevance and inclusion including results from gray and white literatures. A total of 30 papers were considered via full-text review, and of those, 16 papers were included for the analysis; Figure 1-1 shows the workflow followed in this review. Open access articles, articles published in peer-reviewed journals and conference proceedings were included. From these included papers, data were extracted and collected to define the number of experimental conditions, visualization format of the scenery, the chosen type of restorative environment and the physiological method used to assess a potential restorative effect. This information is summarized in Table 1-1.

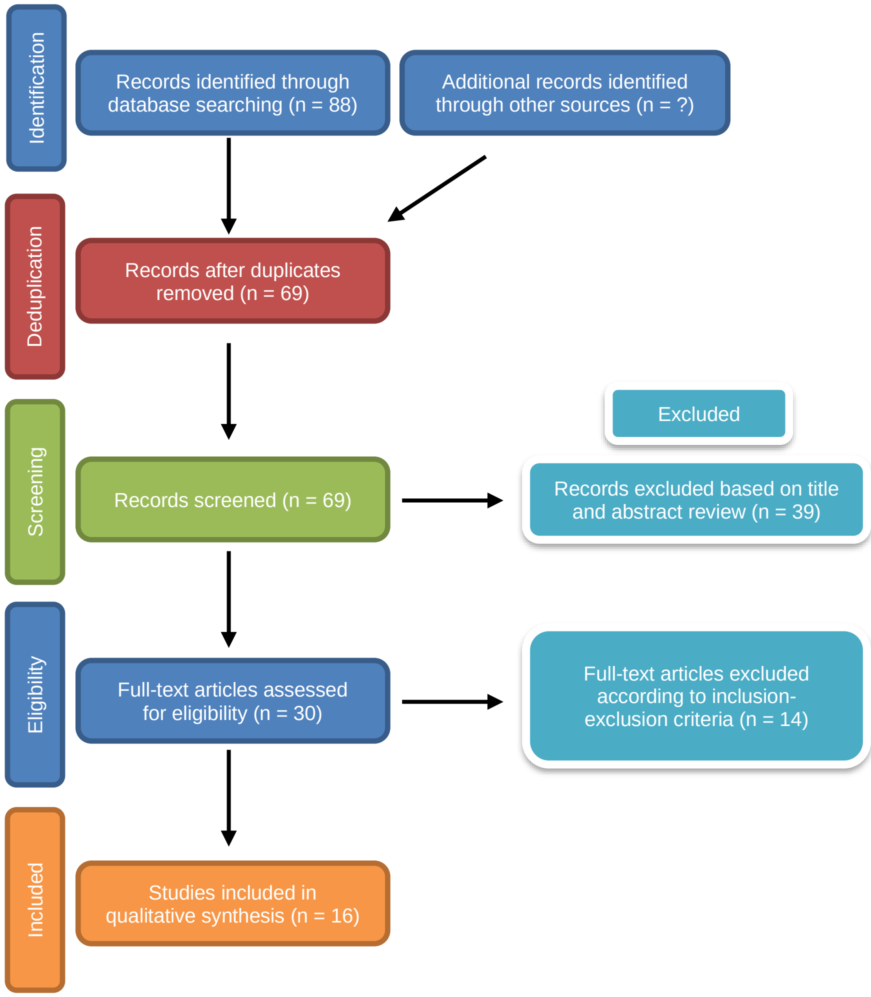

Figure 1-1 PRISMA flow diagram followed for this review

Demographics

16 articles with a total sample size of 708 participants were included in this scoping review. All included papers summarize studies that were implemented and published since 1998 and included people of all ages and origins; 13 of the 14 papers noted that the participants were healthy. The studies had a minimum of 12 participants as sample size; two studies had more than 100 participants (120 and 154 participants). Only one study included only male subjects; this study was conducted in Sweden and represents 30 people measured. The remainder of the studies include males and females, with more females studied than men overall (58% of the total sample was female). The gender of 22 participants was not reported. Four studies took place in the USA, three in Sweden and two in the Netherlands. The remaining studies took place in Japan, Taiwan, Canada, Switzerland, Germany, China, Australia and the UK.

Table 1-1 Characteristics of included studies

Study	Sample	Location	Exposure time	Focus of study	Stimuli / Type of nature	Physiological measures
Ohsuga et al. (1998)	27 healthy subjects, Mean 35 years, 30% female	Hyogo, Japan	5 min.	Improve the quality of life for bedridden patients and the elderly.	Simulated forest stroll, birds chirping and a babbling brook; fragrance of trees.	HR (ECG), RESP
De Kort et al. (2006)	80 healthy subjects, Mean 24 years, 64% male	Eindhoven, Netherlands	10 min	Investigate the importance of immersion in a mediated environment.	Compilation of nature scenes without sound, semi-open bushes and shrubs, as well as trees and water.	SCL (GSR), IBI (ECG)
Valtchanov et al. (2010)	22 undergraduate students, Mean 21.5 years	Ontario, Canada	10 min.	Examine whether immersion in a virtual computer-generated nature setting could produce restorative effects.	Photo-realistic forest with various shrubs, flowers, trees, small bodies of water (streams and small ponds), and rocks.	SCL (GSR), HR (ECG)
Annerstedt et al. (2013)	30 healthy Swedish males, Mean 27.7 years	Sweden	40 min	Explore physiological recovery in two different virtual nature environments (with and without exposure to sounds of nature).	Trees in a forest surrounding a path leading to a stream of water, reminiscent of a natural setting in Scandinavia.	Cortisol, HR, T-wave, HRV (ECG)
Anderson et al. (2017)	18 healthy participants, Mean 32 years, 50% female	New Hampshire, USA	15 min	Evaluation of VR-presented natural settings for reducing stress and improving mood.	Large expansive natural vistas with views of water. Beach locations including natural vistas not including animals.	EDA (GSR), HRV (ECG)
Gerber et al. (2017)	37 healthy adults, Mean 48 years, 62% female	Berne, Switzerland	10 min	Test the feasibility and effects of controlled visual and acoustic stimulation in a virtual reality setup in an intensive care unit.	Three 2D nature videos containing natural scenes; (a) hot-air balloon perspective of mountains, and water world filmed (b) over or (c) under sea level.	HR (ECG), RESP, Blood oxygen
Reynolds et al. (2018)	14 adults with moderate to severe dementia, Mean 85 years, 57 % female	Arizona, USA	60 min	Test whether a virtual nature experience, within a memory care unit, could reduce stressful emotions of agitation and anxiety among patients with dementia.	Unedited nature video: waterfall in the foreground and a distant view of mountains in the background, with naturally occurring sounds.	HR (ECG)
Van Almkerk et al. (2018)	36 students, Mean 23.3 years 27% female	Enschede, Netherlands	Total of 200 seconds	Investigate the role of a more quantifiable parameter – fractals- in the restorative effects of virtual nature.	Virtual nature containing stress with specific fractal dimensions ranging from 2.1 to 2.9.	EDA (GSR), HRV (ECG)

Table 1-2 cont. Characteristics of included studies

Study	Sample	Location	Exposure time	Focus of study	Stimuli / Type of nature	Physiological measures
Yu et al. (2018)	30 healthy participants, ages between 20-29, 56% female	Taipei, Taiwan	9min and 30 seconds	Examine the influence of forest and urban environments on restoration.	The Aowanda National Forest Recreation Area at Nantao, Taiwan, famous for its forest and waterfalls.	HRV (ECG), alpha amylase
Amores et al. (2018)	12 participants, Mean 28.2 years, 33% female	USA	5 min	Propose a virtual reality experience that integrates a wearable EEG headband and olfactory necklace that passively promotes restoration.	Beach.	EEG
Blum et al. (2019)	60 healthy participants, Mean 33.5 years, 52% female	Freiburg, Germany	10 min	Investigate the benefits of using virtual nature environment to administer immersive heart rate variability biofeedback.	Virtual beach scenery at sunset; it included palms, rocks, several light sources and a campfire.	HR, IBI (ECG)
Gao et al. (2019)	120 Chinese college students, Mean 20.7 years, 52% female	Xianyang, China	10 min.	Employ virtual reality technology to investigate the psychophysiological responses and individual preferences for different simulated natural environments.	Various set of landscapes with different percentage of visual field covered with tree canopies.	EEG
Hedblom et al. (2019)	154 individuals, Mean 27 years, 52% female	Stockholm, Sweden	3 min	Compare the effects of visual stimuli to the effects of congruent olfactory stimuli and auditory stimuli on physiological stress restoration.	Park environment was dominated by lawn and managed pine trees. Forest resembled a primeval forest with different tree layers.	SCL (GSR)
Schebella et al. (2020)	52 participants, Mean 37.6 years, 54% female	Australia	5 min	Investigate whether recovery from stress differ between urban and natural immersive virtual environments.	Videos of real parks located in metropolitan Adelaide, South Australia, along with soundscapes and olfactory stimuli.	EDA (GSR), HR (ECG)
Wood et al. (2020)	18 participants, Mean 32.2 years, 55% female	Colchester, UK	20 min	Examine the influence of the visual exercise environment on the response to a psychosocial stressor.	Scenes extracted from “Evening run through endless forest” (Outside Interactive, MA, USA)	Salivary cortisol
Biber et al. (2020)	13 participants, Mean 67.08 years, 62% female	Virginia, USA	10 min.	Understand how different immersive technologies impact the effect of both nature and urban environments on acute stress.	Nature images	GSR, HRV (ECG)

Synthetized findings

Experimental conditions

The most recurrent experimental design among the articles was comparing the effects of restorative environment with a control condition without varying the immersive technology. Control conditions included abstract painting slides [3], a movie film [4], urban settings [5], and standard bio-feedback treatment [6].

Two studies focused on understanding how different immersive technologies impacted the effect of virtual nature on acute stress; either varying the screen size between two natural conditions [7] or letting participants experience nature and urban mediated environments through a flat computer screen, a 180-degree vaulted screen or a virtual reality viewer [8].

A model of experimentation that is also recurrent is comparing variations of a restorative environment against a control. Some of this setting variations include restorative environments with and without natural congruent sounds [9], natural settings with high or low fractal-based natura potential [10], several forest environments with varying vegetation [11], restorative environments with variations with low, moderate and high biodiversity density or different restorative environments such as beaches and rural landscapes [12].

Three studies could not be included into the categories above mentioned; that is, they presented alternative experimental designs. One study compared the effects of all the functionalities of the system designed by the researchers, that is, wide-angle vision, scented breeze, three-dimensional sounds and a custom foot device to simulate a walk through the virtual environment, to a control condition which only included the walking device [13]. One other study added a blank screen as a control condition [14] while others compared three two-dimensional videos that contained different natural scenes [15].

Elicitation materials

Five studies [4, 7, 13-15] reported using two-dimensional films of real natural landscapes as elicitation material. The minimum duration reported for this format was 10 min [7], while the longest duration was a 1-hour fixed-angle raw nature video [4]. Four studies [5, 16-18] reported using 360-degree real environment videos as presentation materials. Only one study [12] reported its duration in 15 minutes. Three studies built their restorative environments using game engines [3, 6, 10]. Two studies [8, 19] reported using panoramic photographs, while only one study [12] reported the resolution of such photos as 2560 by 1440 pixels. Finally, in Hedblom's study [11], 360-degree photographs were used, while Annerstedt et al. [9] did not report his audiovisual material format.

Hardware

The head-mounted display was used as the hardware to perform the immersion in eleven studies. Two studies [12, 15] reported using the Oculus Rift model DK2 head-mounted display (Oculus VR, Menlo Park, CA); additionally one study [6] used the CV1 version to present the restorative environment. Other authors reported have used Oculus brand head-mounted displays [11, 18] , but only in one study the used model was specified as the Oculus Go [8]. Moreover, the HTC Vive head-mounted display (developed by HTC and Valve Corporation) appears to be used in two studies [5, 10], while some other head-mounted display brands such as the NVIS (Reston, VA) [20], the Samsung Gear and Google Daydream VR [17], or the Pico Goblin VR [19] have also been reported to be used within the literature.

In four studies, screens were used as hardware to perform the immersion. LCD screens [13, 21], high-definition televisions [4] and flat laptop screens [8] were included in this category.

Alternative hardware used to perform the immersion include the GeoDome (developed by Elumenati), which consisted of a domed screen with a 180-degree view on which visual stimuli were projected while participants sat without using headphones [8], and the CAVE system (developed by EON Development Inc) with three rear-projected walls (4 m x 3 m) and a floor projection [9].

Restorative environments

Some studies presented more than one restorative setting.

In seven studies, the forest was presented as the restorative virtual environment. Six of these seven studies were reproduction of real environments. Recreated environments included: a journey leading to a stream of water assimilating an existing environment in Scandinavia [9], the Aowanda National Forest Recreation Area in Nantao, Taiwan [5], an urban forest that had not been managed for more than 30 years resembling a spring forest [11] and visual scenes from "Evening Run through Endless Forest" [22]. A study recreated a forest in an area equivalent to 1600 square meters based on the model from the video game Elder Scrolls IV: Oblivion [20] while other authors focused their design on the detail of treetops [10]. Finally, one study [19] did not reported the influence of their design but described its restorative environment by having a visual coverage of the scene dominated by tree-shrub canopies.

In three studies, the park was used as a restorative natural environment [11, 18, 19]. Descriptions of these type of environment included: visual coverage moderately dominated by shrub canopies [18, 19], lawns and managed pine trees [11].

In four studies, semi-open landscapes were presented as restorative natural environments [8, 11, 18, 19]. Additionally, some authors presented the beach as the restorative virtual environment. Beach representations included locations on the Australian coastline [16] and a beach setting where palm trees, rocks, various light sources, and a campfire could be found [6]. Finally, one study presented two different categories of restorative environments, namely, an underwater world scene with scenes shot above sea level (waves on a beach, a waterfall in the jungle) and below sea level (coral reefs and fish) [19].

Physiological measures and reported effects

Heart rate (HR) was used as an indicator of the physiological response to stress in 7 studies. A wide range of electrocardiogram instruments used to record beats per minute was identified. Two studies reported using vital signs monitoring systems [13, 15], two studies reported using pulse oximeters [3, 4], while the rest used E4 Empathic electronic wristbands [18], a Polar H7 chest strap [6] and disposable electrodes [9]. The reported results are mixed, the majority reported a lower heart rate after the interventions [3, 4, 6, 9, 15], one study reported no significant differences [18], while Ohsuga et al. [13] attributed to the movement of the legs the increase in heart rate.

Heart rate variability (HRV) was used as an indicator of physiological stress in 5 studies. Because heart rate variability is a derivative of the heart pulse rate, the researchers collected the pulse using electrocardiograms. Three studies reported using electrodes to record the encephalogram [8, 9, 16], Yu et al. [5] used wrist rings, and one study [10] did not report the instrument used to capture these signals. The results reported in the literature are mixed, having found no significant differences in the physiological responses of the participants [5], decrease in the high-frequency component (HF) [9, 16], increase in the LF / HF ratio [16] and an apparent reduction in physiological stress [10].

Only one study reported using the inter-beat interval (or cardiac period -IBI) as a physiological measure of stress [7]. Two BIOPAC Ag-AgCl disposable shielded electrodes with a contact area of 10mm placed on each wrist were used in this study in order to collect the EKG signal. Reported results indicated a faster recovery in the more immersive condition.

Skin conductance (SC) or Electrodermal Activity (EDA), or Galvanic Skin Response (GSR) was used as an indicator of stress in 7 studies; however, one study did not report results since the readings were incomplete [18]. The instruments most used to measure skin conductance were Ag / AgCl electrodes located on the index and middle fingers of the dominant hand [11, 16], the non-dominant hand [3, 7] and three fingers of each participant [8]. Additionnally, a study measured this physiological response in the wrists using Empatica E4 bracelets [18]. Reported results include significantly lower stress levels in restorative environments during recovery periods [3, 7, 11], a decrease in EDA below baseline [16] and, inversely, above baseline levels [8], and SNS less active in the presence of virtual nature compared to control stimuli [10].

Blood pressure (BP) was used as an indicator of physiological stress in 3 studies. Details on the blood pressure monitors used among the literature could not be retrieved [8, 13, 15]. The reported results are mixed; with no significant difference in both systolic and systolic components influenced in the physiological responses of the participants [5, 13], reduction both BP components [15].

The electroencephalogram, measure used to record brain activity and mental state, (EEG) was used in 2 studies [17, 19]. One study [17] reported using a modified version of the low-cost commercial wearable headband for non-medical purposes Muse (Interaxon Inc, Toronto) was used. This flexible headband provided readings from the TP9, AF7, AF8, and TP10 electrodes located based on system positions 10-20 while an algorithm was used that calculated a "Relax" score based on the Rényi entropy [23]. Other authors [19] reported using a portable NeuroSky brain wave device was used to measure human physiological responses via electrodes attached to the scalp and alpha waves (range 8-13 Hz) were used as the primary indicator of physiological stress since higher values of EEG alpha waves indicate a better restoration of physiological stress [24]. Reported results suggested that the impact on users' relaxation increased with the duration of exposure to the system, while in others, the least degree of stress was detected when the participants' eyes were closed.

Two studies used the respiratory rate as a physiological indicator of stress. Both used vital sign monitoring systems to record these responses. Although there were inaccuracies in some participants' measurements, one study [15] reported a significant decrease in respiratory rate. On the other hand, Ohsuga's [13] study reported an increase in respiratory rate, attributed to the leg exercises performed during the intervention.

Salivary cortisol was used as a physiological indicator of stress in two studies [9, 14]. In one study [9] cotton swab sampling tubes (Salivette, Leicester, UK) were used to collect saliva samples, whereas, in Wood's study [14], saliva samples were collected using salivettes (Sarstedt Ltd Leicester, UK). The processing methodologies differed from each other; in Annerstedt’s study [9], the samples were processed with radioimmunoassay (RIA) designed for the quantitative in-vitro measurement of cortisol; however, results reported a lack of effect of the restorative environment on the cortisol response. In Wood's study [14] an enzyme-linked immunosorbent assay determined cortisol concentrations. This study reported significantly lower cortisol reactivity of participants in the control condition than participants in the natural condition.

Other less common physiological stress measurements found in the literature include alpha salivary activity, T wave, blood oxygen, and cardiac coherence.

Yu et al. [5] used one of the salivary enzymes, the alpha-amylase, through which the sympathetic nervous system's activity can be detected [25]. The sympathetic nervous system's activity induced by psychological stress is differentiated by a higher level of alpha-amylase activity in saliva. In their study, salivary alpha-amylase was measured using a salivary amylase monitor (DM-3.1, NIPRO - Japan) by measuring hydrolyzing reaction time. A decrease in the SAA of the participants after experiencing forest environments was reported.

Annerstedt et al. [9] examined participants’ T-wave; its amplitude is suggested to be related to sympathetic **β**-adrenergic influences on myocardial performance [26]. In that study, the T-wave amplitude was calculated as the difference in mV between the maximum magnitude in the window of 100-300 ms after the peak of the R-wave and the mean of the isoelectric period (50-40 ms) before the peak of the R-wave (between the P-peak and the Q-wave [26]) for each beat and averaged over 5 min. TWA was reported to rise rapidly and then stabilize or decrease slightly.

In Gerber's study [15], using finger pulse oximetry, peripheral capillary oxygen saturation was measured using a vital sign monitoring system (Carescape, Monitor B650). Blood oxygen did not decrease during virtual reality exposure.

In Blum's study [6], the RMSSD - Root Mean Square of the Successive Differences was calculated using the Kubios HRV software [27], an indicator of cardiac vagal tone. Participants in both conditions were reported to have substantially increased cardiac coherence and cardiac vagal tone, suggesting that the virtual reality-based implementation benefits were not manifested.

Discussion

The objective of this scoping review was to scan the literature comprehensively to (1) identify under what type of experimental protocols it could be observed a positive impact on physiological stress by experiencing virtual nature, (2) describe what types of reproduced natural scenery provide said impacts, (3) describe the most commonly used physiological measures of effect, and (4) identify the strengths and gaps in the literature (in terms of methodology) to guide future research.

Strict search limits were used to screen articles in seven interdisciplinary databases, ultimately identifying only 16 peer-reviewed and open-access manuscripts that met the scoping review inclusion criteria. The 16 studies examined in this review revealed that half of the papers implemented a group (nature) versus control (urban) experimental protocol while the rest added variations of the group condition, that is, several natural sceneries compared to an urban. It could also be shown that the most prevalent visualization format used was two-dimensional films (n = 4) and immersive 360-degree videos (n = 3).

In terms of the type of reproduced natural scenery, it was demonstrated that half of the studies reproduced forest scenes, even though parks, beaches and landscapes also appear as used scenery to elicit stress restoration responses. This review finally showed that as little as 6 min of virtual nature exposure significantly and positively impacted defined physiological markers related to relaxation compared to equal durations spent in control settings. Across the 16 studies included, 11 different measures were used to assess changes in participants' physiological markers of stress during virtual nature exposure, including derived calculated measures of main physiological indicators (ECG, EEG, EDA).

Overall, within the included studies, statistically significant differences in physiological health markers of stress were associated with being exposed to virtual nature, including decreased heart rate, salivary cortisol, blood pressure, skin conductance, and sympathetic nervous system activity. Studies that reported mixed results or no decrease in physiological stress attributed some of these results to having included physical activity in their experimental protocols. No significant effect found within these interventions was also attributed to poor data collection processes. The findings of this review are similar to studies of the effect of nature exposure on stress measured by physiologic markers and self-report [28]. According to the papers included in this scoping review, virtual nature can also impact physiological stress reduction.

Immersion technologies

Although immersion and presence are two terms frequently used indiscriminately, immersion represents the objective level of sensory fidelity provided by a virtual reality system [29] while presence is the user's subjective psychological response experiencing a virtual reality system. These two effects have been proposed as the key to the efficacy of mediated or simulated environments to restore physiological stress in many of the studies here included. While it is true that experiential realism can be increased through interactivity or multimodal systems, the immersive technology used during the experience also plays a critical role when it comes to attaining a high level of immersion-presence. In applications other than restorative environments, a significant effect of screen size on subjective presence ratings has been demonstrated [30]. High-resolution displays might provide a detailed and realistic image; however, head-mounted displays provide a sense of visual synchrony by occupying a larger field of view and by updating the visual content in real-time depending on the movement of the head. The larger field of view size and the content update makes the viewing experience more like natural viewing therefore achieving a greater sense of immersion. To this end, the research team suggests considering HMDs in more applied research in various populations, such as the elderly, to evaluate the feasibility of these interventions.

Replication or interpretation

There is a distinction proposed by Kort et al. [7] that differentiates audiovisual material captured from real nature and computer-generated nature. Unlike real nature, computer-generated nature is created with a finite number of variables (objects, shapes, sounds, colours, physics, movement, and light) defined by the researcher [7] and limited by recreation methodology. These limitations make the elements present much more similar to each other compared to those found in real nature. So, the effectiveness of the restorative effect in a virtual environment could depend both on the representative quality, which might include the pictorial realism, the dynamism of the scene, even the possibility of interaction, and the content of the scene, which could be the percentage of the visual field covered by foliage or shrubs or other decorative elements such as deadwood.

Since the level of detail is critical when it comes to judging a representation as more accurate and valid [31], a limitation of the first platforms developed was the lack of realism in the scenes since these first proposals used images in two dimensions that probably did not have excellent quality and resolution due to the available technology.

Although to develop a scene in a game engine it is necessary to have someone with the necessary skill to create an environment (since the scenes are programmed through a series of scripts and the use of libraries), this tool provides functionalities such as rendering engine, location and scene graphics support. These attributes could enhance the sense of presence and facilitate interaction with the end-user compared to films shot in two dimensions where the scene's dynamism is predetermined. Besides, the interaction with nature generated by a computer in virtual reality allows the free exploration of the synthetic environment, while films and screens do not provide such possibilities.

At least with current technologies, it is not yet possible to replicate a restorative environment with its infinite multimodal variables and at the same time allow the user to explore it freely. Whether the different methodologies of direct replication constitute a more immersive alternative than the conception of a restorative environment is still a valid question.

Multisensorialism

Virtual reality focuses heavily on the viewing component, but other components such as sound and smell can further immerse users and contribute to the virtual reality experience [32]. When it comes to pain perception, relaxation, or concentration, the sense of smell plays a crucial role [18]. Previous work has shown that odors modulate pain perception and reduce stress and anxiety [33]. Although researchers have suggested the use of smell to induce a state of physiological relaxation, this review reveals it has been underexplored.

The lack of several non-significant impacts of restorative multisensory environments here presented can be attributed to insufficient simulations. Unlike immersion in the real world, fewer senses are stimulated in virtually created environments. Deeper considerations of the multisensorialism of virtual nature experiences should be considered. For example, is it more beneficial a forest with birds or running water sounds? Researchers might as well compare the impact of different types of virtual nature settings, such as, does adding forest odors to the experience provide greater benefit than just being exposed to the visual and auditive cues?

Physiological measures

The present review attempted to clarify and summarize the characteristics of the most widely used physiological instruments and the experimentation protocols of the literature on the effects on the physiology of restorative environments. Although this review showed a wide range of instruments used, the heart pulse and the conductive skin response were the most used.

The electrocardiogram (ECG) is a digital recording of the possible differences that spread to the skin's surface as a result of the electrical activity of the heart which arises from the contraction and relaxation of the heart muscle. Measuring physiological stress using the heart rate is justified because it is a function of the autonomic nervous system activity, which depends on emotional stimuli [34].

The electrodermal activity (EDA) provides a measure of skin resistance by passing a negligible current or voltage through the body and measuring the voltage or current variation between the two sensor leads placed on the skin; thus, considering the skin as a variable resistance. The EDA signal is characterized by a baseline, from which phasic disturbances arise in response to specific events. Measuring physiological stress using the conductive response of the skin is justified by the fact that the mean value of the EDA signal allows us to infer the level of excitation and activation of the sympathetic nervous system since the EDA response is usually observable in a stressful or surprise event when increased perspiration decreases skin resistance [35].

Additional physiological responses were obtained using a variety of measurement derived from main measurements (for example, measurements derived from the heart pulse such as the inter-beat interval (IBI) or heart rate variability (HRV). A large data modality derived from the different methodologies here presented makes challenging a comparison of effects.

Physiological measures can provide numerous advantages compared to other types of measures, such as continuous, non-invasive, real-time and relatively objective assessment [36], facilitating the investigation of complicated phenomena to capture using self-report methods. They would also allow the study of the association of physiological activity with multimodal stimuli that promote a more significant restoration state. A disadvantage is that the recording equipment is susceptible to the user's movement, and in some situations, as in the use of fMRI, the subject's movement is not allowed at all, yielding to technical limitations. Therefore, not all experimental settings will be suitable for these methods.

A mention should be made of the electroencephalogram (EEG) underexploration as a methodology to study the physiological responses in stress restoration. Small, easy-to-operate, cost-effective, consumer-oriented EEG systems are now available and have already been used to study physiological stress. Despite validation against medical or research-grade equipment, these consumer-oriented EEGs have been shown to register reliable signals but not compared to their generally more expensive professional counterparts.

The methodological feasibility of using EEG equipment combined with virtual reality headsets has been studied. Combining these methods would generate relatively small, predictable and easy to clean interference from the VR headset with the recorded EEG signal. The EEG is widely implemented in the development of the brain-computer interface (BCI), so it is expected that in the coming decades, the use of this methodology will grow exponentially in the technology sector and possibly in the study of brain activity during immersive experiences.

Future work

The core purpose of this review was to provide an assessment of the methodologies, frameworks and research findings of studies of virtual nature for stress reduction. As part of the scoping review objectives, several knowledge gaps have been identified:

The first one is concerning the content of the scene. In this review, the different types of scene chosen by the researchers (i.e. forest, beach, park) were discussed, however, there is no evidence of having identified the elements of the scene that could promote a state of relaxation to a greater extent. Very few studies have focused on the content of the scene perceived by participants, for example, there is evidence that the absence of light causes a state of restlessness in the participant while immersed in a virtual forest environment [37]. The results of a study [38] categorized the attributes of a real forest that the participants detected attractive or interesting in (1) distinctive elements (i.e. a veteran tree), (2) subtle details (i.e. tree branches in ornamental patterns and (3) ephemeral events (i.e. the visual interaction of the sun's rays and the branches of the trees, also known as the Komorebi effect) Do preferences for these attributes have an effect on relaxation while on a virtual environment? In the same way, the study by [10] concludes that it is due to the minimalist design of the presented scene, in which only one point of view was presented, that the participants were unable to judge the scene according to ART theory. This scene of a canopy with fractal dimensions, was generated entirely in computer and intentionally with specific dimensions of fractality, however, there is no evidence if the visual elements reproduced with other tools that allow greater fidelity to reality (i.e. high resolution 360 videos) have been examined with the same fractality scale and if there is a correlation between this dimension and recovery from stress.

The second identified knowledge gap concerns replication with different types of populations. That is, in this review only one study developed with elderly participants in nursing homes and with mild formal rates of dementia is reported; the rest of the studies were carried out with population samples of students or healthy adults. There is no evidence whether these stress recovery results could be the same when presenting virtual reality scenes to people with posttraumatic stress disorder, severe dementia, or some other illness, who, by the nature of the latter, perpetually undergo a certain degree of physiological stress.

Finally, the navigation modalities must be studied. That is, among the variety of platforms developed there are those that allow free and active navigation through the scene (i.e. scenes reproduced in game engines), those that do not allow free navigation through the scene, but instead allow passive movement (i.e. scenes played by videos) and those in which there is no passive nor active displacement. However, the potential mediating role of navigation through virtual nature has not been studied in recovery from stress. We believe that this latter approach should not be studied in a dichotomous way, that is, scenes that allow passive navigation versus scenes that do not allow it, instead from a spatial cognition perspective. Since there is evidence of changes in brain activity between different immersive and navigational settings in virtual environments [39] we believe that navigation, studied as a cognitive process, could have a mediation in the relationship of being present in a virtual environment and thus in stress reduction.

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Chapitre 2 EEG-based affective responses to immersion in a virtual forest

2.1 Résumé

Dans cet article, les cadres théoriques qui décrivent comment la nature peut améliorer le bienêtre humain ont été explorés en utilisant la technologie virtuelle immersive comme nouvelle méthode pour induire un état affectif positif. À l'aide d'un visiocasque, les participants ont exploré une forêt virtuelle. La forêt virtuelle a été reproduite à travers trois méthodologies différentes. Tout au long de l'expérience, les états affectifs des participants ont été mesurés à l'aide d'un outil numérique basé sur l'EEG. Il a été émis l'hypothèse que les différences de réalisme, de dynamisme, de contenu des scènes et de mode d'exploration des différents environnements virtuels auraient des effets différents sur les états affectifs des participants. Cette étude soutient un projet future visant à réduire l'anxiété des personnes atteintes de la maladie d'Alzheimer, qui se situent à un stade avancé, qui sont dans un état constant de stress et de confusion et pour lesquelles il est ardu de se rendre dans la nature.

2.2 Abstract

In this article, theoretical frameworks that describe how nature can enhance human well-being were explored using immersive virtual technology as a novel method to induce a positive affective state. Using a head-mounted display, the participants explored a virtual forest. The virtual forest has been reproduced through three different methodologies. Throughout the experience, the emotional states of the participants were measured using an EEG-based digital tool. It was hypothesized that the differences in realism, dynamism, scene content and mode of exploration of different virtual environments would have different effects on the affective states of the participants. This study supports a future project aiming to reduce anxiety in people with Alzheimer's disease, who are at an advanced stage, who are in a constant state of stress and confusion and for whom it is difficult to go out into nature.

Introduction

The decline of human connection with nature appears to be linked to and perpetuated by modern Western developments, including rapid industrialization, urbanization, and consumerism [1]. As a result, people might experience high culture, freedom, liberation, and a perpetual state of change, but also they can experience confusion, loss of direction, unpredictability, loss of control, and anxiety [2]. Over the last decade, researchers and practitioners have looked for alternative mental health treatments and strategies for improving mood and a person's affective state, including nature-based recreation [3]. They have demonstrated a positive association between nature-based recreation and mental health, including improvements in mood, cognition, restoration, and well-being and decreased anxiety and depression symptoms [4-7].

The attention restoration theory [8] and stress reduction theory [9] are two theoretical frameworks that describe how nature might improve human health and well-being. Kaplan's theory [5, 8] states that fascinating stimuli within a surrounding environment involuntarily capture our attention. Unlike urban environments, natural environments would include stimuli that involuntarily capture our attention (such as swaying leaves or the interaction between light and three branches). However, according to this theory, attention can also be easily disengaged from natural stimuli compared to urban stimuli (such as bright lights or vehicle and construction sounds).

In contrast, Ulrich's theory [9, 10] states that an individual's initial response to immersion within an environment is affective rather than cognitive. This theory declares that the structural properties of an environment (such as its complexity and its spatial allocation) prompt an automatic affective response within the individual. According to this theory, urban stimuli would be perceived as more threatening and thus more physiologically arousing.

Immersive virtual reality and 3D video are new emerging technologies for which researchers are investigating new uses to improve our quality of life at home and in clinical settings [11]. Alongside the broad range of interactive and immersive digital installations that exist [12], previous evidence of physiological data support that virtual reality (VR) environments can also assist in reducing anxiety and stress-related symptoms [13]. A substantial part of the research on the restorative effects of nature reproduced on virtual reality has focused on positive psychological and physiological responses. For example, reported improvements in fatigue, confusion, tension, and blood pressure support the use of virtual nature as a way to improve psychophysiological health [14-16].

Despite supporting the idea that virtual nature might contain properties of real nature that produce attention restoration and stress reduction, previous research does not address whether the way it is experienced through immersive virtual reality technologies could influence for these effects. Therefore, it is necessary to identify if different approaches for experiencing virtual nature will have a distinct affective state altering. To address this, the present study examined the restorative effects of three virtual forests differing in characteristics based on VR methodology reproduction and user experience.

The main objective of this study is to assess whether immersive virtual technology can help individuals to promote a positive affective state. The design of our experiment allows us to compare the effect of different reproduction methodologies and between similar types of restorative virtual environments. We replicated three virtual environments that are different in terms of realism, dynamism, scene content and mode of exploration and will be described below. We hypothesised that given that the three virtual environments are different in nature from each other, then there would be a relative restorative effect on participants' EEG-based markers of affective state..

Physiological stress and affective states

The focus of the following sections will be answering the following research question: can the exposure to a virtual environment of a natural environment relieve stress caused by environmental conditions? Therefore, understanding the concepts of stress and recovery from stress will help answer it.

Across many perspectives, stress has been defined as a way a person responds psychologically, physiologically, and often with behavior in response to a situation that threatens their wellbeing. [17]. In addition, recovery from stress involves various positive changes in psychophysiological states and often in behavior or functioning, including cognitive performance. The psychological component of restoration involves positive changes in affective states such as reduced levels of negatively toned feelings (like fear or anger) and increases in positively toned affect. [18]. Moreover, it appears synchronized to its physiological counterpart, increasing the validity of the findings of nature benefits and revealing a close interdependence between these two components. Therefore, measuring affect via physiological measurements seems justified both by stress and attention restoration theories.

By analyzing data collected with objective methods, investigators in machine learning, affective computing, physiological computing [19]and neuroscience are developing innovative methods for recognizing emotional and affective states. Our study utilized an innovative method based on objective measurements (EEG) to investigate the changes in individuals' affective states.

Methodology

Design

The effect of promoting a positive affective state via simulated nature was studied in an experiment in which participants were exposed to a restorative environment under an immersive setting. Immersion was manipulated between-subjects by varying the simulated environment.

To assess whether the restorative effect of the nature depended on the type of immersion, we measured changes in participants affective states using an EEG-based utility which collects and interprets brain waves. Our experiment was conducted in the following order: orientation, wearing equipment, EEG-utility calibration, being exposed to the VR natural environment, and removing equipment. The total time required was 45 minutes.

Participants were asked to refrain from drinking alcohol and caffeinated beverages the night before and during the day of their laboratory visit. In addition, a previous screening was carried out through an online form to rule out that the participant suffered from any neurological condition that could alter the EEG readings. Among the conditions that we verified with the potential participants were that the participant's medical treatment did not include antidepressants or sedatives, that she/he had not received a formal diagnosis (by a health worker) of brain injury, epilepsy, dementia, loss of memory or head trauma. The participants included in this study received compensation for the time invested in our study and for travel fees.

Participants were recruited from the Québec City area and the Laval University using fliers and the university email list and were randomly assigned to a lidar, hybrid or 360-degree condition. The ethical approval for the installation study was sought and obtained in September 2021 from the Research Ethics Board of the IRDPQ.

Setting

The experiment was carried out in a laboratory at the Interdisciplinary Research Center in Rehabilitation and Social Integration (CIRRIS). The participants were seated on a chair during the entire session. The equipment for taking physiological records was placed behind the participant and is described in the next sections. We ensured a calm and noise-free surrounding outside the lab room.

Equipment

Virtual reality headset

For the virtual reality experience, participants were randomly assigned to a lidar, hybrid or 360-degree forest condition. These simulated environments were displayed to the user in an HTC VIVE Cosmos (as shown in Figure 1), a head-mounted virtual reality display with a 2880x1700 combined pixel resolution and audio integrated into on-ear, form-fitting headphones. The need to use the controllers depended on the scene to which the participant was assigned.

Figure 2-1 HTC VIVE Cosmos head-mounted display used in this study

Olfactory stimulus

To dispense scents, we used a scent diffuser to provide the participant the same olfactive stimuli for the three conditions as the three simulated environments were reproduced from the same natural environment. A constant mist deliver was set, and the type of scent used in this work was diluted natural Balsam fir oil. Participants were given the option to remove this element if wished.

Electrode cap

The EEG, serving as a measure for brain activity and the current affective state, was recorded using a modified version of the commercial Gelfree BCI Electrode Cap (OpenBCI, NY, USA). It is a low-cost wearable EEG system for nonmedical purposes, shown in Figure 2. The flexible cap provides fourteen active electrodes, located at the international 10-20 system electrode positions Fp1, T8, C4, F3, P8, F7, O1, O2, Fp2, T7, C3, F4, P7, F8, P3 and P4; and two reference electrodes located on the earlobes. In order to determine the users' affective states, we computed the user's emotional state based on a new real-time facial expression recognition based on EEG data "NeuroExpress" [20].

Figure 2-2 BCI Electrode Cap for nonmedical purposes

NeuroExpress

Using AI models, NeuroExpress [20] (BMU Labs, Montreal, Canada) recognizes facial expressions data from the EEG cerebral signals with a precision reaching 92% compared to the camera-based Facial expression recognition software iMotions Facet [20]. The tool NeuroExpress visualizes in real time the intensity of each facial expression as curves over time (6 outputs/sec). It outputs 10 facial expressions classified in 6 basic affective states (Happy, Anger, Surprise, Fear, Disgust and Sadness), 1 secondary emotion (Contempt), and 3 non-classified emotions (Valence, Arousal and Neutral).

Virtual environments

The virtual environments presented here are three faithful reproductions of natural forests located in the surroundings of Quebec City (Canada): the Duchesnay Forest and the Stoneham Mountain. All virtual environments were reproduced in similar weather conditions, partially sunny and breezeless, to ensure that all scenes had the same degree of movement. Although the lidar scans and 360-degree immersive video were not captured at the same time of year (the lidar scans in spring and the immersive video during autumn) efforts were made to ensure that vegetation, such as grass and canopy foliage, were not obscured by dry weather and appeared homogenous among the three scenes. In terms of content, the three scenes are characterized by the absence of people close to the camera, closed but defined spatial configurations, the predominant presence of native tree species, the exclusion of animal species and a first-person perspective.

The “lidar forest”

The "lidar forest", shown in Figure 3, is a virtual forest completely reconstructed from lidar data; up to 21 different scans from a terrestrial lidar scanner were combined to reconstruct an area of approximately 10 hectares (ha). After joining the scans and coloring the point cloud from images, data was downsampled and the Unreal Engine lidar plugin was used to visualize and broadcast the dense point cloud to the HMD. The final environment consisted of a static (i.e. no leaf or branch movement) yet complex environment with a spatial resolution of 1 point per half squared centimeter. The participants experienced an active exposure to this scene since the participant could freely move his head observing his surroundings and exploring voluntarily throughout the delimited forest path using the joystick, although the navigation speed could not be varied.

Figure 2-3 The "lidar forest"

The "hybrid forest"

The hybrid forest, shown in Figure 4, was conceived employing a novel pipeline that combines the use of lidar data and three-dimensional models to reproduce virtual environments. For this, the ground surface was reconstructed using only lidar data up to a height of approximately 50cm; in this way, elements adjacent to the ground such as rocks, loose leaves, branches and even small bushes and sectioned trunks, could be represented by means of point clouds. A stem map allowed us to know the positions and diameters of the trees present in the forest where the scans were made, these data were used to place trees of predominant species in the area through the virtual environment. Three-dimensional models of sugar maples, basswood, balsam fir and paper birch were sketched using the SpeedTree 3D tree library and software and then imported into the Unreal Engine. The final environment consisted of a forest environment with about 500 trees in the visual field; the crowns of these trees reacted to the variations of the simulated wind and the interaction of the light with the branches of the trees could also be appreciated. The participants, as in the previous environment, experienced an active exposure to this scene, being able to freely turn their heads and move at will along the delimited forest path using the joystick, although without being able to vary the navigation speed.

Figure 2-4 The "hybrid forest"

The “360-degree forest”

The "360-degree forest", shown in Figure 5, is a 360-degree video produced using a high definition GoPro Max action camera and a Mavic DJI Pro drone. The footage simulated a walk at a slow speed of approximately 12 minutes in which a stream of water, trunks and treetops of native species could be seen. To disguise the sound of the drone's propellers, a second panning, this time walking the same path was recorded to capture the sounds of the forest and running water. Both videos were processed with the GoPro Player utility and edited with Adobe Premier PRO. The final scene consisted of an immersive video with 5.7k resolution, encoded with the h.264 codec and was reproduced to the participants with the VIVEPORT VIDEO application. Particular attention was paid to editing the immersive sound in which the constant sound of running water predominated. The participants experienced a passive exposure to this scene since although the participant could move his head and freely observe his surroundings, the camera motion was involuntary, and its speed could not be varied; as a result, the user was neither able to move at will.

Figure 2-5 The “360-degree forest”

Procedure

After obtaining the participant's consent, the experimental process, the procedures, and the function of the relevant equipment within the experiment were explained to them. Each group of participants was asked to experience only one type of virtual environment, which was randomly assigned upon arrival.

The portable EEG electrode was then placed on the participants' scalp, and they were asked to sit facing the wall to temporarily exclude external visual stimuli. They were then asked to remain seated to allow the NeuroExpress utility to self-calibrate in order to identify baseline measurements of their affective states.

Next, the head-mounted display was used to allow the participants to explore the virtual environment corresponding to his/her group assigned. All participants’ EEG-based affective states data EEG data were collected during the watching time. Finally, the head-mounted display and portable EEG electrode were removed from participants.

Statistical analysis

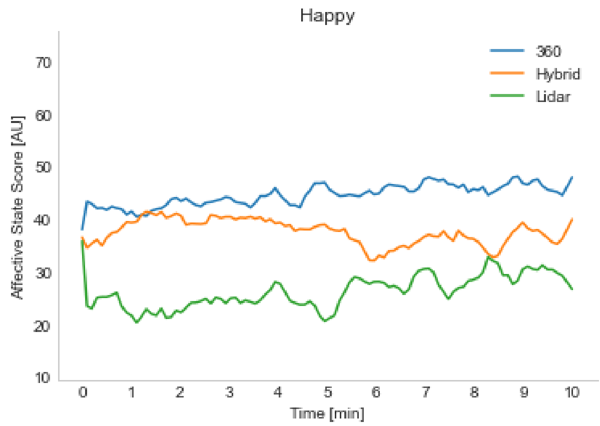
In order to test whether the difference in terms of scene content and interaction resulted in any difference on the affective states of the participants, two-way mixed ANOVA were performed for each of the affective state scores including time (1 to 10 minutes) and group (360, hybrid and lidar) factors. For each of these variables, the means and standard deviation values were also calculated. Tests of simple effects were also conducted with Bonferroni adjustments to further analyze the effect of the significant interactions. All the tests were conducted using the IBM SPSS software (IBM Inc.).

Results

Thirty-four participants aged between 19 and 47 years old (mean age = 26.71, standard deviation = 5.76), took part in this study in October 2021. Of these thirteen participants, 33% were male and 67% were female. There were eleven subjects in the lidar and 360 forest groups and twelve in the hybrid forest group.

Effects of virtual nature on affective state scores

The results of the EEG-based affective states scores during the lidar, hybrid and 360 conditions are visualized in Figures 2-6 to 2-15. Box plots of the NeuroExpress affective state means are shown in Figures 2-16 to 2-25, with their corresponding values listed in Table 2-1.



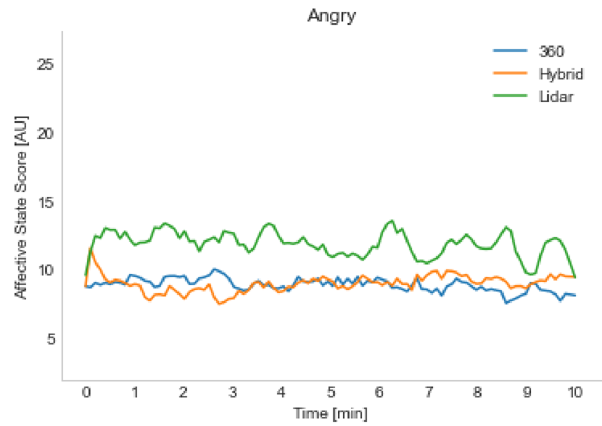
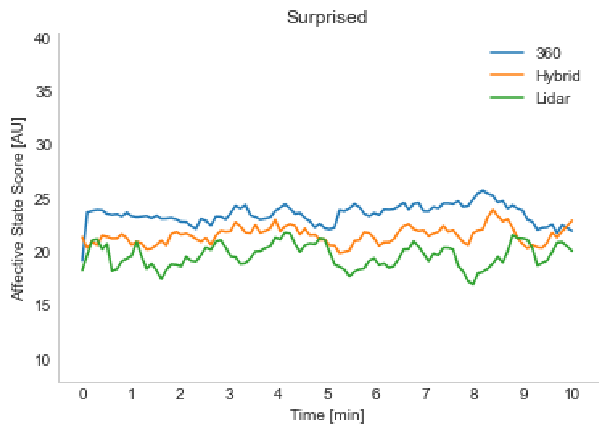


Figure 2-6 (Left) Scores of Happy affective state over time for all conditions

Figure 2-7 (Right) Scores of Angry affective state over time for all conditions



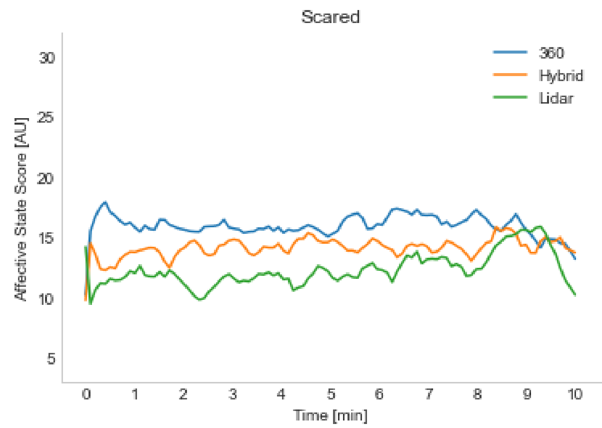
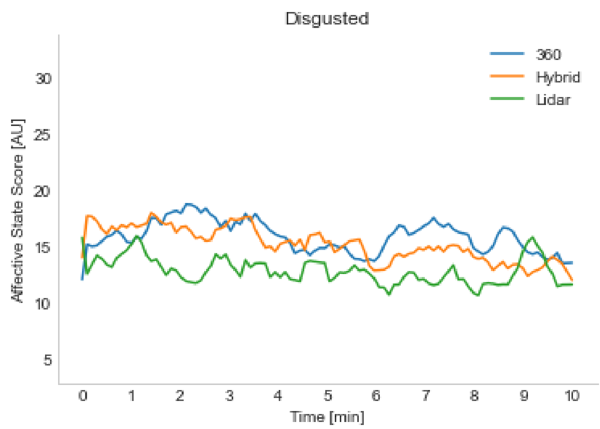


Figure 2-8 (Left) Scores of Surprised affective state over time for all conditions

Figure 2-9 (Right) Scores of Scared affective state over time for all conditions



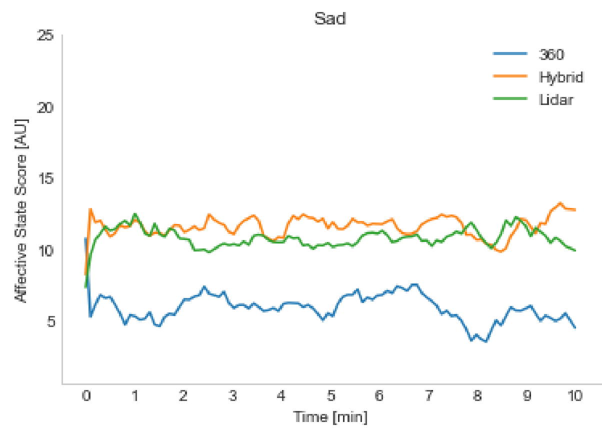
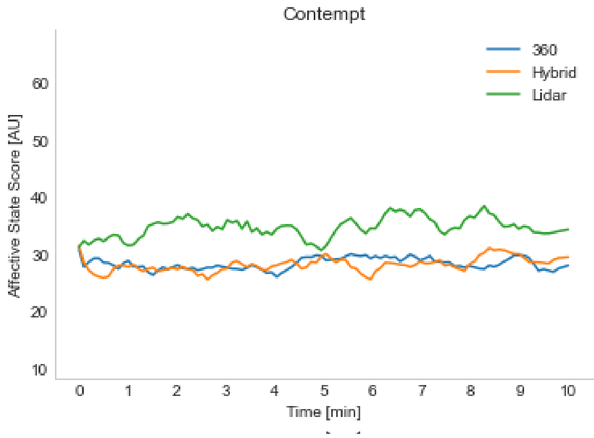


Figure 2-10(Left) Scores of Disgusted affective state over time for all conditions

Figure 2-11(Right) Scores of Sad affective state over time for all conditions



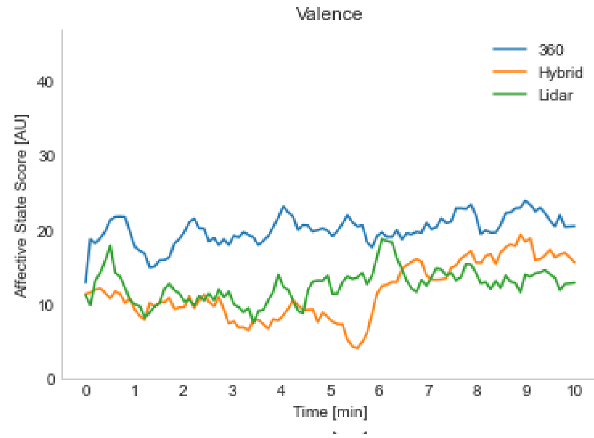
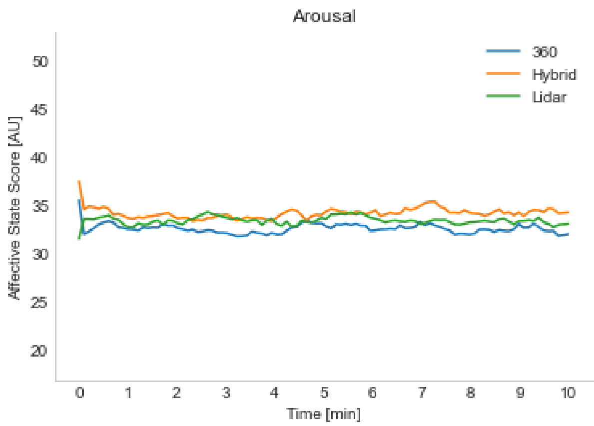


Figure 2-12 (Left) Scores of Contempt affective state over time for all conditions

Figure 2-13 (Right) Scores of Valence affective state over time for all conditions



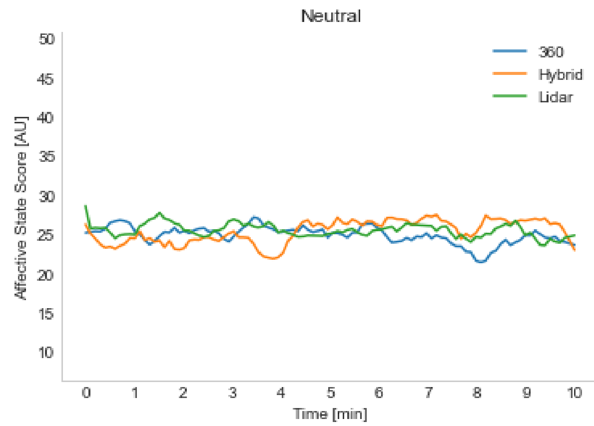


Figure 2-14 (Left) Scores of Arousal affective state over time for all conditions

Figure 2-15(Right) Scores of Neutral affective state over time for all conditions

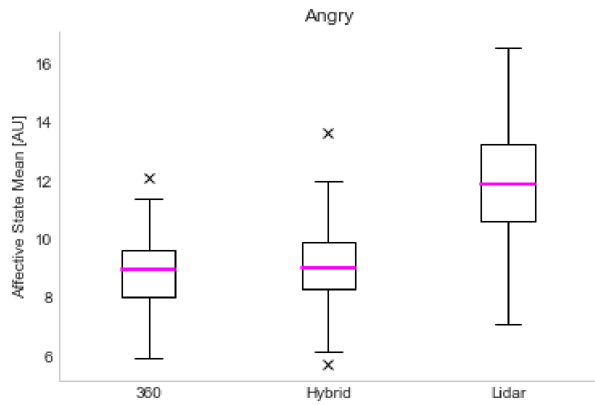
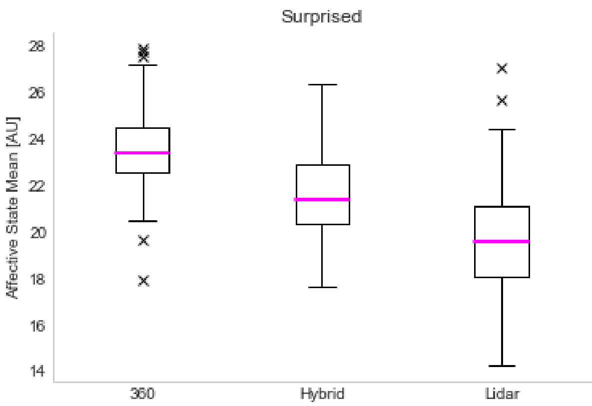


Figure 2-16 (Left) Mean box plots of Happy affective state for all conditions

Figure 2-17 (Right) Mean box plots of Angry affective state for all conditions



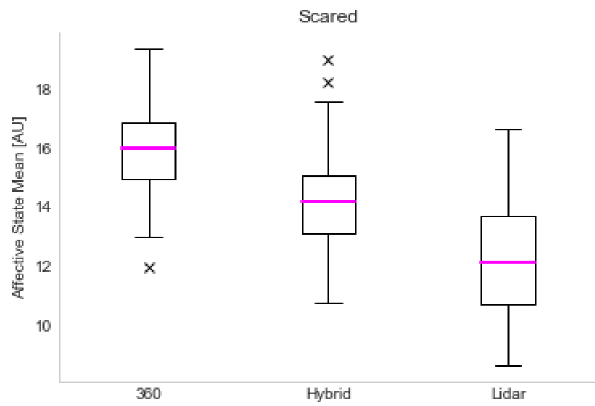
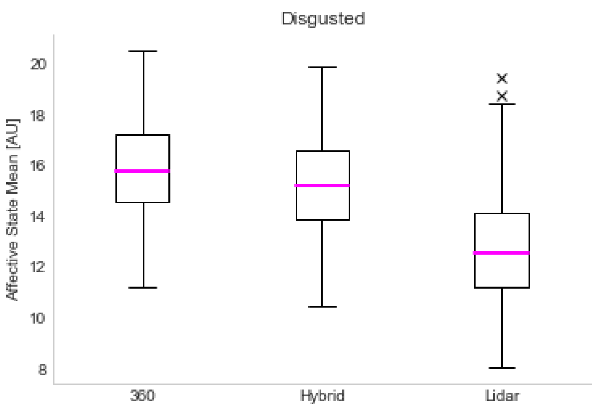


Figure 2-18 (Left) Mean box plots of Surprised affective state for all conditions

Figure 2-19 (Right) Mean box plots of Scared affective state for all conditions



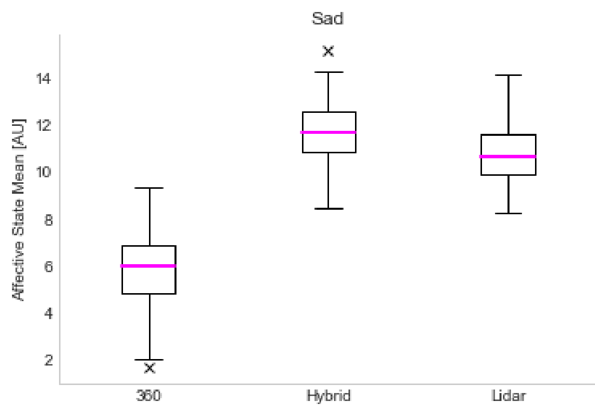
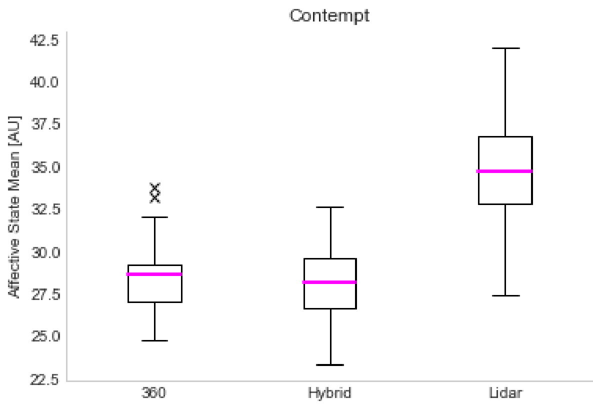


Figure 2-20 (Left) Mean box plots of Disgusted affective state for all conditions

Figure 2-21 (Right) Mean box plots of Sad affective state for all conditions



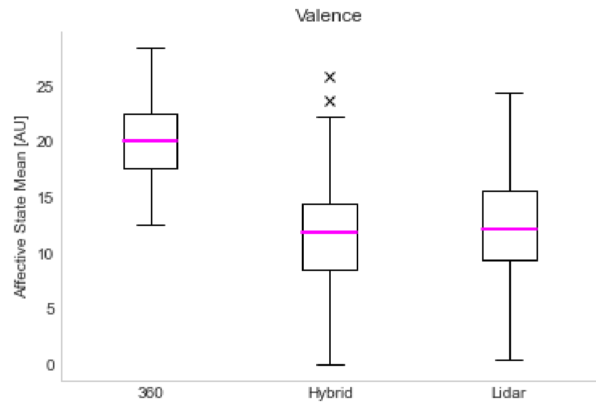
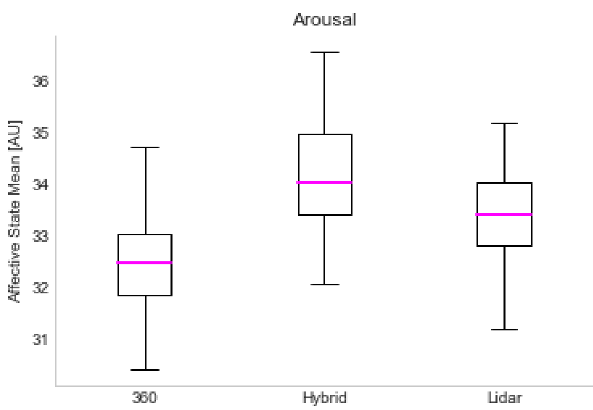


Figure 2-22 (Left) Mean box plots of Contempt affective state for all conditions

Figure 2-23 (Right) Mean box plots of Valence affective state for all conditions



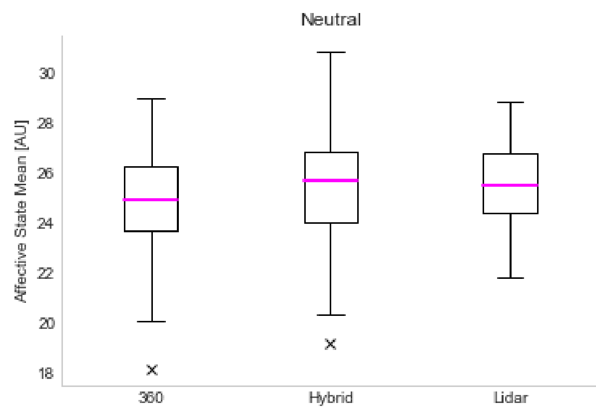


Figure 2-24 (Left) Mean box plots of Arousal affective state for all conditions

Figure 2-25 (Right) Mean box plots of Neutral affective state for all conditions

Table 2-1 Mean and standard deviation of the affective state scores during study

Affective State	Condition	M	SD	Affective State	Condition	M	SD
Happy	360	44.67	2.96	Sadness	360	5.87	1.54
	Hybrid	37.63	3.52		Hybrid	11.65	1.38
	Lidar	26.22	4.47		Lidar	10.81	1.38
Anger	360	8.93	1.19	Contempt	360	28.31	1.81
	Hybrid	9.05	1.32		Hybrid	28.13	1.97
	Lidar	11.93	1.83		Lidar	34.70	2.96
Surprise	360	23.55	1.78	Valence	360	20.11	3.45
	Hybrid	21.50	1.77		Hybrid	11.75	5.01
	Lidar	19.64	2.30		Lidar	12.55	4.39
Fear	360	16.02	1.41	Arousal	360	32.51	0.83
	Hybrid	14.21	1.55		Hybrid	34.13	1.00
	Lidar	12.30	1.99		Lidar	33.39	0.83
Disgust	360	15.90	2.01	Neutral	360	24.96	1.82
	Hybrid	15.24	2.08		Hybrid	25.40	2.26
	Lidar	12.83	2.16		Lidar	25.54	1.65

Effect of time

The results of the Two-Way Mixed ANOVA showed that there was no significant main effect of time (df = 98, 3430) on Happy (F = 1.054, p = .341, η_p^2 = .029), Anger (F = 1.205, p = .086, η_p^2 = .033), Surprise (F = 1.231, p = .063, η_p^2 = .034), Fear (F = 1.128, p = .186, η_p^2 = .031), Sadness (F = .804, p = .920, η_p^2 = .022), Contempt (F = 1.102, p = .234, η_p^2 = .031), Arousal (F = .996, p = .493, η_p^2 = .028) or Neutral (F = .795, p = .931, η_p^2 = .022) affective state scores.

In contrast, there was a significant main effect of time on Disgust (F = 1.250, p = .050, η_p^2 = .034) and Valence (F = 1.369, p = .010, η_p^2 = .038) affective state scores.

Table 2-2 Results of Two-Way Mixed ANOVA of the experimental effects on affective states scores

Affective State	Variables of Interest	F	df	p	η_p^2	Affective State	Variables of Interest	F	df	p	η_p^2
Happy	Time	1.054	(98,3430)	.341	.029	Sadness	Time	.804	(98,3430)	.920	.022
	Condition	3.311	(2,35)	.048	.159		Condition	3.039	(2,35)	.061	.148
	Time:Condition	1.366	(196,3430)	.001	.072		Time:Condition	1.094	(196,3430)	.182	.059
Anger	Time	1.205	(98,3430)	.086	.033	Contempt	Time	1.102	(98,3430)	.234	.031
	Condition	1.962	(2,35)	.156	.101		Condition	.645	(2,35)	.531	.036
	Time:Condition	1.264	(196,3430)	.009	.067		Time:Condition	1.160	(196,3430)	.068	.062
Surprise	Time	1.231	(98,3430)	.063	.034	Valence	Time	1.369	(98,3430)	.010	.038
	Condition	1.375	(2,35)	.266	.073		Condition	3.271	(2,35)	.050	.157
	Time:Condition	.998	(196,3430)	.494	.054		Time:Condition	.831	(196,3430)	.956	.045
Fear	Time	1.128	(98,3430)	.186	.031	Arousal	Time	.996	(98,3430)	.493	.028
	Condition	.161	(2,35)	.852	.009		Condition	3.287	(2,35)	.049	.158
	Time:Condition	1.183	(196,3430)	.046	.063		Time:Condition	.886	(196,3430)	.867	.048
Disgust	Time	1.250	(98,3430)	.050	.034	Neutral	Time	.795	(98,3430)	.931	.022
	Condition	1.541	(2,35)	.228	.081		Condition	.100	(2,35)	.905	.006
	Time:Condition	.948	(196,3430)	.683	.051		Time:Condition	1.210	(196,3430)	.028	.065

Post hoc comparisons with Bonferroni corrections were further performed for significant factors. Pair-wise comparisons with Bonferroni adjustments were further performed for factor time. For Disgust affective scores, a significant difference was found between minutes 1 and 7 ($p = .001$), between minutes 1 and 9 ($p = .025$), and between minutes 4 and 7 ($p = .024$) and are shown in Figure 8. For Valence affective scores, no significant difference was found for factor time during pair-wise comparisons.

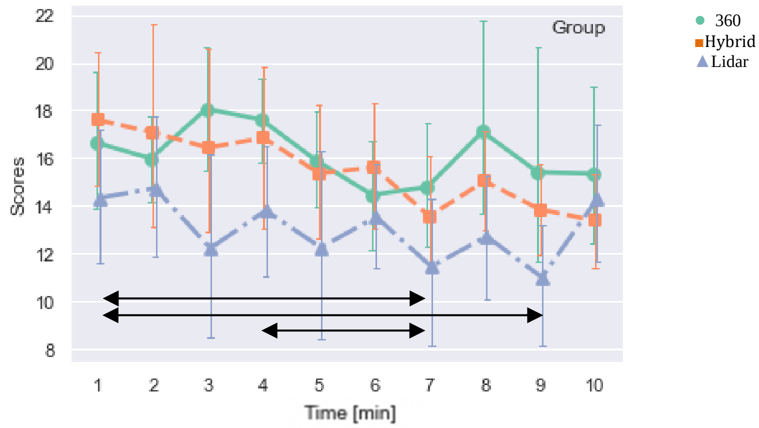


Figure 2-26 Scores of affective state Disgust over time for all groups (↔ indicate $p \leq .05$)

Effect of condition

The results of the Two-Way Mixed ANOVA showed that there was no significant main effect of condition (df = 2, 35) on Anger (F = 1.962, p = .156, η_p^2 = .101), Surprise (F = 1.375, p = .266, η_p^2 = .073), Fear (F = .161, p = .852, η_p^2 = .009), Disgust (F = 1.541, p = .228, η_p^2 = .081), Sadness (F = 3.039, p = .061, η_p^2 = .148), Contempt (F = .645, p = .531, η_p^2 = .036) or Neutral (F = .100, p = .905, η_p^2 = .006) affective state scores.

In contrast, there was a significant main effect of condition on Happy (F = 3.311, p = .048, η_p^2 = .159), Valence (F = 3.271, p = .050, η_p^2 = .157) and Arousal (F = 3.287, p = .049, η_p^2 = .158) affective state scores.

Pair-wise comparisons with Bonferroni adjustments were further performed for group factor. For Happy affective scores, a significant difference was found between 360 and lidar forest group condition (p = .043). For Arousal affective scores, a significant difference was found between 360 and hybrid group condition (p = .045). For Valence affective scores, no significant difference was found for factor group during pair-wise comparisons.

Interaction between time and condition

The results of the Two-Way Mixed ANOVA showed that there was no significant interaction between time and condition (df = 196, 3430) on Surprise (F = .998, p = .494, η_p^2 = .054), Disgust (F = .948, p = .683, η_p^2 = .051), Sadness (F = 1.094, p = .182, η_p^2 = .059), Contempt (F = 1.160, p = .068, η_p^2 = .062), Valence (F = .831, p = .956, η_p^2 = .045) or Arousal (F = .886, p = .867, η_p^2 = .048) affective state scores.

In contrast, there was a significant interaction between time and condition on Happy (F = 1.366, p = .001, η_p^2 = .072), Anger (F = 1.264, p = .009, η_p^2 = .067), Fear (F = 1.183, p = .046, η_p^2 = .063) and Neutral (F = 1.210, p = .028, η_p^2 = .065) affective state scores.

A test of simple effects was also conducted with Bonferroni adjustments to further analyze the effect of these significant interactions finding significative comparisons shown in Table 2-3, all other comparisons not shown were found not significative (p-value > .050).

Table 2-3 Comparison of interaction between variables

Factor	Affective State	Time Variable (min)	Comparison	p
Time*Group	Happy	1	360 vs Lidar	.038
		6	360 vs Lidar	.014
		7	360 vs Lidar	.034
		8	360 vs Lidar	.033
	Neutral	9	360 vs Hybrid	.015

Discussion

In this paper, six basic emotions (Happy, Anger, Surprise, Fear, Disgust and Sadness), one secondary emotion (Contempt), and three non-classified emotions (Valence, Arousal and Neutral) were used in the current study to examine how being immersed in virtual nature affects an individual's affective state. The results showed that Disgust affective scores decreased in time across all three conditions, that the Happy and Arousal affective scores varied between 360 and lidar and 360 and hybrid, and that there was a factor interaction between 360 and lidar Happy affective state scores. We found that although experiencing nature in virtual reality can improve a feeling of Disgust, the mode of experiencing a virtual forest environment can also play a significant role in its restorative effects.

Our first finding was converging evidence, primarily based on the Disgust measure, that natural scenery experienced through innovative VR technologies produced a restorative effect. Being immersed in the virtual nature setting prompted a decrease in negative Disgust affect, as seen in Figure 8. This finding is consistent with several previous studies that reported that virtual nature could have restorative properties on affect and physiological stress [21].

Furthermore, the way in which the virtual environment is allowed to be explored, apart from the natural setting shown, could have directly influenced the observed restoration. Except for the virtual environment they explored, all participants followed the same protocol. The three virtual environments were faithful recreations of different environments and offered different modes of exploration, i.e. participants could explore at will using the joystick in the lidar and hybrid environments, while in the 360-degree condition they could only look at what they wanted.

These results are not conclusive; however, we have been able to identify, based on pairwise comparisons of Happy's affect scores, that those immersed in the 360-degree condition may be likely to experience a significant improvement in affect, thus reducing stress. If more statistically significant results are available, this study could support our predictions suggesting that the virtual nature exploration modality, specifically the passive experience, is likely to be responsible for an observed positive change in affect. In a similar study, Brivio et al. [22] had already reported that a 360-degree panoramic environment was no different from a computer-generated environment in promoting a sense of presence, reducing anxiety and improving emotional states. One possible explanation for this inconsistency is that these authors used 360-degree and game engine-based videos in their protocol but did not grant participants the option of using a joystick in any group conditions. Although studies have found no effects in learnability or presence among the use of joystick, teleportation or leaning techniques for in-place locomotion [23], there is still no study comparing passive viewing without joystick use against active exploration of a virtual environment.

Another possible explanation is related to the soundscape differences among the environments. In contrast to the rest of the environments which included mostly air and bird noise, only the 360-degree environment had running water sounds. The higher Happy scores for the only environment with flowing water sounds are consistent with Jeon et al. 's research [24], which found that streams and lake waves are preferred over the sound of birds in the forest; however, our results may be due to the small sample size or due to a large individual variation in the sample.

Despite no significant differences between hybrid forest and lidar forest being found on pair-wise comparisons, it is noteworthy that hybrid forest scores on Happy affective state scores (M = 37.63 SD = 3.52) were higher than those of the lidar forest (M = 26.22, SD = 4.47). As evidenced by physiological measurements, this is consistent with findings suggesting that subjects exposed to more visual realism felt a stronger sense of presence in VR applications [25]. An additional feature of this study was to explore the innovative use of lidar technology in therapeutic applications. Although in this study, the environment recreated with lidar underperformed compared to the 360-degree and the hybrid forests, we believe that exploring the adoption of advanced point cloud visualization strategies by making them dynamic and interactive could improve the level of realism of the scene, therefore increasing a sense of presence and consequently improving the affective state of the user.

The two-dimensional Valence-Arousal plane first described by Wundt et al. [26] appears to be a congruent approach for explaining the significant difference ($p = .045$) between 360-degree and hybrid group conditions on Arousal affective state scores. According to his model, Excitation or Annoyance are categorized in the high Arousal axis, while Calmness or Sleepy are situated in the low Arousal axis. We suggest that the 360-degree environment that underperformed compared to the hybrid environment is perceived as less stimulating because specific attentional resources were not focused on using the joystick for active exploring. Supporting this, is a study exploring episodic memory in amnestic mild cognitive impairment and Alzheimer's disease proposed that actively exploring an environment does not trigger the same cognitive processes as viewing that environment as a video [27].

Future work

We did not observe statistically significant results for additional affective scores mainly due to the small sample size. Therefore, increasing the sample size according to the observed effect sizes in a future study seems an interesting alternative. Another explanation might be due to the use of the EEG and the HMD combined, as there are no many studies that have achieved this but could lead to a high noise-to-signal ratio. It should be mentioned that few participants commented on a slight discomfort when wearing both helmets at the same time. Future work, then, would consider using less invasive electrodes or smaller devices such as the NeuroSky portable brainwave device.

In this research we learned new insights for developing immersive restorative environments. A few participants remarked on the environments' realism, while others criticized it. This feedback will lead to a restructuring of the proposed project and will be emphasized in the future design process. For instance, people expected to see animals browsing around. Even when participants were familiar with tree species shown within the environments, they might also be familiar with squirrels or marmots surveying around a forest, something familiar to find during summer within the real environments that were reproduced.

Since this study continues to support the effectiveness of simulated nature using a consumer-grade such as the HTC VIVE HMD and toolkits available to the general public, we believe that researchers should explore targeting therapeutic solutions that can be brought to populations whose degenerative conditions produce an acute and constant state of stress, decrease in quality of life and are deprived of easy access to a real restorative environment, such as populations with Alzheimer's-type dementia. Future work will consist of implementing the methodology for designing interactive and immersive installations focusing on people with disabilities [28] on those scenes we consider appropriate for this population: the 360-degree scene and the hybrid environment. In addition, we would also consider the lidar environment if more dynamism could be added to the environment.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Audiovisual examples

Some video extracts of the virtual environments presented here are available on the website of the Communauté de Recherche Interdisciplinaire sur la Vulnérabilité: https://www.criv.online/frreyes-foretvr/

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Conclusion

L'objectif de ce projet de maîtrise était de développer des technologies d'assistance potentielles basées sur la réalité virtuelle pour favoriser un meilleur état affectif pour les personnes qui vivent avec l'anxiété et le stress en raison de leur maladie neurodégénérative. Le système numérique de promenade en forêt se veut une alternative pour soulager ces symptômes qui affectent et aggravent l'humeur et la qualité de vie de ces patients.

Ce mémoire présente donc la viabilité d'utiliser ce système d'assistance numérique dans un premier temps avec des personnes sans maladies neurodégénératives. La possibilité de combiner un système d'électroencéphalogramme pour mesurer quantitativement les changements d'états affectifs est également présentée, dans un premier temps chez les personnes en bonne santé.

Bien qu'il s'agisse d'une approche innovante, c'est-à-dire de vivre une expérience à travers un visiocasque tout en enregistrant l'activité cérébrale grâce à des électrodes placées sur la tête, il faut être prudent en voulant utiliser cette méthode pour de futurs tests avec des patients. Cette prémisse précédente est basée sur certains commentaires provenant d'un petit pourcentage de participants sur la façon dont il peut être inconfortable d'utiliser les deux appareils en même temps. Elle est également basée sur la faible puissance statistique des résultats, ce qui pourrait indiquer des altérations des lectures dues à l'utilisation simultanée de ces deux systèmes électroniques.

Les différents environnements présentés sont basés sur les principes des théories de la réduction du stress et de la restauration de l'attention, bien que les versions présentées dans la thèse ne soient pas les versions finales.

L'axe principal des travaux futurs sera d'enrichir au moins deux des environnements que l’on a utilisés dans cette expérience ; ceux qui ont généré une plus grande réponse affective chez les participants, la forêt hybride et la forêt à 360 degrés. Un travail plus approfondi avec la forêt recréée avec des données lidar pourrait être envisagé si les nuages de points pouvaient être rendus dynamiques. Il existe des applications de visualisation sur écrans d'ordinateurs qui permettent de dynamiser ces données, cependant cette méthodologie n'a pas encore été explorée pour son utilisation en réalité virtuelle.

Une partie de cette amélioration du système consistera à mettre en œuvre la méthodologie de conception universelle itérative pour fournir une approche à l'usage des personnes handicapées. Le système résultant fera partie des essais expérimentaux avec des patients partenaires pour analyser les avantages et les inconvénients de la dernière version de cet outil potentiellement thérapeutique.

Les travaux techniques présentés ici s'inscrivent également dans un programme de recherche plus large visant à développer divers systèmes d'aide et d'assistance basés sur la réalité virtuelle, très utiles dans le développement de futures technologies d'assistance.

Des extraits vidéo des environnements virtuels présentés ici sont disponibles sur le site de la Communauté de Recherche Interdisciplinaire sur la Vulnérabilité : https://www.criv.online/frreyes-foretvr/.

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